DAY THREE

NEW TECHNICAL DEVELOPMENTS. FLIGHT INSPECTION SYSTEMS

NEW TECHNICAL DEVELOPMENTS. NAVAIDS AND FACILITIES

GNSS FLIGHT INSPECTION

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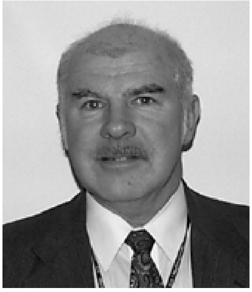

DIRECT ANTENNA CURRENT MEASUREMENTS PROCESS OF IMAGE TYPE GLIDE SLOPE ARRAYS

ABSTRACT

Special Instrument Landing System (ILS) receivers are used to evaluate the performance of all Glide Slope facilities. The maintenance, repair, and restoration of the image type glide slopes have been accomplished by the measurement of near field composite antenna currents. This is an indirect measurement of antenna currents which represent the characteristics of the glide path angle and off-path sensitivity.

Instrument Landing Systems (ILS) Field Support Engineers of the Federal Aviation Administration (FAA) National Airways System Engineering Division have for many years successfully utilized a direct measurement, an induction field measurement method, to optimize the radiated signal indications of image type glide slope. This method uses a vector voltmeter (VVM) to measure the induction field antenna currents (amplitude and phase).

This paper provides an overview of the VVM method in setting initial antenna currents to theoretical values (in preparation for a reference airborne evaluation) and for taking reference readings after overall system performance is deemed optimum for the user. The latter readings serve as the long term, stable references that permit most image type glide slope antenna systems to be optimally maintained, repaired, and restored to service without a special airborne evaluation.

OVERVIEW

Portable ILS Receivers (PIR) are used to evaluate the performance of all glide slope facilities. Airborne receiver indications confirm in-flight correctness of ground facility performance and ground based receiver indications provide reference readings used to maintain or restore optimum signal values. Radiated signal characteristics such as glide path angle and off-path sensitivity are indirect derivatives of the detected modulation output products taken from these calibrated standards.

Ground facility personnel record facility reference readings immediately following airborne evaluations reporting optimum values for operational performance parameters. Some reference readings for image type glide slope systems are obtained using the indirect method with a PIR assembly located in the near radiation field of the antenna array. These radiated signal readings are seen as representing optimum signal amplitudes and phases in the antenna elements. Obtaining repeatable and reliable receiver indications at these near field check points is difficult due to unavoidable variations in electrical and physical properties in this measurement environment. Some airports have ground measurement points that are difficult to access or are in locations that are undesirable and measurement readings that may contain interference. Spectral emissions and signal reflections from vehicular traffic in the area, undesired signal reception from outside the local area, and seasonal changes in ground surface reflection properties are three factors that can invalidate PIR indications of glide slope performance.

ILS Field Support Engineers of the FAA National Airways System Engineering Division have for many years successfully utilized the direct method, an induction field measurement, to optimize the radiated signals indications of image type glide slopes. This method involves using a VVM to take amplitude and phase readings of pre-radiated currents near the antenna surface. Direct samples of RF signals taken in the induction field provide the requisite repeatability needed to maintain and restore optimum glide slope system performance and assure radiated signals that correlate with airborne receiver indications of angle and width.

The direct measurement method can be used on most all image type antenna systems. This includes the null reference, sideband reference, and capture-effect glide slope arrays. The direct method uses an RF antenna probe and a vector voltmeter and does not require ground measurement points. A flight inspection is not required to restore the glide slope after all system electrical and physical properties are verified, i.e., all transmitter parameters are set to reference values and antenna heights and offsets have not changed.

EQUIPMENT

The direct measurement method requires a vector voltmeter, radio frequency (RF) probe, and quality double shielded coax. The coax is very important for good repeatable results. ILS Field Support Engineers in the FAA National Airways System Engineering Division have for many years successfully used the following equipment: Hewlett Packard model 8508A vector voltmeter, Antenna Products Glide Slope RF Probe, and RG-400 coax with «N» connectors (figures 1 through figure 4). The RF Probe may also be called an «H» Probe.

Figure 1. Vector Voltmeter

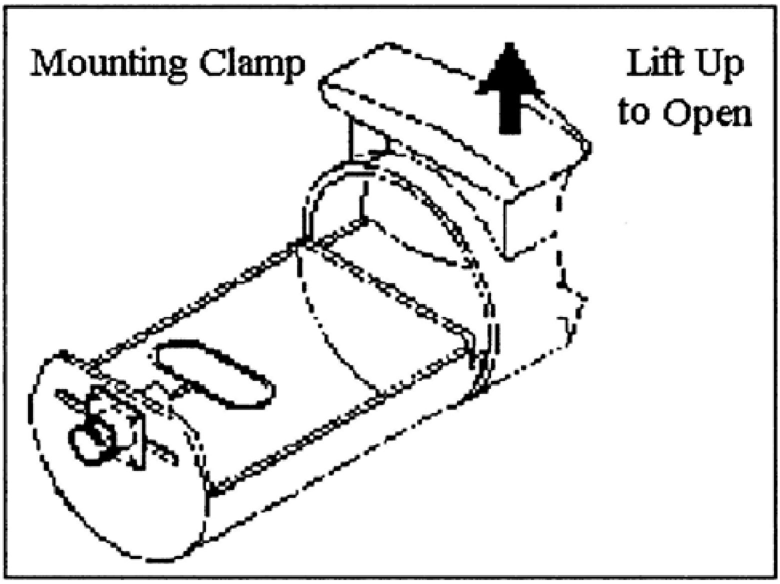

Figure 2. Drawing of RF Probe.

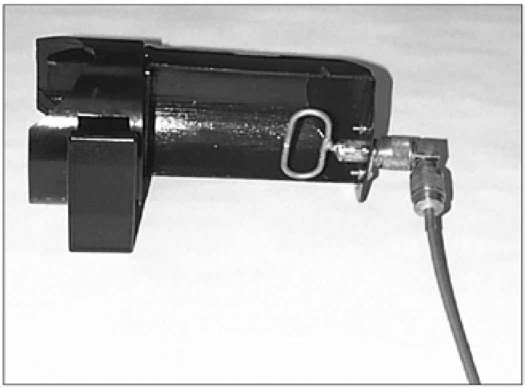

Figure 3. RF Probe.

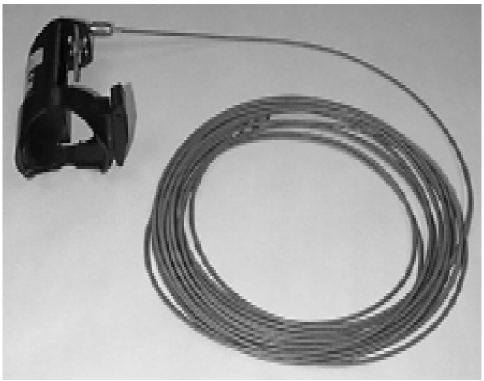

Figure 4. RF Probe with RG-400 Coax.

ANTENNA SYSTEM PHASING

Antenna System Phasing Before Initial Flight Check

The capture-effect glide slope system will be considered in this example although the concept applies to other image type glide slope configurations. The transmitter and antenna distribution unit, (Amplitude Phase & Control Unit - APCU), are adjusted for theoretical or operational values. Once the transmitter and APCU are optimized, the transmitter unmodulated carrier is connected to the Sideband Only (SBO) input of the APCU. The transmitter SBO coax is terminated. The Carrier Sideband (CSB) input to the APCU is terminated. The clearance transmitter is turned off or the transmitter output and APCU input are terminated.

This configuration will provide carrier at all three

Figure 5. RF Sniffer manufactured by Bird Electric.

antennas. The middle antenna is used as a reference. Using the vector voltmeter, connect channel A to the non-directional RF sniffer (figure 5), and sniff the RF at the APCU SBO input (figure 6). This measurement will establish a reference for the vector voltmeter.

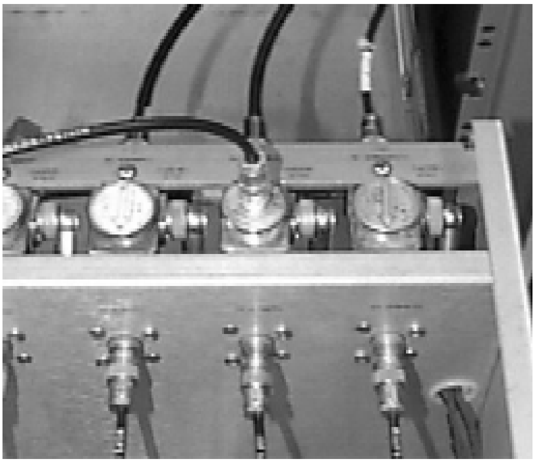

Figure 6. RF Sniffer inserted into the SBO RF body of the APCU input port.

Connect channel B of the vector voltmeter to the middle antenna monitor return coax. Connect the RF probe to the other end of the middle antenna monitor coax using a piece of good quality double shielded coax with a length sufficient to allow moving the RF probe to the upper or lower antenna. The coax must be phase stable, (RG-223 coax was found to be unsuitable for this procedure). Position the RF probe on the center dipole of the middle antenna and zero the vector voltmeter, (remember to terminate the antenna monitor port with a 50 Ω load). See figures 7 and 8.

This direct measurement of the antenna current in the induction field will provide reference data for future repairs and restorations.

Figure 7. Installing the RF Probe on the Center Dipole.

After obtaining reference readings, without making any changes to the system, remove the RF probe and place it on the upper antenna, center dipole. The reading should be 180 degrees. Repeat this test for the lower antenna. The reading should also be 180 degrees. These are initial phase readings and will most likely change during the antenna system phase optimization using the flight inspection aircraft. For initial phase setup adjust the upper and lower antenna phase for the expected 180 degrees.

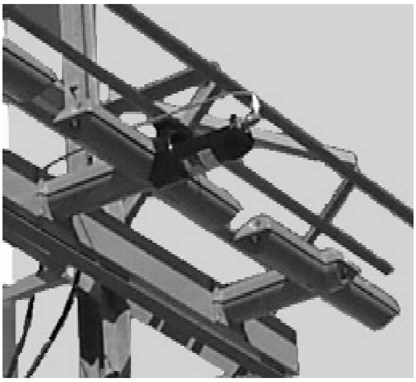

Figure 8. RF Probe on Center Dipole of Middle Antenna

Optimizing The Antenna System Phase During Flight Check

Optimization of the middle antenna and lower antenna is accomplished as usual, with the system configuration set for normal operation. With a fixed line length, advance and delay the middle antenna phase, (one «N» type elbow is equivalent to about 19 degrees at glide slope frequencies). This is usually accomplished with an «N» type elbow inserted between the APCU middle antenna output port and the middle antenna feed coax to delay the middle antenna . To advance the phase of the middle antenna, insert an «N» type elbow in the APCU output port of the upper and lower antenna output ports and their antenna feed coaxes. Adjust the lower antenna phase for optimum width and structure below path results, as normally done.

Upper antenna phase is optimized as usual by dephasing the upper antenna approximately 54 degrees, (three «N» type elbows is equivalent to about 54 degrees at glide slope frequencies), and observing the path decrease during the airborne evaluation. The upper antenna will be at optimum phase when the path has decreased nearly the same amount when the antenna phase is advanced and delayed equal amounts. Example, the path should go down from the nominal value of 3.00 degrees to about 2.85 degrees +/- 0.05 degrees when the upper antenna is dephased approximately 54 degrees. To dephase the upper antenna, use the same technique as used with the middle antenna. Delay the upper antenna phase by inserting three «N» type elbows in the APCU output port of the upper antenna and the upper antenna coax feed. To advance the upper antenna insert three «N» type elbows in the APCU lower and middle antenna output ports, and the lower and middle antenna coax feed lines.

The antennas have now been phased for optimum airborne receiver indications and no further adjustments to the antenna phase is desired.

Antenna System Reference Readings After Flight Check

Use the procedure labeled Antenna System Phasing Before Initial Flight Check to measure the antenna system reference values only, with no adjustments made that would change the antenna system phase. Use a vector voltmeter to measure and record the upper and lower antenna current, phase and amplitude, with respect to the middle antenna. These reference readings will be the antenna system reference values and represent the overall system performance as deemed optimum for the user. These readings serve as the long term, stable references that permit most image type glide slope antenna systems to be optimally maintained, repaired, and restored to service without a special airborne evaluation.

Measurements at the APCU output ports going to the antennas, the monitor recombiner input ports with the antennas in the circuit, and the monitor recombiner input ports with the antennas bypassed with an «N» barrel adapter are extremely valuable. These extra measurements will assist in troubleshooting, future repairs, and system restoration.

Maintaining Antenna System Performance After Flight Check

Antenna currents can now be measured in the induction field with the vector voltmeter and compared with the reference readings using the procedures in Antenna System Phasing Before Initial Flight Check to determine system performance.

The recorded reference values taken at the APCU output to the antennas, the readings taken at the monitor combiner input ports and readings taken at the antenna induction field points all will be very useful in the restoration of the glide slope system. This permits phase and amplitude verification and/or adjustment to restore optimum performance.

Any physical or electrical system parameter changes will require new reference values to be obtained. Example; to compensate for changes in the environment or glide angle the antenna phase or placement is changed, then establishing new reference values is required.

CONCLUSION

The direct method of measuring antenna currents in the induction field provides the most stable and repeatable results. The direct method is not as susceptible to influences of environment, i.e., the movement of aircraft, vehicles, and RF interference.

The facility performance can be evaluated without external variables and environmental concerns that influence indirect ground measurements. The use of this method does not require ground check points.

Maintenance and repairs can be performed that include the replacement of system components, antennas, coax cable, RF amplifiers, power dividers and phasors in the APCU. The complete glide slope facility performance can be restored with a high level of confidence using the direct method.

A flight inspection is not required to restore a facility to service if all electrical and physical reference parameters are maintained.

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DESIGN CONSIDERATIONS IN INSTRUMENTATION FOR FLIGHT INSPECTION – DATA ACQUISITION SYSTEMS & GRAPHIC PRINTERS, ARCHITECTURES, OPERATING SYSTEMS.

ABSTRACT

Flight inspection systems fall under the category of hard real-time systems. They have demanding requirements for very accurate data/time correlation of inputs from a variety of avionics receivers and navigation sensors, high reliability, resilience to shock, vibration and to demanding environmental conditions, electromagnetic compatibility, compactness, and light weight. Systems are also required to be highly stable in terms of their longevity and support, an issue particularly relevant in times when conventional PC hardware becomes obsolete a few months after introduction.

In this paper we address the issues above within the framework of the design and integration of hardware and software components for such systems. We discuss architectures, operating systems, and their impact on data/time synchronization. We present efficient distributed processing architectures for such systems, and discuss new advances in the graphic printer/chart recorder technology they include.

INTRODUCTION

Advances in the technologies underlying the design of flight inspection systems offer a broad spectrum of possibilities to the designer. A trend noticeable in recent years, has been that of producing simpler, low-cost systems that take advantage of the widespread availability of PC hardware and software. Enticing as this is, it is critical to keep in mind that the ultimate objective of flight inspection is ‘safety in aviation’, and consequently the quality, accuracy and reliability of the instrumentation employed are equally important [1].

The design of flight inspection systems must be approached from the perspective of *hard real-time systems*. They have demanding requirements for very accurate data/time correlation of inputs from a number of avionics receivers and navigation sensors. With centimeter-accuracy achievable with modern DGPS techniques, any small synchronization errors in the inputs to the position estimation algorithms can result in large position errors. Reliability of the equipment, in particular in an environment in which vibration and demanding environmental conditions play a role, is critical. Often ignored, electromagnetic compatibility is extremely important in installations with numerous electronic instruments. Finally, the always important issue of a system’s stability, in terms of its longevity and support, has become particularly relevant in recent years, given the extremely quick obsolescence of standard PC hardware.

This paper deals with hardware and software design considerations, for systems with the characteristics mentioned above. In the first section we discuss general mechanical and hardware considerations, including PC-based systems and commercial-off-the-shelf components. A second section describes two forms of distributed processing and the related issues of standard interconnection buses and networking backbones. This is followed by a section on operating systems and their impact on real-time performance. A final section introduces a number of architectures for flight inspection systems, incorporating the concepts developed earlier, and with especial emphasis on the modern graphic printer/chart recorder technology they include – an instrument which directly addresses the issues of reliability and quality control.

The paper also offers reviews and a comprehensive list of references for the technologies covered.

GENERAL CONSIDERATIONS

In this section we address briefly general environmental and electrical considerations in the design of electronic instruments, which are particularly important in the demanding conditions of flight inspection aircraft.
From the environmental perspective, in addition to the test criteria of RTCA DO-160, and the basic requirement for small dimensions, light weight, and low power consumption, a number of additional issues are important.

For shock/vibration tolerance it is best to have boards mounted vertically, and fastened at (at least) two points on the edge opposite to the connector. A passive backplane is preferable, since the mechanical stresses that result from supporting plug-in cards can lead to failures in active motherboards. Always important, these issues are much more critical than in the past, given the nature of the packaging of modern integrated circuits and printed circuit board manufacturing – e.g., ball grid array (BGA) packaging, surface mount technology (SMT).

For heat dissipation, the passive backplane/vertical plug-in module approach also facilitates designs with good airflow on heat generating components.

Pin & socket, standard size connectors should be used (e.g., DE-9P, DB-25P, etc.). The high level of integration in some commercial-of-the-shelf (COTS) products can be misleading, as most of the I/O is usually combined in a single 'miniature' connector which is extremely impractical to interface to.

Cabling and wiring must be simplified, and wherever possible eliminated. In our experience, problems with these are involved in many equipment repairs.

Electromagnetic Compatibility (EMC)
Although *electromagnetic interference* testing has been an issue for many years, it was not until 1996 that compliance with *electromagnetic susceptibility* (or immunity) standards became mandatory in commercial products, a result of EU regulations. The basic immunity standards come from the IEC (the family of IEC1000-4-x standards, now EN 61000-4-x). Limits of radiated and conducted interference from IT equipment are defined in EN55 022, and CISPR22. RTCA DO-160 sets out requirements for airborne equipment, and MIL-STD-461 for military applications.

Approximately 75% of EMC problems are related to I/O ports [2]. They are the gateway for electrostatic and fast transient discharges to enter an instrument, and for interfering signals to escape, either by conduction of spurious signals on the I/O lines, or radiation from the cable. The performance of the transceiver devices driving the ports is critical for overall EMC performance.

RS232 serial ports are particularly vulnerable to various forms of over-voltage. Protection can be achieved using current diversion, current limiting, or a combination of them. Unfortunately, the external structures required are seldom used in low cost equipment, and are particularly difficult to incorporate in portable computers. With the move toward single-supply, charge-pump-based transceivers (with on-chip high-frequency clock oscillators), emissions are also a concern.

PC-Based Architectures
A PC-based architecture is desirable for a number of reasons, some of which have significant technical merit: (a) vast amounts of both development and application software are available; (b) the fast-

paced advancement of hardware for the PC-platform: processors, chip sets, interconnection buses; (c) large selection of COTS components; (d) lower cost for equivalent functionality. Other factors play a role because of their tremendous impact on the 'folk psychology', and they basically come down to the fact that «PCs are *everywhere*, and *everybody* knows how to use them».

The PC-based approach, however, presents as well some very significant disadvantages in the context of demanding real-time embedded applications: (a) PCs are essentially designed for office environments. Even the so-called 'ruggedized' PCs are often little more than a conventional PC packaged in a custom chassis with custom power supplies. Little or no attention at all is paid to EMC. (b) Conventional operating systems such as DOS and Windows (3.x, 9x, NT, CE) are inadequate for embedded real-time environments. (c) The PC market is extremely volatile – hardware becomes obsolete within a few months, and software is constantly «upgraded». (d) One is at the mercy of Microsoft and Intel.

Commercial-Off-The-Shelf (COTS) Hardware

The potential benefits of adopting COTS components are very compelling. The time-to-market and development cost of a new design are much lower than the alternative of a proprietary design. With high-quality COTS hardware one is dealing with proven, fully tested designs. This is very significant given the complexity, high degree of integration, and clock frequencies of modern hardware.

In some cases, however, COTS products will either offer only a sub-optimal solution (e.g., some, but not all the functionality desired is available, or otherwise, unnecessary features and functions are included), or simply offer no solution for a particular requirement (e.g., specialized hardware and firmware for unique instrumentation).

Rapid MTTO (Mean Time to Obsolescence) is also a major concern. Essentially, it results from three facts [3]: (a) Intel's monopoly controls the majority of the computer hardware market; it will make technological changes to its own advantage; (b) the rest of the market must follow suit to avoid being left out; (c) there is more computer manufacturing capacity than demand.

A model to calculate MTTO is proposed in [3]:

$$MTTO = ALC/N^{1/2} \quad , \qquad (1)$$

where ALC is the observed average life-cycle of the most volatile semiconductor technology on a board, and N is the number of such components on the board. If we take for example PCI chips, which have an observed life-cycle of 15 months, with 3 such chips on a PC motherboard we would have an MTTO of 8.66 months.

For the instrument designer, dealing with COTS components implies a dependence on external parties. The selection of a component should take into consideration more than just technical issues. In particular, the supplier should be examined carefully for its reliability, reputation, stability, and support.

DISTRIBUTED PROCESSING ARCHITECTURES

In this section we describe two forms of parallelism we consider critical to achieve high performance in embedded, I/O intensive systems such as those found in flight inspection. These concepts are at the core of the system architectures we discuss in a later section.

Even the latest and fastest processors will have their performance severely affected if they have to deal with a high density of interrupts. Every time an interrupt is received, the processor must save its current context information (integer and floating point registers, status flags, system control registers, and all internal status information) before servicing the interrupt, and must then restore it before returning to the task that was active at the time the interrupt was received. As the complexity of processors grows, the amount of information that must be saved/restored increases, often canceling the advantage that might be gained in speed.

The use of intelligent peripheral modules can be extremely beneficial. The peripheral or 'slave' processors may handle time critical tasks, I/O, and interrupts, relieving the main processor of these responsibilities (Figure 1a).

In general, DSPs, microcontrollers and RISC processors have architectures better suited to rapid context switching and low interrupt latencies than CISC type processors, and are therefore the preferred choice for use in intelligent peripheral modules.

In addition to I/O and interrupt handling, the processor in a slave module may also take care of digital signal (pre)processing. For example, an analog input module may use oversampling techniques and digital filtering to achieve alias-free A/D conversion, with simple, low cost, single-pole antialiasing filters. They will typically run highly efficient code (written in 'C' or assembly language) under a proprietary RTOS (usually a basic kernel executive and interrupt handlers).

The main processor must work in a real-time framework, handling communications with the peripherals, data manipulation, file management, graphics, networking, and data/time synchronization. It may also have to implement critical algorithms to process the output from a front-end module in the instrument. Developing a proprietary RTOS with such capability is not viable, and a commercial RTOS is the best alternative.

Main processor and slaves are tightly coupled and communicate via shared (dual ported) memory. Data transfers to the main processor may be via DMA. A robust communications protocol must be employed.

This modular architecture allows for flexible scaling of system performance, eases debugging, simplifies maintenance, and allows customization.

A different form of distributed processing may be implemented at a higher level, where we partition a system into host and *front-end* sections (Figure 1b). The host is the central component, the data acquisition system *per se*, as we have described above. The front-end is a self-contained subsystem that has a dedicated function. It will normally involve some proprietary hardware (and firmware), combined with some COTS components, on a standard bus and a passive backplane. Depending on the functionality required, either a proprietary or a commercial RTOS is used.

This approach once again allows flexibility for customization of the instrument: front-ends designed by third parties may be easily incorporated, provided that all communications protocols specified are followed, as well as electrical and mechanical specifications. Furthermore, the front-end may be re-packaged as an independent instrument, which may be connected to some other 'host' or a simple data logger.

Depending on the functionality implemented in the front-end, and the bandwidth required for data transfer to the host, the link between them may be anything from simple RS232/422 to some form of high-speed serial link at up to several hundred Mbits per second.

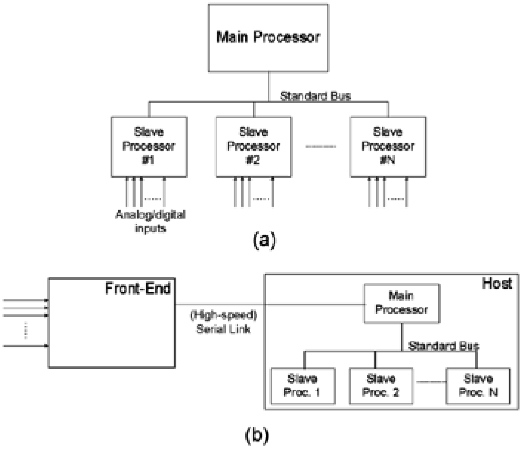

Figure 1 – Two forms of distributed processing

Local Interconnection Buses
A standard bus is used for (local) interconnection within the host system, and one for interconnection within the front-end. The interconnection bus is critical to the performance of a computer system, and must be selected very carefully. The time-line in Figure 2 provides a historical perspective on standard buses. The most relevant are discussed below.

The origins of the VME bus date back to 1981, out of the Motorola division in Munich, Germany. It was originally developed to support the 68000. By 1985 hundreds of companies had adopted it, and in 1987 it was approved as an ANSI/IEEE standard. Thanks to its ruggedness, reliability and well defined specifications, it has had tremendous success in real-time, multiprocessing and military applications. It supports up to 21 cards, allows multiple bus masters, and functions well as the basis for a multiprocessor system. The Eurocard form factor with pin-and-socket connectors results in better reliability, corrosion resistance, and vibration resistance than card-edge connectors. Especially in the 3U form factor, its great rigidity minimizes the bending that causes much of the user-related board failures.

Theoretical top speed was 40 Mbytes/sec in 1981. VME64 at 80 Mbytes/s became a standard in 1994. Use of sub-buses on the P2 connector has led to further increases in bandwidth: 160 Mbytes/sec in 1991, 320 Mbytes/sec in 1996, and 640 Mbytes/sec in 1998. Changes to the standard have always maintained backward compatibility. Very extensive information has been published on VME; refer for example to [4].

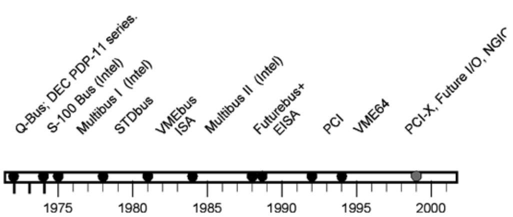

Figure 2 – Local interconnection buses

PCI started in 1992 as local bus to speed-up video performance in desktop PCs. It dominates the desktop market, and has therefore great appeal as it is backed by this multi-billion dollar market. This close tie with the PC market, however, has the disadvantage of short MTTO of PC components.

PCI is based on a single bus master; it is a local bus for I/O peripherals, and not an interprocessor communications link. In its basic form it was limited to a maximum of 4 interrupts per device, and to 4 expansion slots. Although moving toward 64-bits-at-66-MHz implementations, most commercial hardware implements its 32-bits-at-33-MHz form (132 Mbytes/sec).

In desktop PCs, PCI adapters are inserted into card edge connectors on a motherboard. A PCI card is fastened at one point only, on the edge opposite to the connector. This mechanical arrangement does not tolerate shock and vibration very well, and the card edge connectors are subject to shifting (or even disconnection) [5]. The use of an active backplane worsens the situation: mechanical stresses involved in supporting cards may lead to failures on the motherboard.

The great success and popularity of PCI have prompted the creation of several form factor variations [5, 6] that use the PCI electrical specification (Table 1). Many of these form factors are much better suited than the original for embedded applications in rugged environments.

New developments show a trend toward serial buses for connecting hosts to major peripherals, networked subsystems and clusters. In contrast to parallel bus systems, these offer greater reliability, availability and serviceability. Examples are Future I/O, and NGIO. Also interesting is the development of PCI-X (essentially a simplification of PCI, it is 64-bits wide with speeds from an initial 66 MHz to 133 MHz.

	Dim. [in]	Conn.	Standard
Desktop	12.3 x 3.9	Edge	PCI-SIG
PCI	6.9 x 3.9		
Passive Backplane	12.3 x 3.9	Edge	PICMG
PMC	5.9 x 2.9	P&S	IEEE
Compact PCI	6.3 x 3.9	P&S	PICMG
CardBus	3.4 x 2.1	P&S	PCMCIA
Small-PCI	3.4 x 2.1	P&S	PCI-SIG
PC/104-Plus	3.8 x 3.6	P&S	PC/104

Table 1 – Form factor variations of PCI

Networking Backbone

For many years the preferred networking backbone in avionics systems has been MIL-STD-1553. Its bandwidth (1 Mbps) however, is rather limited for today's applications. A number of alternatives and their transmission rates are summarized in Figure 3, and in Figure 4 (based on [7]) we show the maturity state of these technologies. Particularly interesting are some forms of Ethernet, IEEE-1394, and fibre channel.

Ethernet is now available in a variety of forms (see for example [8]), starting with 10BASE-T at 10 Mbps (IEEE Std. 802.3). 100BASE-T or 'Fast Ethernet' operates at 100 Mbps (IEEE Std.802.3u), and may use twisted pair cabling (100BASE-TX) or fiber optic cabling (100BASE-FX).

1000BASE-X or 'Gigabit Ethernet' offers 1 Gbps (IEEE Std. 802.3z, ratified in June/1998). 1000BASE-SX uses short wavelength laser (up to 100 m between nodes), 1000BASE-LX uses long wavelength laser (well over 500 m between nodes), and 1000BASE-CX uses short-reach copper links (for interconnection of equipment in the same room or rack, with a special twin-ax cable). 1000BASE-T (IEEE working group 802.3ab; draft nearing completion) allows use of existing generic cable – twisted pair used for 10BASE-T, 100BASE-T.

All forms of Ethernet use the widely implemented CSMA/CD protocol; its inherent non-deterministic, collision-rich nature is seen as a disadvantage in some applications.

IEEE-1394 supports 100-, 200- and 400-Mbps speeds using a shielded, jacketed round cable with 2 shielded twisted pairs, and 2 power wires. Up to 63 nodes may be connected in a tree topology, with 4-5 m between nodes. A root device is selected during initialization, but no specific host is required. It supports asynchronous and isochronous transfers, and hot-swapping of devices. Refer to [9, 10] for more information.

Fibre channel can yield speeds anywhere from 133 Mbps to 4 Gbps. It may be implemented using different physical media, including copper coax, twisted pair, and optical fibre. For example, using shielded twisted pair one can achieve 266 Mbps at 50 m, while with long-wave laser on optical fibre, one can get 1.062 Gbps at 10 km. The (ANSI) standard defines three topologies: point-to-point, fabric switch, and arbitrated loop (AL). With AL up to 127 ports may be connected serially or in loop fashion, and it may be combined with point-to-point connections (if guaranteed performance is required). See [9, 11] for more details.

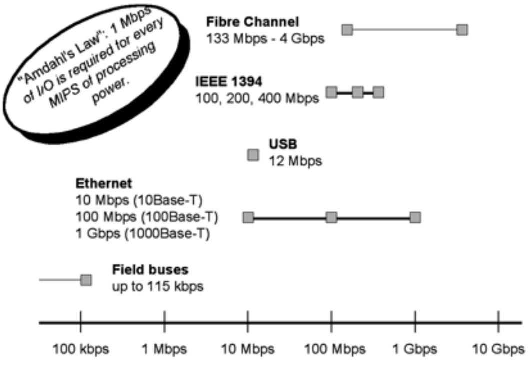

Figure 3 – High-speed interconnection standards

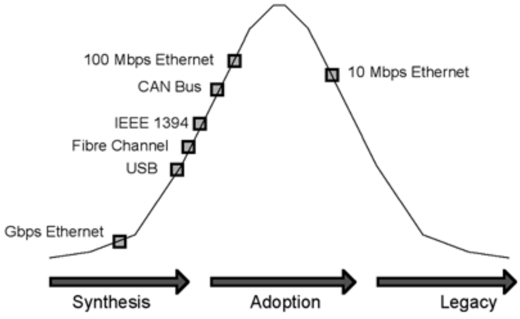

Figure 4 – Technology adoption/maturation status

OPERATING SYSTEMS

In very general terms, real-time systems are characterized by the fact that correctness depends not only on logical results, but also on the timeliness of the results[1]. Real-time tasks must be executed so that *each* task meets its timeliness requirement, whereas non- real-time tasks must be executed so that the average response time of these tasks is minimized.

There are four basic requirements of an operating system (OS) intended for embedded, real-time applications: *determinism* (the ability of the system to perform tasks within precisely defined periods of time), *responsiveness* (the ability to respond quickly to events, such as external interrupts), *preemptiveness* (processes with higher priority must be allowed to preempt execution of lower priority processes), *and reliability* (for example, true multitasking operating systems with separate memory space and resources for each process, avoid a complete system «crash» in the event one process deadlocks).

To help discuss the merits of various types of operating systems, some terminology is first clarified (Figure 5). The *context switch* time T_C is the time from the last instruction of one user-level process to the first instruction of the next user-level process. It involves the time to save and restore the contexts of the processes involved, and the OS overhead inherent in re-scheduling.

The *interrupt latency* T_L is the time from the start of the physical interrupt to the execution of the first instruction of the user-level process's interrupt service routine (ISR). It includes latency in the interrupt controller, the worst-case interrupts-disabled time from either system or application software, time for the CPU to recognize the signal, and the OS's preamble to the first instruction of the ISR. This last overhead includes additional interrupt entry services to keep track of nested interrupts on processors of the Intel 80x86 architecture – others, such as Motorolas's 680X0, have built-in support to handle this.

The *scheduling latency* T_S is the time from the execution of the last instruction of the ISR to the first instruction of a user-level process readied by the interrupt. It includes the exit process through the OS for possible rescheduling, the OS's scheduling latency, and the context switch if a higher priority task has been readied by the interrupt.

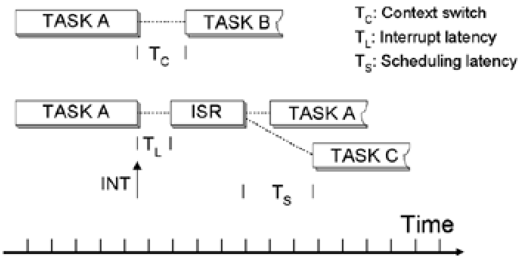

Figure 5 – RTOS terminology

Multitasking can be *cooperative* (tasks must voluntarily yield control of the processor) or *preemptive* (the OS can take control of the processor without a task's cooperation). *Scheduling* is the process used by the OS to determine which thread executes.

Figure 6 summarizes the suitability of various types of operating systems for real-time work v.s. mainstream type applications. In what follows we expand on this subject.

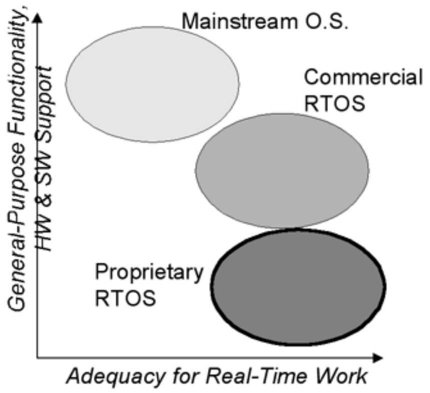

Figure 6 – Mainstream v.s. RTOS

1 There is extensive literature published on the subject of real-time systems. See for example [12], and the many references therein.

Mainstream Operating Systems

Neither DOS nor Windows (in any of its forms) satisfies all the critical requirements discussed earlier. Data acquisition systems running under them are bound to have problems with missing and/or non-uniformly sampled data, and in general, unpredictable performance.

DOS is a 16-bit, single-tasking OS that limits applications to a maximum of 640 kbytes in size. It lacks determinism and responsiveness; in particular, use of 'traps' to request services from the OS dramatically increases latencies.

Windows 3.x sits atop a cooperative – rather than preemptive – multitasking foundation [13]; some applications can take upwards of 10 seconds to transfer status (such as the open/closed state of a valve) [14].

Windows 9x offers preemptive multitasking for DOS and 32-bit Windows applications (but uses cooperative multitasking with all 16-bit applications), and has a priority-based, non-deterministic task scheduling policy. It still cannot guarantee response times, and although it may be adequate for some applications with response times in the order of seconds, it is in general considered unsuitable even for most soft real-time applications [15].

Like 9x, NT offers preemptive multitasking for DOS and 32-bit Windows applications, and priority-based, non-deterministic task scheduling. It also allows preemptive multitasking of 16-bit applications [13].

When an interrupt occurs, NT preempts all tasks and uses a deferred procedure call; it performs only part of the required action and places the rest in a queue for later execution. Essentially, then, all real-time tasks execute in background mode, in the order received.

Despite offering high performance processing, NT does not guarantee response times. For example, although average response times for a periodic timer can be under 30 μsec, there are also many events with latencies that exceed tens of milliseconds [16]. When switching tasks, context saving/restoring may take anywhere from 1 to 100 msec; external influences may interrupt the process delaying things even further [14]. In summary, although usable in some soft real-time applications, NT remains severely limited for hard real-time work [17].

The omnipresence of the Win-32 API and GUI are definite assets of NT. On the other hand, in addition to its inadequacy for real-time work one must consider the issues of stability and support – Microsoft is well known for frequently changing strategies, and for rather poor customer support –, and NT's massive size and demand for resources – consider, for example, that the software for the space shuttle requires about 26 million lines of code, with one additional million lines of mission-specific code per flight; the Windows NT 5.0 (2000) environment boasts a massive 30 million lines of code [18].

Windows CE represents Microsoft's first attempt specifically aimed at the embedded market (in particular the handheld PCs). It is a customizable OS with a (relatively) small footprint – the minimum 'reasonable' configuration requires 256 kbytes of RAM and 512 kbytes of ROM. It supports only a subset of NT's Win-32 API – about 500 out of 1000+ services in a full Win-32 implementation.

Like NT and 9x, CE offers preemptive multitasking with priority-based non-deterministic task scheduling. It is an improvement over NT/9x in that interrupts are handled by a combination of an ISR (interrupt service routine) and an IST (interrupt service thread). The ISR is kept small and fast, and sends a signal to the OS to awaken the IST. The IST is essentially like any other thread in the OS, and as such may have its priority controlled. Note however, that CE does not support nested interrupts – data that arrive at very short time intervals may be lost [19].

In general CE is considered adequate for many soft real-time applications, but the lack of support of hard real-time determinism remains a major drawback [19, 20]. As in the case of NT, programmer familiarity with the API, and user familiarity with the GUI are great advantages, as is the (already) extensive HW and SW support.

Some companies offer real-time extensions for both NT and CE, but the lack of a standard makes these proprietary approaches unattractive.

RTOSs: Proprietary and Commercial

Although development of proprietary RTOSs is in decline, there are a number of applications where they offer the best alternative – for example, when even the very small overhead introduced by commercial RTOSs cannot be tolerated, or when some of their functionality is either not required, too costly, or is better developed internally to exactly suit the requirements [21].

In recent years the quality and features of commercial RTOSs have improved dramatically. This, coupled with the allure of a short time-to-market, has resulted in a great increase in their use.

When judging commercial RTOSs, the distinction between *soft* and *hard* real-time is important. Some alternatives offer only a best effort to complete a process in real-time, while others offer a guarantee.

The key issue is how the scheduler handles real-time processes. Most RTOSs will allow the interrupt handlers to be scheduled as threads, support different levels of priority, and offer flexible scheduling methods to deal with processes with the same priority level. Some examples are FIFO scheduling (the running process runs until it blocks, or until preempted), time-slicing (the running process is given only a «time-slice», after which it is preempted), and adaptive scheduling (process priorities are adjusted according to their activity).

Current commercial RTOSs have latencies and context switch times of only a few microseconds. They usually have modular architectures, with a very small, focused kernel that supports a minimum set of features (*microkernel*), and optional modules that provide flexible services in the areas of user interfaces, drivers and communications. Integrated development tool environments with graphical user interfaces are now common, and of comparable quality to those of mainstream operating systems.

The list of commercial RTOSs shown in Table 2 is intended for illustration only, and is by no means exhaustive; the review article in [22] from which it is compiled, lists more than 50 suppliers of RTOSs.

	Target CPUs	*Language support*	*Typ. context switch*	*Multiproc. support*
Aonix ***ObjectAda***	68K, MPC8xx, 175PowerPC0A, x86 protected mode	Ada	?	
Integrated Systems ***pSOS***	ARM, i960, MIPS, MPC8xx, 68K, PowerPC, SPARC, x86, etc.	Assembly, C(++), Java	1000 clock cycles	√
Lynx Real-Time Sys. ***LynxOS***	68K, MIPS, MPC8xx, 175PowerPC0A, x86 prot., SPARC	Ada, Assembly, C(++), Java, Fortran, Perl	?	√
QNX Software Sys. ***QNX***	MIPS, MPC8xx, 175PowerPC0A, x86 prot.	Assembly, C(++), Java	2.6 µsec	√
Wind River Sys. ***VxWorks***	68K, ARM, i960, MIPS, 175PowerPc0A, x86 prot., SPARC,M-CORE, CPU32, etc.	Assembly, C(++), Java	10 µsec	√

Table 2 – Some commercial RTOSs

ARCHITECTURES WITH MODERN GRAPHIC PRINTERS/CHART RECORDERS

Figure 7 shows simplified block diagrams of several system configurations that may be built around the concepts described earlier. All systems have in common the use of a graphic printer/chart recorder (GP/CR). This instrument has traditionally been an integral part of most flight inspection (FI) systems, and remains critical in ensuring the overall quality and accuracy of the flight inspection mission. Notice also that in all configurations a PC is included, but (with the exception of the system in Figure 7d) always relegated to non-critical functions.

In Figure 7a the signals output by avionics receivers and other equipment are input to both the FI front-end, and (in some cases indirectly, through the front-end) to the analog and various digital input modules in the host. This provides the system with a level of redundancy. The front-end transfers (processed) data to the host through the networking backbone. The host records all data and drives the GP/CR in real-time. A PC is shown connected to both the host and front-end subsystems. It may be used, for example, to provide the operator interface, to maintain a database of inspections, and to print high-quality reports and/or images on the GP/CR.

Mechanically, the system in Figure 7a may be packaged in a number of ways: (a) the host may be built-in into the GP/CR's chassis; (b) host and front-end may be packaged in the same chassis; (c) both host and front-end may be built-in into the GP/CR's chassis. [2]

The system in Figure 7b is similar to the one in Figure 7a, but the host subsystem has been eliminated. The FI «front-end» in this case is the complete FI system. Note also that the GP/CR has been replaced with a '-A' version, i.e., one which supports various intelligent analog and digital (e.g., ARINC 429) input modules; this preserves the redundancy offered by the system in Figure 7a.

The system in Figure 7c is a simplification of the one in Figure 7b, where the basic GP/CR is used instead of the GP/CR-A version, thus losing some redundancy.

Much simpler than any of the other configurations, the system in Figure 7d uses the GP/CR-A as the central component for data acquisition and real-time monitoring, while the PC takes on the added responsibility of all data processing and recording.

Not shown explicitly in Figure 7, the issue of synchronization of all data received from avionics receivers, navigation sensors and telemetry equipment is critical (see for example [23]). The sub-meter accuracy offered by modern DGPS receivers would be meaningless if large position errors were introduced due to poor synchronization – for example, at 180 knots ground speed, a 10-msec delay introduces a position error close to one meter. Typically the PPS (pulse-per-second) signal output by the GPS receiver (in the FI front-end or the host subsystem) may be used by other processors for synchronization. A very fast response time is required to minimize errors; this response time is a direct function of not only the hardware and the speed at which it operates, but as we discussed earlier, of the underlying operating system.

Synchronization to other instruments (including the GP/CR), may be greatly improved and simplified with the use of a GPS receiver with a standard time-code signal output such as IRIG-B [24]. The signal may be distributed to the instruments in daisy-chain fashion.

The graphic printer/chart recorder (GP/CR)
For many years the benefits of a GP/CR in a flight inspection system have been well established:

- The chart record is an official document of the mission.
- Signals may be recorded on the chart in real-time, in «raw» form, i.e., without any filtering

2 The first configuration has been part of RMS INSTRUMENTS' product line for quite some time; the second, with a front-end's functionality other than FI, is part of current development.

and/or artifacts that may be introduced while sampling, processing, digitally recording, and then retrieving the information.

- A clear, high-resolution,[3] real-time record of the mission, on wide (300 mm) chart format, is an excellent quality control tool. Depending solely on a computer screen (usually crowded and in demand for other tasks) to monitor the progress of a mission, is a rather poor alternative as the information will scroll out of view after a few seconds.
- The GP/CR may be used as a backup and/or for redundant recording.

GP/CR technology has advanced very significantly in recent years. In addition to the «core» enhancements (3X better resolution on both axes, up to 30X faster print speeds, 1000X faster sampling rate of analog inputs, and greatly advanced software features), new functions in the context of flight inspection have become possible (Figure 7): (a) with laser printer resolution (300 x 300 dpi) the GP/CR may be used for generation of final reports; (b) true 16-level gray scale printing allows near-photographic quality reproduction of computer images.

To illustrate some of the concepts discussed earlier, we consider the problem of task scheduling in the GP/CR. For a set of m periodic tasks $\{\tau_1 \ldots \tau_m\}$, the *processor utilization factor* is defined as the fraction of processor time spent in executing the task set:

$$U = \sum_{i=1}^{m} C_i / T_i \ , \qquad (2)$$

where C_i are the tasks run-times and T_i their request periods. The *least upper bound* to processor utilization in fixed priority systems can be shown to be [25]

$$U_B = m(2^{1/m} - 1) \ . \qquad (3)$$

In other words, for all task sets whose processor utilization factor is below this bound, there exists a fixed priority assignment which is feasible. From (3), it is clear that for large m we have $U_B \approx \ln 2$, i.e., roughly 70%.

The worst-case operating conditions involve a print rate of 1535 lines/sec, which results in a request period of 651 µsec for the main task, τ_1 (which handles sampling of up to 32 'waveform' and 16 'logic' channels, scaling, processing, bit map generation of traces, grids, and chart annotation information). As many as seven additional interrupt-driven tasks, $\{\tau_2 \ldots \tau_8\}$, may also be active; they include control of the print process, communications, and interface to mechanical components. For this set of eight tasks, the exact least upper bound is $U_B = 0.724$.

The task subset $\{\tau_2 \ldots \tau_8\}$ has a relatively small processor utilization factor, say 15%. Even then, the run-time of the main task would have to be limited to $C_1 < (0.724–0.15)\text{x}651$ µsec = 374 µsec, in order to guarantee feasible scheduling of the task set.

It is well known [25] that the *rate-monotonic priority assignment* (RMPA) is optimum, in the sense that no other fixed priority assignment rule can schedule a task set which cannot be scheduled by the RMPA. It assigns higher priorities to tasks with higher request rates. Assume then that $p(\tau_1) > p(\tau_2) > \ldots > p(\tau_8)$, and $T_1 < T_2 < \ldots < T_8$, where $p(\tau_j)$ denotes the priority of task τ_j.

Under certain circumstances the least upper bound can be relaxed to 1 [25]. It is required that $\{T_m/T_i\} = 0$, for $i = 1, 2, \ldots, m–1$, where $\{T_a/T_b\}$ denotes the fractional part of T_b/T_a, i.e., $\{T_a/T_b\} = T_b/T_a – [T_b/T_a]$, with $[x]$ denoting the largest integer smaller or equal to x. In the case of the GP/CR however, such condition can be met only for a subset of the task set, namely the main task τ_1, and the group of

3 A modern GP/CR has 3552 print elements (dots) at 300 dots/in along the amplitude axis, and, of course, practically unlimited length along the time axis, also at 300 dots/in. 16-bit signals may be reproduced with resolutions of around 2 lsb/dot (lsb = least-significant-bit). In contrast, a typical computer screen will offer only 1280 x 1024 pixels for resolutions no better than about 125 pixels/in.

tasks that control the print process. The least upper bound cannot be increased beyond 72.4%.

The requirement for $C_1 < 374$ µsec proved to be impossible to meet with a single state-of-the-art, 32-bit processor. This led to an architecture with two tightly coupled 32-bit processors and a math co-processor working in parallel. The system uses a proprietary, finely tuned RTOS – notice that context switching or interrupt latencies of more than a few microseconds would represent a large percentage of the main task's period.

CONCLUDING REMARKS

The design of systems for flight inspection must be approached from the perspective of real-time systems in the 'hard' sense. In addition to performance under such requirements, key issues include reliability, resilience, ease of configuration and/or customization, longevity and support. Both the system's architecture and the operating system(s) underlying the application software are critical. We have discussed issues in the design of such systems, and have illustrated some of the ideas presented through several configurations, with special emphasis on the use of modern graphic printers/chart recorders.

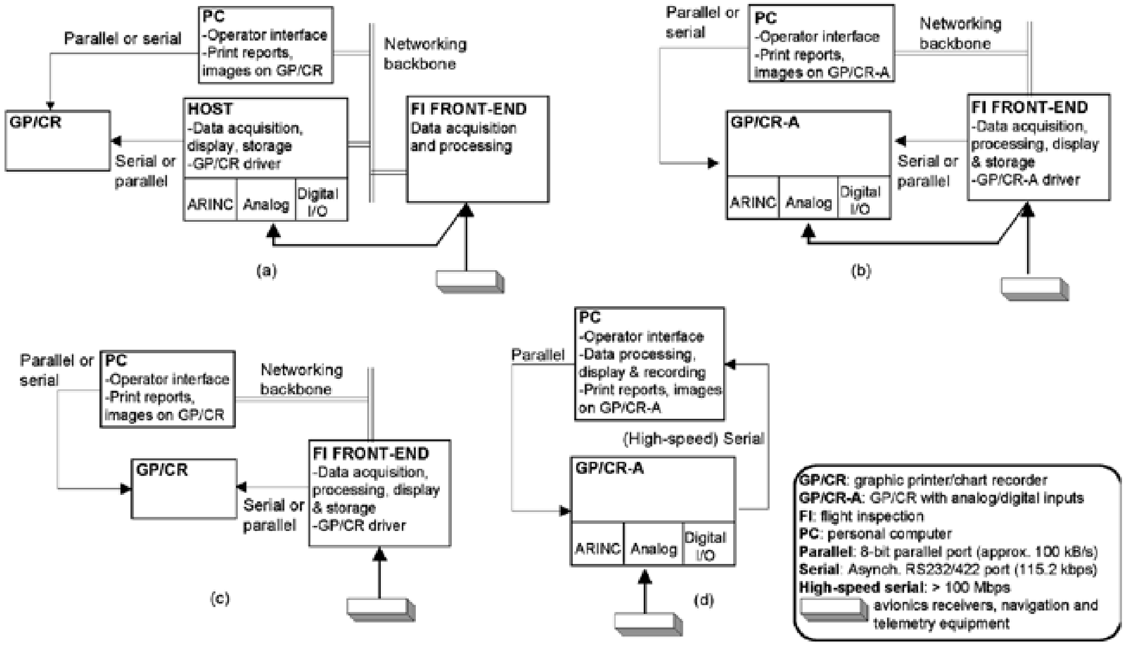

Figure 7 – System architectures with graphic printer/chart recorder

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CHILE'S NEW FLIGHT INSPECTION EQUIPMENT

ABSTRACT

The three aircraft dedicated to Flight Inspection by the Dirección General de Aeronáutica Civil (DGAC) in Chile have been upgraded in the past two years with new light-weight Flight Inspection Systems from RVA Aerospace Systems Limited of Canada.

The DGAC Cessna Citation II has dual MICROFIS systems in a compact rack. The two systems operate as independent Flight Inspection Systems to provide 100% backup in the event of a system failure.

A Piper Seminole aircraft based on Easter Island temporarily «borrows» one of the MICROFIS systems from the Citation when inspections are required on the island. The Citation can continue to perform en-route navaid inspections even with the one system removed.

A Beech King Air 200 aircraft has a 1987 era semi-automatic system upgraded to almost fully automatic status with the addition of an RVA GPSU-2500 simulated RTT system.

Work is in progress by the supplier of these systems to add Differential GPS capability to provide fully automatic performance for ILS approaches.

BACKGROUND

The DGAC of Chile currently has three aircraft dedicated to flight inspection.
Until recently, a Cessna Citation II was equipped with a SAFIS originally delivered in 1987, a Beech King Air 200 had a 1981 TFIS system while a Piper Seminole based in Easter Island had a 1981 PFIS.

Early in 1998, the SAFIS was removed from the Citation and replaced by two MICROFIS Flight Inspection Systems developed by RVA Aerospace Systems Limited of Canada. Modifications to the aircraft, as well as installation and initial flight testing of the new systems, was performed in Canada by RVA. These systems have been in continuous operation since July 1998.

The PFIS system was removed from the Seminole and the aircraft was modified to accept a single MICROFIS system.

A Ground Support System, also developed by RVA, was delivered at the same time for long-term storage of all inspection results.

During 1999, the SAFIS previously removed from the Citation was installed in the King Air to replace the TFIS. A GPSUpgrade system was supplied by RVA to upgrade the SAFIS to give it an automatic inspection capability similar to that of the MICROFIS systems.

Unique Flight Inspection Requirements

The new Flight Inspection equipment in operation with the Dirección General de Aeronáutica Civil in Chile meets the general requirements defined in ICAO and FAA documentation for the inspection of ILS (including Category III), VOR, DME, NDB, VHF COMM, VHF DF, SSR and PAPI.

Chile has some unusual geographical features which require additional unique characteristics not normally found in most flight inspection systems.

Topography. Chile is a long narrow country which is bounded on one side by the sea and by high mountain ranges on the other side. Most VOR facilities are therefore installed in essentially a straight line running the length of the country. Also, with the flight inspection aircraft based in Santiago approximately in the centre of the country, it is not cost-effective for the aircraft to return to base each evening.

The new systems provide several features that save flying time and operating costs while they are operated under these conditions.

- With each system tuned full-time to two different VOR stations, complete VOR outbound and inbound radial inspections can be performed simultaneously without losing half of the received data as in time-sharing or multiplexed systems.

- With dual, independent MICROFIS systems, inspections can still be performed even with a receiver or computer failure in one system. This 100% redundancy capability means that the aircraft does not have to make the long haul back to base for an equipment failure.

Wide operating temperature range. In addition to normal seasonal temperature variations, the digital theodolite ground equipment has to operate in hot, desert like conditions in the north of the country and in sub-zero conditions in the Chilean Antarctic.

A special controller was developed for the RTT ground station to allow operation over this wide temperature range.

Difficult access to transmitters. Some VOR stations are installed on the mountain range to provide the necessary coverage. Access to some of these locations is difficult and previously a theodolite operator had to be transported to the facility by helicopter whenever an inspection was required.

With the new equipment, GPS data is used for accurate aircraft position information, and so it is no longer necessary to use this costly procedure to inspect VORs.

Easter Island inspections. A Piper Seminole aircraft, modified for flight inspection but containing no flight inspection equipment, is permanently based on Easter Island which is approximately 2000 miles over water from the mainland.

Previously a manual Flight Inspection System was carried to the Island and installed in the aircraft twice a year for performing inspections.

One of the modular MICROFIS systems normally installed in the Citation is now temporarily removed and installed in the Easter Island aircraft when inspections there are required. No additional system is therefore required to support this operation. While one system is operating on the Island, the other system is still used to perform enroute inspections in the Citation.

CITATION II EQUIPMENT

The MICROFIS design is unique in that it allows the flight inspector to sit anywhere inside the aircraft and does not require him to sit facing the equipment rack. The operator has a single laptop computer with a large colour display on which is presented all the required inspection information from the two systems.

Figure 1 Operator position

The two Flight Inspection systems in the DGAC Citation are installed in the rear of the cabin where a small storage box used to be. This design configuration allowed both systems to be installed with no reduction in seating capacity.

Figure 1 Dual MICROFIS installation

Each system consists of the flight inspection receivers, a signal processing computer, GPS receiver and UHF theodolite data receiver. With the exception of the laptop, all the equipment for one Flight Inspection System is contained within the Receiver Computer Unit, which is a 35 Kilogram case that can easily be carried by one person.

Each system is capable of inspecting ILS, VOR, DME, NDB, SSR, VHF, PAPI using either GPS data or inputs from a digital theodolite. The RTT is required only during ILS and PAPI approaches, with all other inspections being fully automatic which can be performed in any weather or visibility conditions.

Photographs of the operator position and dual installation are given in Figures 1 and 2.

The equipment is presently being upgraded so that ILS approaches can be performed using either Differential GPS or the RTT as a backup.

Inspection data from both independent systems is given on the same laptop display in both a numerical format and in a graphical form. Menu selection and data presentation are easy to understand for anybody familiar with Windows type displays. A typical screen is shown in Figure 3.

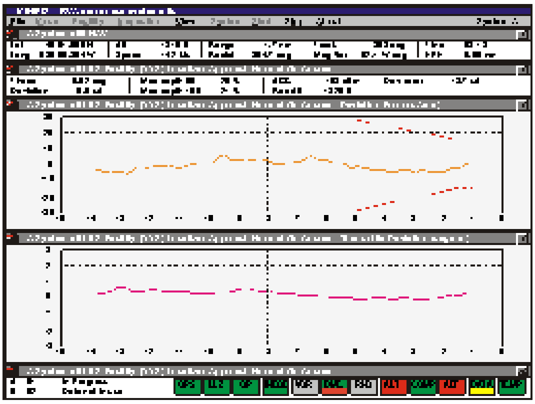

Figure 3 Typical inspection screen

Receivers are automatically tuned by each system computer when the operator selects one of the facilities stored in the Facility Database. Calibration data for the Collins 51RV-5DF VOR/ILS receivers is stored in the system and is used to correct the receiver outputs during an inspection.

All inspection results are presented in real-time and can be printed on the portable printer at the operator position. The raw and processed inspection data is stored in the computer for transfer to the Ground Support System upon landing.

Results and graphs from previous inspections are stored in the laptop and can be displayed for comparison with current results.

The dual MICROFIS configuration provides several advantages:-

- Each system is independent, so that a failure in one system does not affect the operation of the other system. A spare laptop computer can be carried to avoid a laptop failure halting the inspection mission.
- Each system can inspect a different VOR, so that inbound and outbound radials can be inspected simultaneously.

- One system can be removed in a few minutes and carried to Easter Island via commercial airlines for use in the Seminole aircraft. Both the Citation and Seminole can perform inspections at the same time using one MICROFIS system.

- Results from the two independent systems can be compared for reassurance that the systems are operating correctly and accurately.

SEMINOLE EQUIPMENT

Minor modifications were made to the Seminole on Easter Island to add a GPS antenna and the mechanical mounting to accept the MICROFIS system. The operator sits alongside the installed Receiver Computer Unit in this 4 seat aircraft with his laptop and printer on top of the protective cover as shown in the photograph of Figure 4.

The Seminole therefore has all the same capabilities and features of the Citation aircraft, except that information is available from only one system.

Figure 4 Seminole installation

Inspections are performed on the VOR/DME, non-category offset ILS, NDB and PAPI. The equipment is removed in a few minutes and returned to the mainland when the inspections are complete. The real-time printout allows inspection results to be available before the inspector leaves the island.

KING AIR EQUIPMENT

The TFIS installed in this aircraft was replaced with the later model SAFIS which was previously removed from the Citation. The SAFIS required the use of an analogue theodolite or ground check-points for all VOR/DME and ILS inspections.

A GPSU-2500 Upgrade system, also developed by RVA, was added to the SAFIS to provide GPS based inspection capability for all enroute navaid inspections. Additional wiring and switching was incorporated to avoid any changes to the SAFIS. The operator can now perform enroute inspections in any weather and visibility conditions, with the GPSU supplying computer generated signals equivalent to an RTT located at the facility being inspected.

In addition to having the usual SAFIS inspection data available, the operator now has a laptop colour display showing additional processed information and graphs such as continuous bearing error in both orbits and radials.

The menus and displayed data are similar to those on the MICROFIS laptop so that inspectors can easily transfer from one aircraft to another.

GROUND SUPPORT SYSTEM EQUIPMENT

A Ground Support System (GSS) was delivered at the same time as the Flight Inspection Systems to collect and store all the department's flight inspection results. Special application software was written by RVA to collect, organise and display all this data.

The equipment consists of an office level computer system with a large, high-resolution colour display, a laser printer and an RMS GR-33A Graphic Printer.

Inspection data stored in a MICROFIS laptop computer can be downloaded via the computer network into the GSS and organised into inspection types, dates and types of runs. Any stored results can be displayed in numerical and graphical formats for additional analysis of the inspection.

Results from previous inspections can be transferred from the GSS into any laptop computer prior to departing for another inspection for later comparison with the new set of inspection data.

In addition to it's purpose of archiving inspection results, the GSS is also used to store the Master files of the Facility Database and the Receiver Calibration Tables. These files can be uploaded into any of the Flight Inspection System laptop computers to ensure that they all contain the same, latest data.

Final Reports can be generated on this system using standard, pre-stored formats. Reports, Results and graphs can be printed on the laser printer while selected inspection parameters can also be printed on the graphic recorder.

DIFFERENTIAL GPS UPGRADE

A programme is currently taking place to add Differential GPS capability to the two MICROFIS Flight Inspection Systems. This will allow the systems to be fully automatic in the calibration of ILS approaches up to Category III without the need for the RTT. The improved performance will also be appropriate for providing an independent assessment of future WAAS and LAAS installations in Chile.

The upgrade being developed by RVA uses the Ashtech Z12 Sensor operated in the Real Time Kinematic (RTK), or Carrier Phase Differential (CPD) mode. Separate GPS receivers installed in each Receiver Computer Unit will preserve the 100 % redundancy capability of the existing MICROFIS systems.

The Differential GPS Ground Station includes another Ashtech Z12 Sensor in Base configuration together with a hand-held computer/controller for the display and entry of data. Data is transferred to the aircraft via the same UHF transmitter modem presently used in the RTT ground unit.

The DGPS Ground Station can also accept digital theodolite data to provide a backup capability when the DGPS system is not operating.

During performance assessment of the DGPS system, advantage is being taken of the dual independent characteristic of the two MICROFIS systems. One system will be operating in DGPS mode while the other will be using digital RTT data at the same time. In this way, a direct comparison will be possible between the two measurement systems flying exactly the same flight profile.

IN CONCLUSION

With a mixture of new and upgraded systems, Chile is fully equipped to meet it's flight inspection requirements at the start of the new millennium.

By taking advantage of the flexibility and the modular concepts embodied in the RVA flight inspection system designs, the Dirección General de Aeronáutica Civil has been able to re-equip it's three aircraft at a minimum cost.

The ease with which a fully capable Flight Inspection System can be moved from one aircraft to another has reduced the number of systems required.

The redundancy inherent in the system configuration has also reduced the amount of spares necessary and should lead to a reduction in aborted missions due to equipment failure.

The use of GPS and DGPS positioning will lead to a further reduction in wasted flying time by making all inspections possible regardless of weather and visibility conditions.

The multi-processor design of the new systems offers significant growth capability for additional flight inspection capacity in the future.

References

1. Boletin DGAC, Mayo 1998

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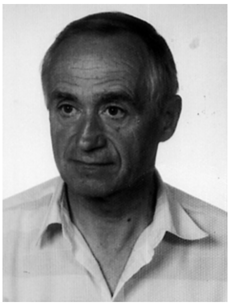

FLIGHT CHECKING OF GPS-BASED NON-PRECISION APPROACHES

Abstract

Flight checking of GPS non-precision approaches differs from checking conventional non-precision approaches as there is no direct influence on the accuracy and availability of the GPS signal. Only local abnormalities and interference can be detected. Due to the global relationship between the runway and the GPS approach procedure, the check of the navigation data base must assure the correctness of all way point data. Methods to validate the data base are discussed. Flight checking of GPS non-precision approaches can use as a reference system either a laser tracker and/or differential GPS. Using a position update at threshold may substitute the laser tracker reference system.
Finally the paper summarises the experiences gained during the flight checking of the first 8 GPS non-precision approaches that are implemented on a trial basis in Germany.

1. Introduction

There is a distinct difference in checking conventional radio navigation systems and a GPS-based non-precision approach. As there is no geographical coupling between the runway and the navigation system, the data base and the software of the flight management system of the aircraft are the main elements to generate the proper flight path that guides the aircraft to the selected runway.

Another difference between a conventional navaid and the GPS is the variation of the system accuracy due to the continuos change in the spatial orientation of the satellites. In consequence, flight checking methods for GPS non-precision approaches will differ from checking conventional navaids.

As the GPS signals are very weak, interference can disturb the GPS signals locally to an extent that literally no GPS guidance is possible. So flight checking has to observe the frequency spectrum close to the GPS frequency band to detect any possible disturbances to the GPS signals.

2. GPS Approach Design

Fig. 1 shows the GPS-Approach into the runway 26 R at Munich airport. The approach shows the Y-design according to ICAO PANS OPS conventions. The Y is formed by the two initial approach way points (IAWP) that are collocated with the Milldorf (MDF) VOR and the Moosburg (MBG) VOR and the missed approach way point (MAWP), that is identical with the runway 26R threshold. The straight-in segment of the approach is defined by 4 way points:

- the initial way point, IWP, coded as DM537,
- the final approach way point, FAWP, coded as DM536
- the FMS coding way point, coded as DM535 and
- the missed approach way point, MAWP, coded as RW26R

and, for the missed approach,

- the missed approach turning way point, MATWP, coded as DM534.

The internal coding of these way points defines whether it is a fly-over or a fly-by way point. The definition of a coding way point allows a plausibility check of the orientation of the final approach and missed approach turning way points in that all these way points have to be orientated in a straight line.

3. Flight check objectives

There are several check objectives before the flight check will be done:

Check of the design of the approach procedure

Check of the navigation data base (lab. evaluation)

Checking the correctness of the approach chart layout

Checking of the RAIM prediction data

During the flight check the items to be checked are:

Check of threshold co-ordinates with the aircraft positioned at threshold

Evaluation of the position accuracy

Evaluation of signal quality and availability

Check of the navigation data base (plausibility checks)

Evaluation of flyability, workload and safety

Evaluation of the obstacle situation

3.1 Checks before flight evaluation

Essentially, the design check will verify the procedure by computing the tracks and distances between the approach way points. Erroneous co-ordinates should be detected by these computations. As there is only a global relationship between the runway and the GPS approach procedure, the check of the navigation data base must assure the correctness of all way point data. The existing guidance material of JAA and the European Organisation for Civil Aviation (EUROCAE) has to be applied for the navigation data base checks. The approach chart layout has to be cross-checked against the approach procedure design. Generally the layout will be checked by a flight check pilot, entitled to check non-precision GPS-approaches. Finally, the predicted RAIM data for the time period of the calibration flight have to be analysed.

3.2 Checks during flight

3.2.1 Threshold co-ordinates

Starting the flight checking mission, the aircraft will be positioned at the threshold of the NPA-runway for a plausibility check of threshold co-ordinates. Within the flight management system of the aircraft the displayed distance to go to the threshold - which is the missed approach way point (MAWP) - should read less than 0.1 nautical mile.

3.2.2 Position accuracy

Fig. 2 shows the basic configuration of a GPS-NPA flight checking system. To determine the position accuracy, there are basically three reference systems available:

- laser tracker
- differential GPS
- position update at threshold

Fig. 3 shows the error budget of the position reference system used for GPS-NPA flight checking. During the flight check the total system error and its components according to the formula shown in Fig. 3 will be recorded. During the commissioning flight checks of the trial procedures at Augsburg, München and Braunschweig, a laser tracker in combination with differential GPS was used as the position reference.

As the threshold will be overflown in a very low altitude, when flightchecking the GPS-NPA approach. The discrete position information by setting the event marker of the flight inspection system upon overflying the threshold, can be used as a discrete position update. Using the position update information in combination with some form of backward integration within the flight inspection software, will improve the overall accuracy of the reference system.

3.2.3 Signal quality and availability

The frequency spectra close to the GPS frequency band were evaluated during the flight checks. For the 8 GPS-NPA procedures, no marked disturbances were found.

3.2.4 Navigation data base

During flight inspection of the GPS approaches two kinds of plausibility checks of the data base of the flight management system were done:

- positioning the aircraft at threshold and checking the displayed distance to the threshold. For all 8 GPS approaches the distance reading was 0.0 nautical miles.

- displaying the whole approach profile on the flight management system, all final approach way points have to be orientated on a straight line with the distances between way points corresponded with the distances in the approach chart.

3.2.5 Workload, flyability and safety

When calibrating conventional precision or non-precision approaches, only in very rare cases the calibration engineer consults the pilot whether the flight safety and/or the flyability of the approach procedure is a factor. With GPS-NPA procedures the pilot is explicitly requested to file a flight inspection report and stating whether or not flyability, workload and the safe conduct of flight is satisfactory.

In addition, the quality assurance system of the Deutsche Flugsicherung,DFS (German airtraffic control agency) requires the pilot to be entitled for his flight checking duties. To be certified for assessing flyability and safety, he has undergo one week of theoretical training and a simulator training (Boeing or Airbus type) with emphasis on using the flight management system for GPS-NPA approaches. After this training he has to do 5 GPS NPA flight checks under supervision of a certified pilot. For each GPS NPA procedure the pilot has to file a standardised written report containing approximately 20 yes/no-questions about flyability, workload, safety and the obstacle situation.

3.2.6 Obstacle situation

During the flight check the pilot is requested to check whether detects new obstacles not depicted in the approach chart. If so he should note the approximate position of the new obstacle detected, so that the exact obstacle situation can be evaluated by a ground crew.

4. Results

Within Germany and since October 8th 1998, there are 8 stand-alone GPS-non-precision approaches commissioned, all of those on a trial basis for authorised operators only. The approaches are established for:

Augsburg, runway 25 and 07
Braunschweig, runway 26 and 08
München, runway 26L, 26R,
08L and 08R

To apply for the use, the aircraft operator has to hold an ops-approval from the Luftfahrt Bundesamt, LBA (.German aviation authority).

Up to now the following aircraft operators are holding ops-appovals:

- Augsburg Airways
- Deutsche Lufthansa
- Eurowings
- Flight Inspection International
- Technische Universität Braunschweig

After commissioning of the 8 approaches, in the period from October 1998 to end of April 1999 174 approaches were documented and analysed. The pilot reports stated:

- approach accuracy (compared to localizer deviation) 0.2 to 0.5 dot, equalling 0.5 degrees of localizer deflection.
- flyability was excellent
- workload was low
- there were no RAIM alarms.

During flight checking the flight inspection reports confirmed all of the pilot reports as above.

Additionally, the DFS analysed the data of the surveillance radars during the GPS NPA procedures. The radar data confirmed the accuracy statements of the pilots. The airtraffic controllers were able to operate the GPS approaches with no problems and no negative effects to the airtraffic control for other aircraft.

5. Conclusions

In October 1998, the Deutsche Flugsicherung, DFS commissioned 8 stand-alone non-precision GPS approaches. Due to the nature of the GPS, flight checking of GPS approaches not only documents approach accuracy but also flyability, pilot workload and safety. The quality assurance system of DFS defines the laser tracker and differential GPS as reference systems for the commissioning of the trial-GPS procedures. Additionally the flight checking pilots must be certified by the DFS.

The flight calibration results proved the GPS NPA procedures to be far more accurate, easily and with a low workload to be flown. However, to fly the GPS NPA procedures under real IFR conditions, some pilot´s training is needed to handle the GPS and flight management systems proficient and safely.

Due to the positive results with the trial procedures, one can foresee quite a number of regional airports, wanting to establish GPS NPA procedures. While for the trial procedures the expenditure by using a laser tracker and differential GPS as a reference system may be justified, a more simple and economical reference system should be used for further commissionings. Position update at threshold with or even without DGPS should be analysed as a more economical reference system.

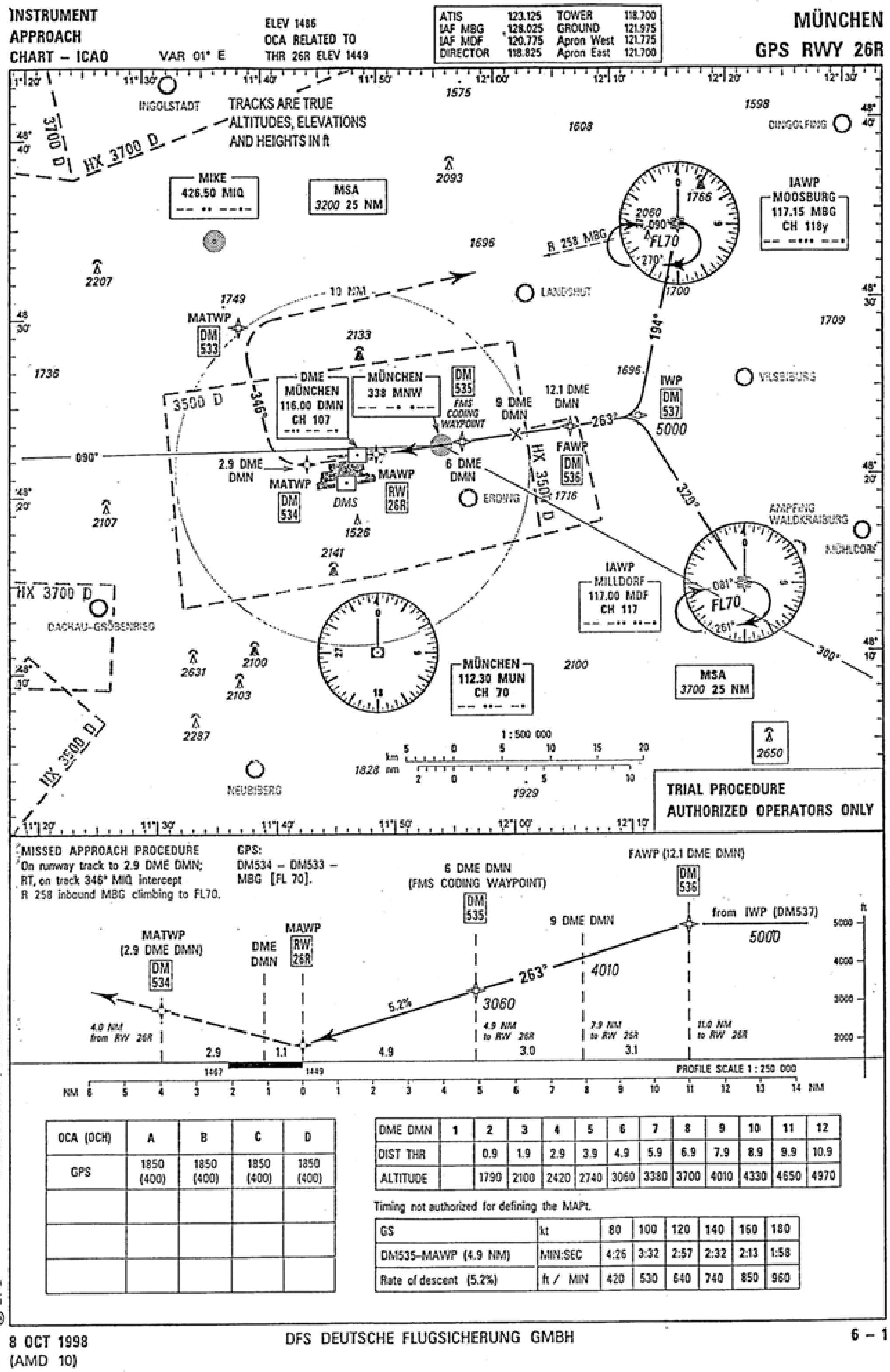

Fig. 1: GPS-Approach München, Runway 26R

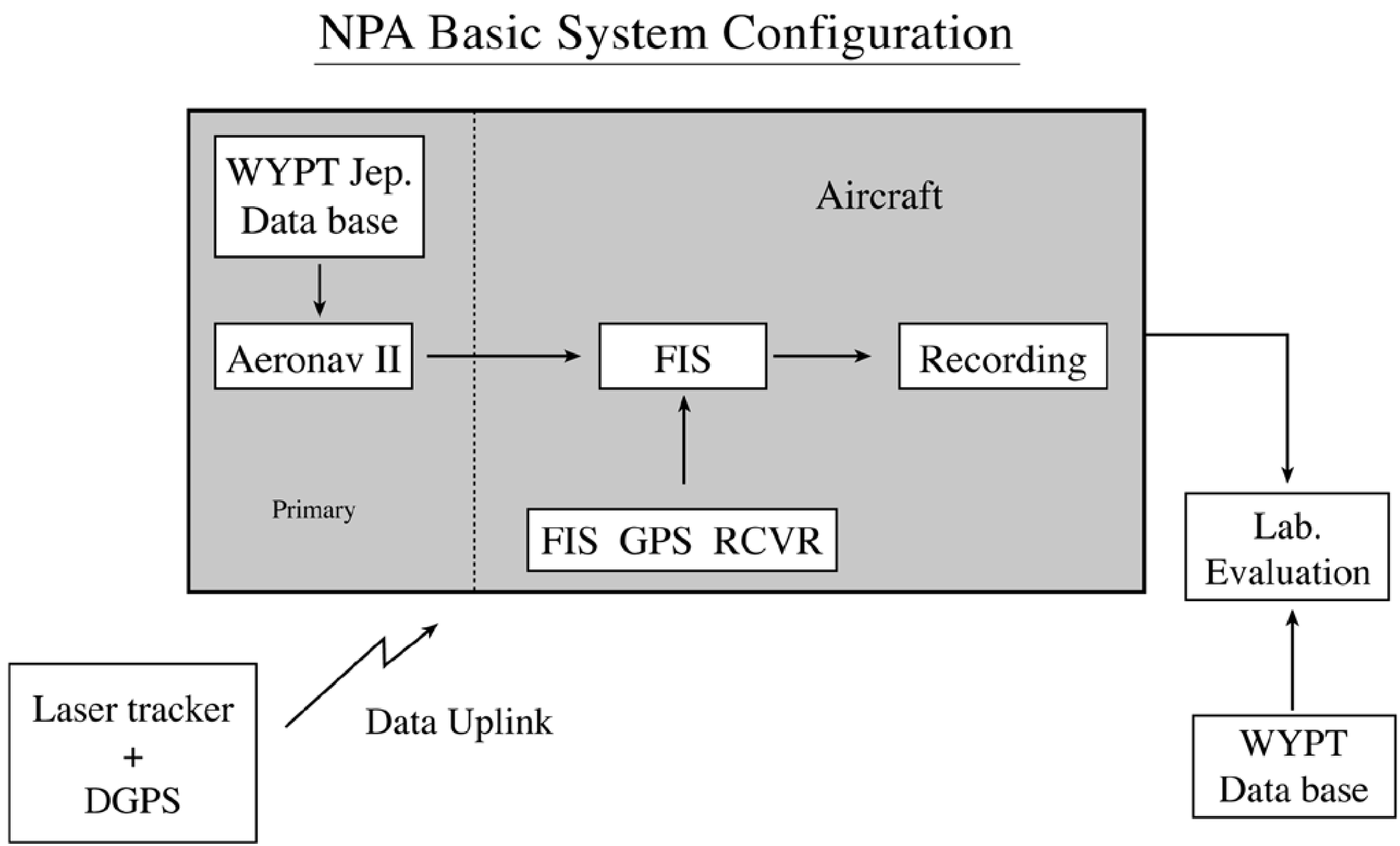

Fig.2: Basic flight inspection system

Position Reference System

NPA Error Budget

$$TSE: = \sqrt{FTE^2 + NSE_G^2 + NSE_A^2} + DBE$$

TSE:	Total System Error
FTE:	Flight Technical Error
NSE:	Navigation Sensor Error (Space segment & GPS RVR)
DBE:	Data base Error

Accuracy of reference system should be a least ±30m and if possible physically of different nature.

Fig.3: Error Budget

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AUTOMATIC FLIGHT INSPECTION AND EVALUATION OF CURVED APPROACHES

ABSTRACT

Until recently aircraft landing approach profiles were limited to single spatial straight lines. There was no other choice, since the guidance path set up by the classical ILS (Instrument Landing System) radio signals are inherently straight. When faced with interfering obstacles within the arrival area the only degree of freedom available to the approach designer was to offset the approach path. Such constraints no longer exist with some of the newer systems like the TLS (Transponder Landing System), WAAS (Wide Area Augmented System) and LAAS (Local Area Augmented System). These systems provide guidance throughout the approach volume, which means that any number of arbitrary paths can be defined.

For most airport runways the designated approaches will most likely remain straight, with the curved approach option applied only when necessary. However, although curved approaches might occur less often, they do represent the general case, so all approaches may be treated as curved, even the trivial cases which do not contain bends. Curved paths may be classified as segmented (defined by one or more segment) or continuous (defined by geometry). For now only the segmented method is addressed.

The Flight Inspection procedures for curved segmented approaches are similar to those associated with current ILS evaluation. The main difference is that some distance measurements have to be interpreted and calculated in the curvilinear sense. This paper presents curvilinear mapping as a prerequisite for curved approach evaluations. The advantage of this remapping is that normal ILS procedures may be applied to the processed data, with little or no modification to existing routines, and that the results emulate those associated with non-curved approaches.

It should be noted that the normal flight inspection parameters must be redefined to accommodate curved paths, so that the approach characterization makes sense to ground-based observers with different view points.

INTRODUCTION

The fundamental objective of any navigation aide is to guide aircraft along some predefined path, with the acceptable navigation performance being judged according to how close aircraft actually follow the path. Acceptable navigation performance limits are usually specified relative to rectangular windows which intersect the path. (See Figure 1.) These windows taken together form a guidance tunnel. Since the performance limits associated with approaches are not necessarily constant (approach tunnels are usually tapered), these tunnels attain complex shapes, bending and twisting as the path curves.

In order to evaluate a Navigation Aide the flight inspection system must map the actual guidance path setup by the facility. To do this it must first determine the position of the test aircraft, and its relative position with respect to its «should be» location (the point on desired path where the aircraft should be). If the aircraft is flying along a straight segment at a reasonable distance from any breakpoints (points where the path changes direction), its «should be» points is abeam the aircraft. The «should be» points are less well defined when the path changes direction. The next step is to determine the Navigation Aide errors based on aircraft measurements, and project those errors to the «should be» points. The locus of the relocated path points represents the best estimate of the actual path. The difference between actual and desired paths represents the Navigation error.

For most approaches the altitude of the approach path will decrease uniformly along the path. In other words the glide slope is constant when measured with respect to distance traveled. This brings up an important concept associated with curved approaches. That is, apparent distances are distances measured on or parallel to a given path. An aircraft located 4 nautical miles from a runway may travel 4.1 nautical miles to get there. Therefore, to correctly measure the glide slope, apparent distances must be used. (This complies with the curvilinear mapping discussed earlier.) The same idea is also applied to the horizontal approach (localizer type) evaluations.

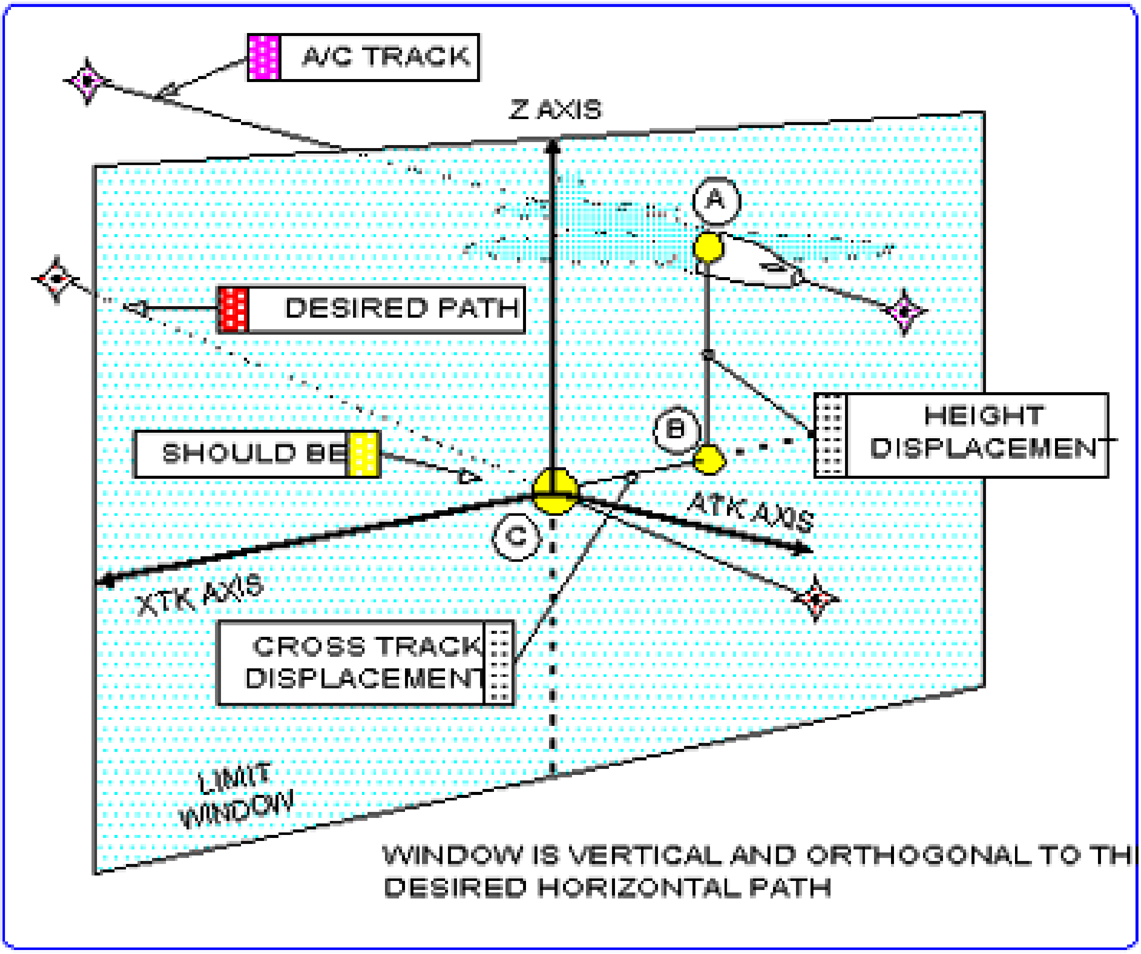

Figure 1. Limit Windows

ORGANIZATION OF A CURVED APPROACH

A curved and segmented approach is organized as a set of waypoints carefully placed within the terminal arrival area surrounding a runway. These waypoints delineate the path aircraft should take prior to landing. Figure 2 provides a map illustrating a simplified waypoint constellation. There may be any number of waypoints, and some are expected to have many more segments than are shown in the diagram. Furthermore, the routing is dynamic and many different approaches many be associated with a given runway. In the example the approach path is routed away from a fixed terrain problem to increase the obstacle avoidance safety margins. This route could be changed to suit all sorts of prevailing conditions.

The waypoints extend from the runway threshold outward. Although not usually included in waypoint lists, the threshold crossing point (TXP) represents an important reference. The TXP should be located at the intersection of the threshold and runway centerline. It is the origin of both the Cartesian arrival reference frame, and the curvilinear referencing system.

Each segment defines a three-dimensional straight spatial line with horizontal and vertical components. If all these segments where straightened out and aligned with the runway centerline, the path would intersect the runway at a particular point, a point which emulates the glide slope origin. The systems being discussed do not actually generate directional radio beams and therefore do not have true emanation points. Nevertheless defining pseudo-origins is very useful mathematically, and retaining the ILS glide slope concepts, although somewhat of an abstraction, helps describe and characterize the non-ILS systems. The same reasoning applies to the localizer. Because of the large degree of freedom available more complexity can be added to the approach designs (such as non-linear tapering). For this introductory paper only the simpler ILS look-alike systems will addressed.

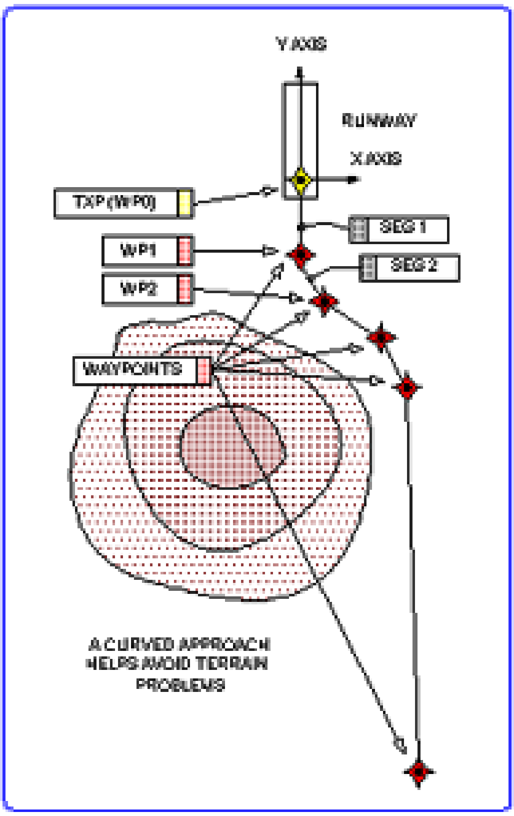

Figure 2. Waypoint Constellations

Before the evaluation of a curved approach can begin, the waypoint constellation must be translated into the arrival frame. The total terminal area extends about 30 to 40 nautical miles from the runway, which means that horizontal positioning can be performed using flat plane triangulation, avoiding the more complex spherical trigonometry. However, the area is large enough to require convergence corrections for bearing measurements, and curvature corrections for altitude measurements.

Figure 3 shows an actual curved approach. Notice the significant S-bend which starts at about 4.5 nautical miles and ends at about 1.5 nautical miles. Notice also the significant offset of 2 nautical miles at the beginning of the approach. These attributes (and a few others) are what force a redefinition of some flight inspection parameters and require modification of associated procedures.

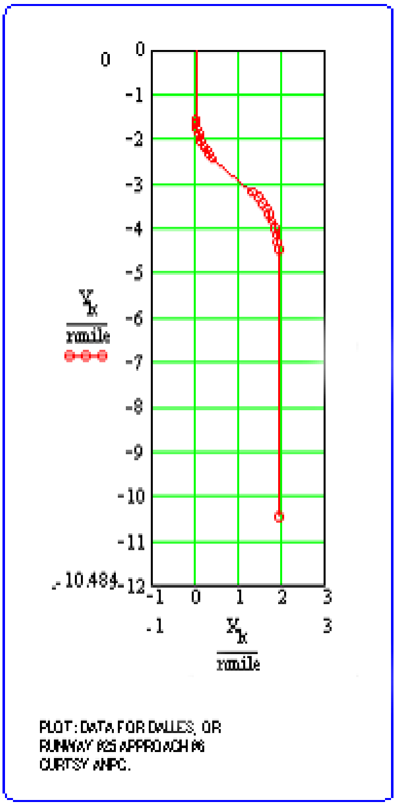

Figure 3. Curved Approach Horizontal Profile

An aircraft 4000 feet ahead of the threshold is 5000 feet from the glide slope (just as if the distances where in a straight line).

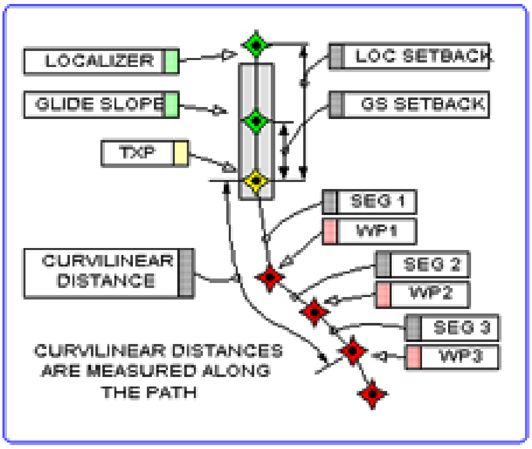

Figure 4. Curvilinear Distances

In order to obtain a proper approach characterization both curvilinear and effective distances must be used. Curvilinear values are associated with navigation plots, while effective distances are associated with off beam adjustment algorithms.

CURVILINEAR DISTANCES

In curved approaches effective distances between points on the path are measured along the path set up by the waypoints. These distances represent the actual travel distances an aircraft would experience if it follows the path exactly. Therefore, the curvilinear distance of any path point (its effective distance to the runway threshold) is simply the sum of all the individual segments connecting it with the TXP. To be consistent with the arrival reference frame, curvilinear distances for path points before the threshold are considered negative and positive for points after the threshold. (See Figure 4.)

The effective distances to the glide slope and localizer pseudo-origins are determined using the same methods as described above, except that now the curvilinear distances must be adjusted by the appropriate setbacks. As an example, consider a runway with a glide slope setback of 1000 feet.

FINAL APPROACH SEGMENTS

The final approach segment usually starts at about 4 nautical miles and ends at the threshold. This part of the approach is heavily analyzed by the flight inspection system. Oddly enough most of the normal straight path characterization parameters still apply to the curved approach, that is if they are interpreted in a curvilinear sense. (See Figures 5 and 6.)

(1) The horizontal path angle (alignment error) is now associated with the angle the path makes as it cross the runway centerline. The path is treated as if all its segments are tied together and rotate as one entity.

(2) The vertical path angle is now associated with the descent along the curved path. In a typical path the descent should be constant.

(3) The ground intercept point is determined by extrapolating a line from the TXP using the horizontal and vertical path angles.

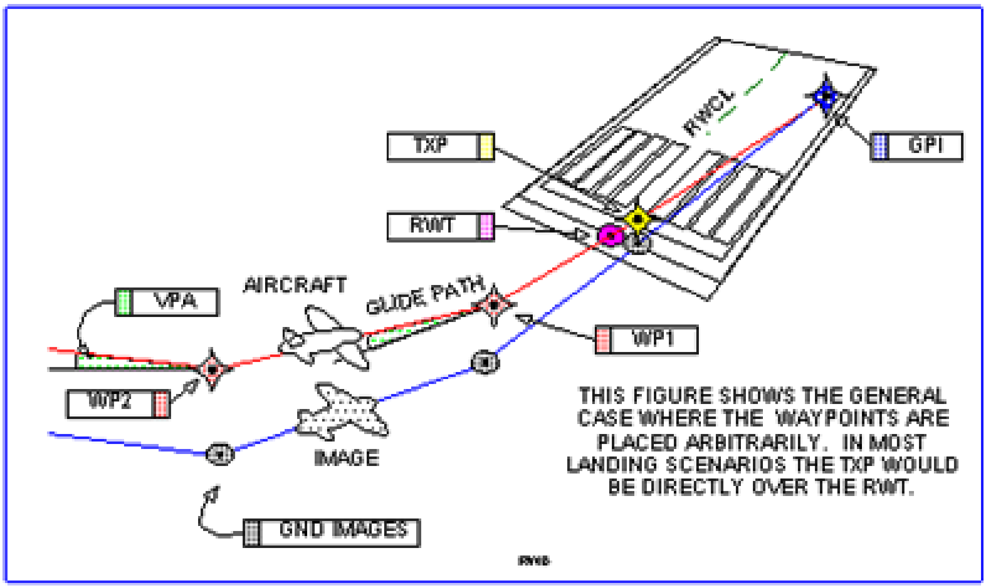

Figure 5. Final Approach Segments

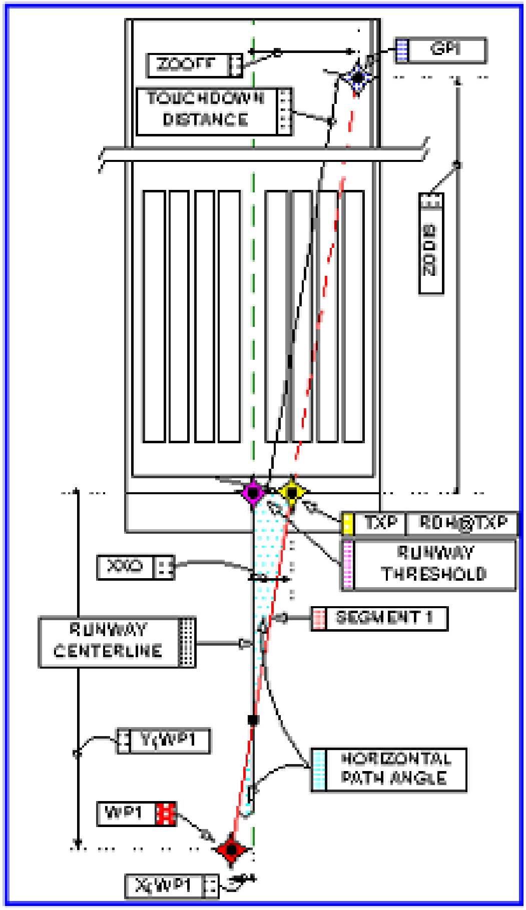

Figure 6. Threshold and Landing Points

EFFECTIVE ILS BEAMS

At present the transponder system is the only system which emulates the ILS with off beam deviation signals. It is entirely possible that WAAS and LAAS systems could, with the appropriate avionics, do the same thing.

If the facility is considered an ILS look-alike, then the localizer deviation signal is proportional to the effective distance measured along the path and the orthogonal displacement from the path. (See Figure 7.) Notice that the beam width edges do not exactly follow the desired path, but are a distorted version of the path. The glide slope follows the localizer but uses its own origin.

As shown in Figure 7, radial cuts that use the pseudo-origin position as a vertex, make cuts that may be unsymmetrical. This can introduce error in the beam width and symmetry measurements. FAA flight inspection specification, Order 8200.1A, calls for perpendicular cuts. Therefore, for best results the flight profile used in these measurements should be the apparent localizer location, which will vary from segment to segment. The apparent localizer coordinates may be determined by extrapolating each segment forward from its «to» waypoint (the waypoint closest to the runway) by its curvilinear distance.

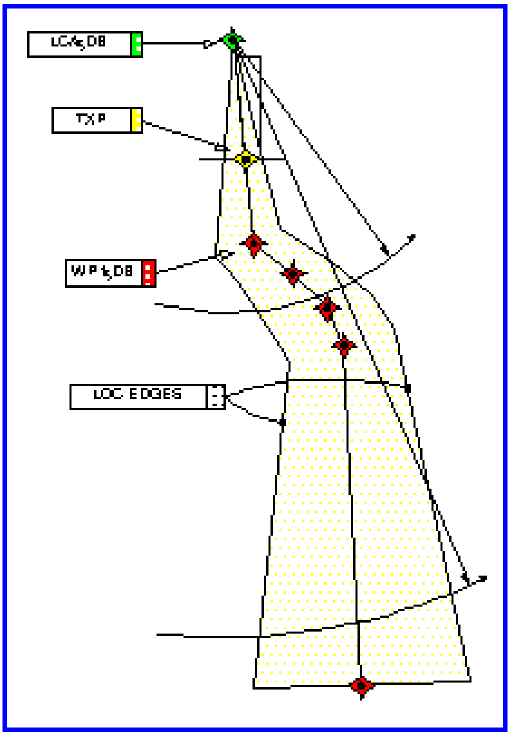

Figure 7. Effective Localizer

The off beam performance gets a bit muddled in the neighborhood of waypoints as the effective signals tend to overlap each other as the path turns. There are even cases where the off beam point may be simultaneously associated with more than one segment. The result is that the off beam effective signals do get distorted. The effect increases with the severity of the bend and the distance from the desired path. It is worse at the beam edges. This characteristic can affect certain measurements. For example, attempts to measure localizer beam width near a bend might produce values that are slightly different from those obtained away from the bends.

Using curvilinear distances and orthogonal offsets remaps the curved approached into one that is more manageable. As can be seen from Figures 8 and 9, the remapped curve appears straight. This remapping procedure should be applied to all the data collected during the inspection runs. This not only simplifies the mathematics involved, but allows the reuse of many existing software routines, including least square reductions.

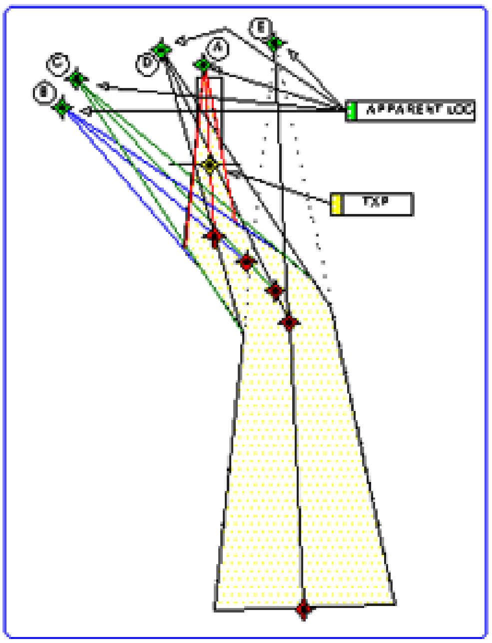

Figure 8. Apparent Localizers

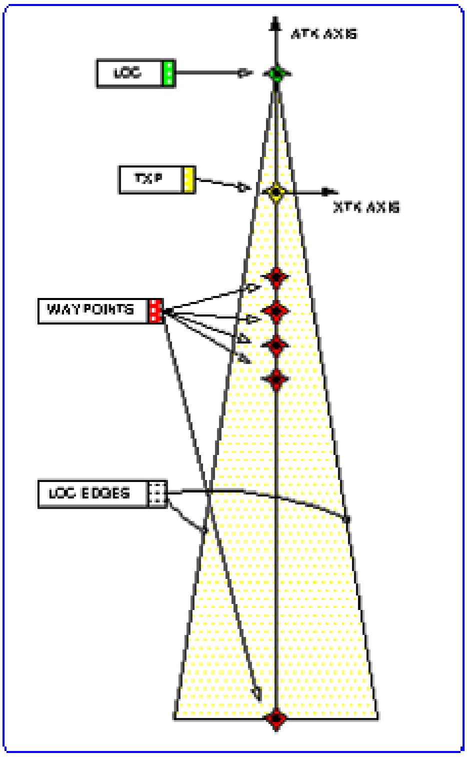

Figure 9. Remapped View

ALIGNMENT ERROR AND STRUCTURE

A plot of localizer cross track (orthogonal) error versus curvilinear distance provides the raw data for a least square determination of the horizontal approach angle. Note that this is the systematic error, a rotation of the entire path from its intended direction. (See Figure 10.)

Alignment is usually measured within one nautical mile of the threshold, an area where multiple waypoints are unlikely. For completeness the concept has nevertheless been presented.

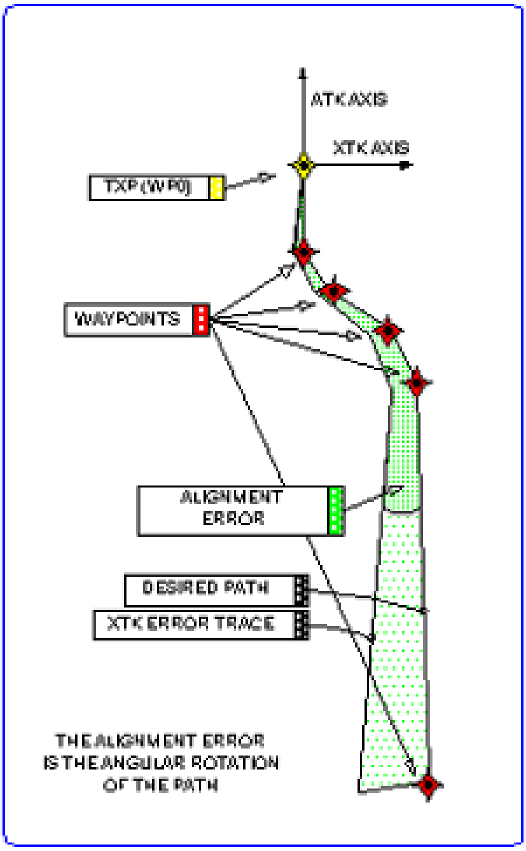

Figure 10. Curvilinear Alignment Error

The localizer structure is the orthogonal deviation measured with respect to a least square reduction of the localizer data and curvilinear distances. (See Figure 11.)

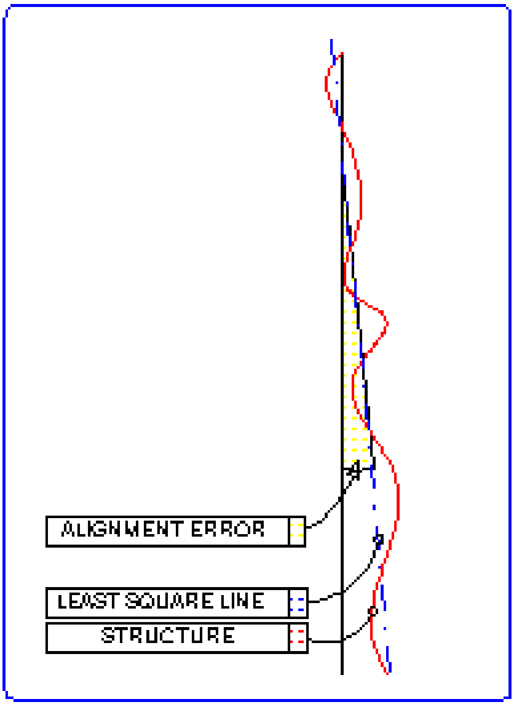

Figure 11. Localizer Alignment Error and Structure

GLIDE PATH ANGLE AND CROSSING HEIGHT

The procedures for determining the glide slope are similar to those for determining the alignment error. The following exceptions should be noted:

(1) The curvilinear distances are measured with respect to the glide slope pseudo-origin.

(2) The least square reduction yields the vertical path angle and threshold crossing height.

A typical glide path plot is shown in Figure 12.

GLIDE SLOPE STRUCTURE

Like the localizer, the glide slope structure is measured with respect to the least square reduction of the path data.

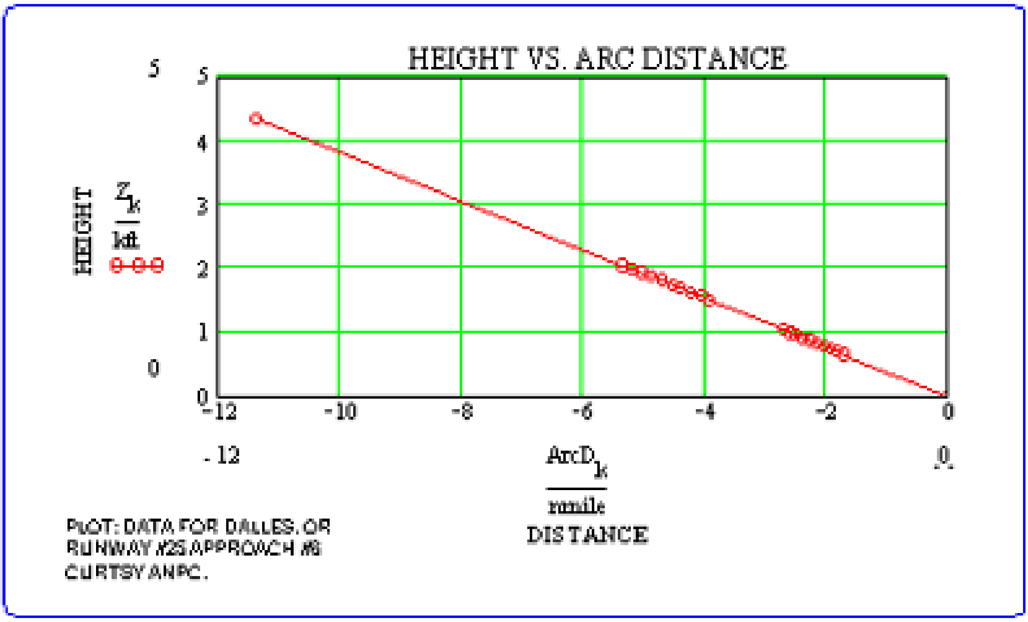

Figure 12. Actual Glide Path

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OFFICE IN THE SKY - THE NEXT GENERATION FLIGHT INSPECTION SYSTEM

ABSTRACT

A joint alliance of four flight inspection and flight test companies is going to optimise overall development efforts by symbiotic effects. Large new developments including test equipment, operation, aircraft modification, and certification are demanding tasks that can be handled easier when shared by experienced specialists.

The current Flight Inspection project aims on a common software platform as a basis for future systems. That means that parallel developments will be performed only once to gain maximum compatibility for optimised cost.

The new FI system will combine the joint experience from dozens of proven systems with a modern user interface and some new key features:

- Easy-to-learn user surface
- Interface to standard office software packages
- Post processing on any desktop PC
- Flexible system configuration by customer
- Common facility data format
- Control of oscilloscope and spectrum analyser via operator console

This joint alliance is a tremendous learning experience for the involved partners with the goal to improve quality and efficiency in Flight Inspection.

INTRODUCTION

The team partners

Aerodata Flugmesstechnik GmbH (ADF), Normarc (NFIS) and Sierra Data Systems (SDS) represent more than 100 years of experience in the Flight Inspection business. Their systems provide reliable Flight Inspection solutions worldwide.

KSR, in addition, is a flight research company who develops systems to acquire the data required to develop aircraft simulation models. KSR brings in some bright experience in the field of flight testing and certification.

The Challenge

Existing systems of all four companies deal more or less with data acquisition. The kernel requirements in that field are quite similar. Even the different flight inspection systems have some kind of common functionality in the implemented features. Individual solutions are found in the user interface. Also storage formats of facility data bases are individual, for instance.

All systems have to deal with slightly different requirements for every individual system, e.g. country-specific tolerances, special procedures etc.. Over the time, more and more customer-specific features were added to the software.

It has been requested for a system that can run on Windows and interface to Microsoft Office. Up to now, the systems are based mainly on real-time computer technology.

This brings up a good chance to efficiently set up a new software basis in an efficient, common approach.

Thus, the harmonization of standards is a huge challenge. It brings benefits to the users of flight inspection systems as well as to manufacturers:

- Compatibility between systems. That means, all systems shall have common features, e.g. support of facility database formats, report builders, procedures, tolerances
- This will enable easy adaptation to hardware changes, like specific receivers. This gives more flexibility to react on necessary hardware swaps
- Common ideas in the individual systems will enhance the flexibility concerning staff scheduling of our service customers
- Identical maintenance functions, easier training of service staff
- Comparable kernel functions, e.g. specific tolerances or procedures are implemented identically
- More efficient development due to symbiotic effects
- New flight inspection tasks are challenging all flight inspection systems in the future, like FANS. This will incorporate a huge manpower effort.
- An additional benefit is expected from using state-of-the-art software design methods and development tools that may not be compatible with existing source codes.

The Solution

The companies came together for working on a joint effort to design and implement a set of reusable components that could be used to create the unique products. Collectively, these components are known as the Common Acquisition Processing Environment (CAPE).

The CAPE flight inspection components satisfy the current flight inspection requirements, while providing a new extensible framework on which future flight inspection systems will be built.

The CAPE project team has taken the challenge to create a new kernel for systems dealing with data acquisition, processing and visualization. CAPE converts the inspection aircraft into a flying special mission office. It is a perfect symbiosis between real-time and PC-office world.

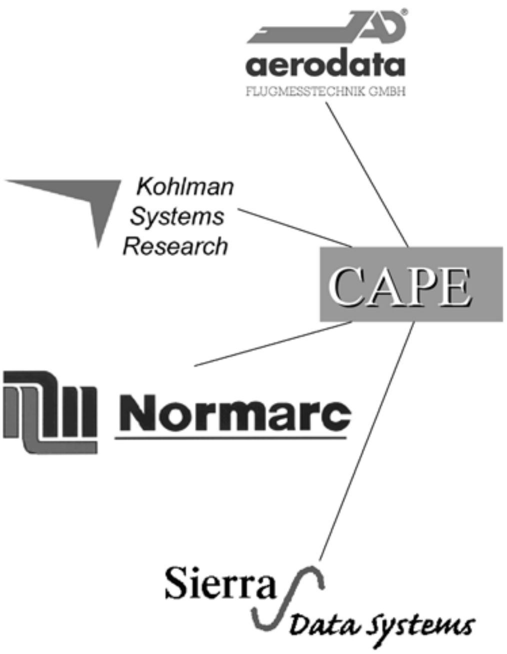


Figure 1: The CAPE team

In addition, the system will be designed in a way that allows an upgrade path for most of the existing systems with a reasonable effort.

FEATURES

The new system brings a lot of improved and additional functionality to the flight inspector to make his job more convenient. This list shows only some new key elements that are directly visible. Of course, all yet existing features are still included.

The screenshots show some ADF-specific elements as an example of what is possible. As mentioned before, the representation of the user interface differs within the systems.

Easy-to-learn user surface

The graphical user interface (GUI) is fully based on Microsoft Windows. Most of the potential users have a desktop PC in their office. The look-and-feel is familiar to windows users immediately. It is designed for office as well as for airborne operation. Standard windows elements are used like menu bars, selector tabs and dialogue windows.

Special care has been taken for alternate operating concepts, because the typical pointing device operation by mouse or trackball is sometimes difficult to handle in an airborne environment. Nearly every action can easily be performed via the keyboard. Virtually every input device that is available in the PC world can be connected.

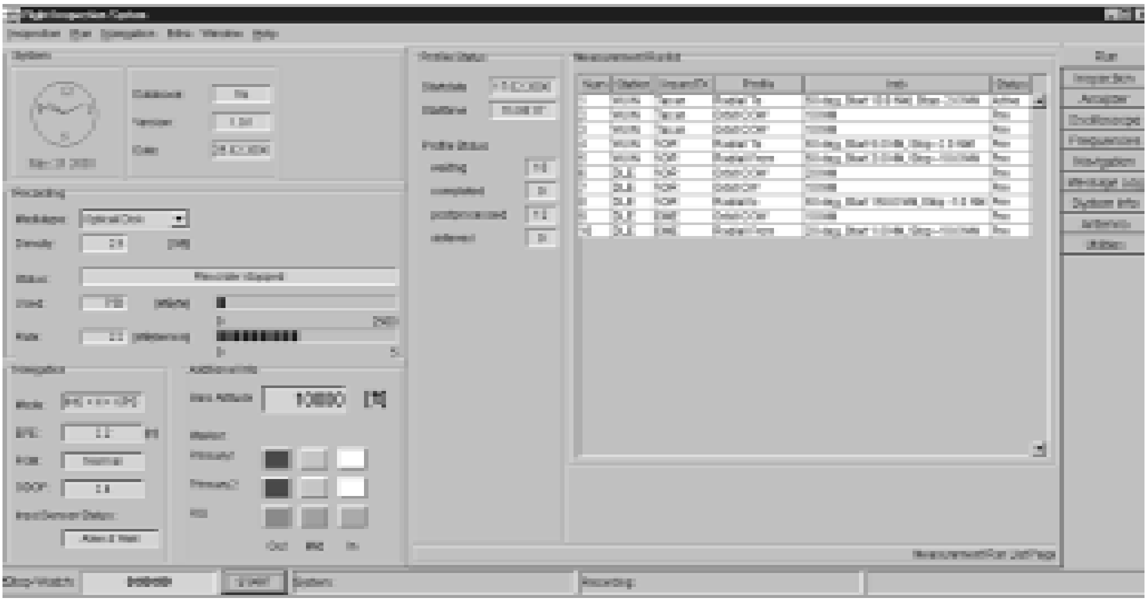


Figure 2: Sample screenshot of a user interface implementation

Sample Figure 2 shows the main screen with status information about

- System Information
- Recording
- Position reference
- Flight Inspection measurement run list

Other important information is easily accessible by a single mouse click or one keyboard action.

The user surface is fully integrated in the Windows mechanisms.

The fully configurable software design allows easy adaptations to the individual customer needs. Latest software techniques like «rapid prototyping» allow to give a quick feedback to the customer and reduce overall efforts.

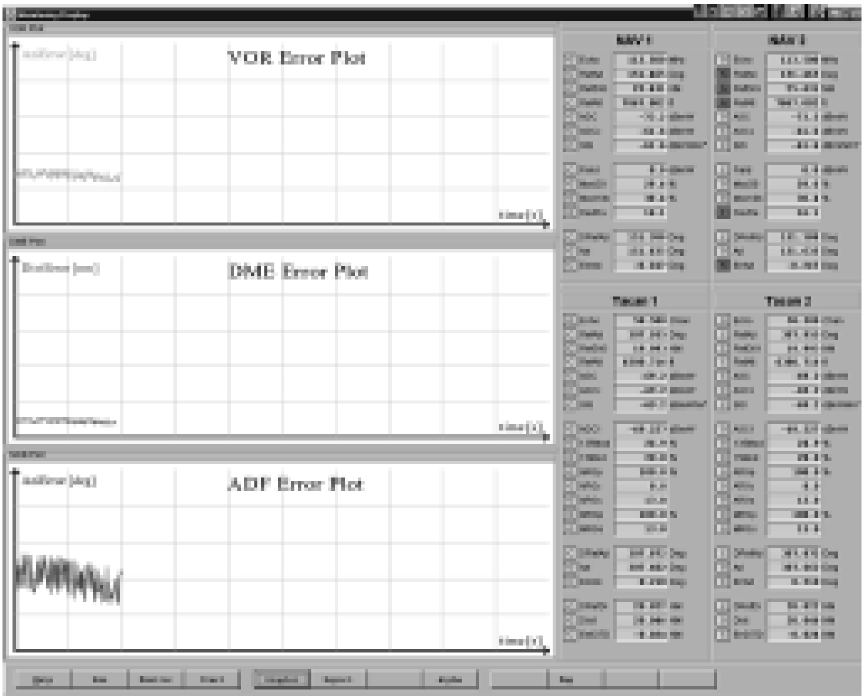


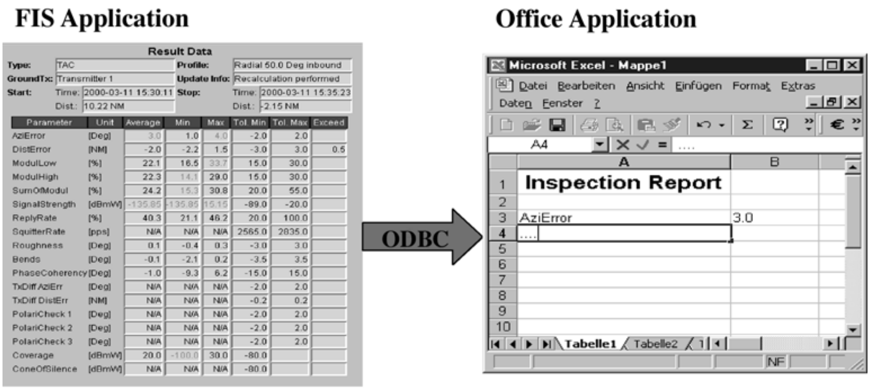
Figure 3: Sample screenshot of graphical and alphanumeric output

Figure 3 shows an overview of a windows-like graphic and alphanumeric display. It allows all functions that are required from modern graphical front ends, like zooming, online definition of charts and so on.

Interface to standard office software packages

All communication channels that are known from the Windows world can easily be used. For instance, customized inspection reports can be generated by using Microsoft Word or Microsoft Excel. Adaptation to special layouts and individual languages as well as incorporation of company logos can be done with office tools where the user is familiar with. Figure 4 shows an example of a link to Microsoft Excel.

Figures from the result sheets are transferred to the office applications. This allows even the application of user-coded post-processing algorithms to the acquired data.


Result Data

Type: TAC — Profile: Radial 50.0 Deg inbound
GroundTx: Transmitter 1 — Update Info: Recalculation performed
Start: Time: 2000-03-11 15:30:11 Dist.: 10.22 NM — Stop: Time: 2000-03-11 15:35:23 Dist.: -2.15 NM

Parameter	Unit	Average	Min	Max	Tol. Min	Tol. Max	Exceed
AziError	[Deg]	3.0	1.0	4.0	-2.0	2.0	
DistError	[NM]	-2.0	-2.2	1.5	-3.0	3.0	0.5
ModulLow	[%]	22.1	16.5	33.7	15.0	30.0	
ModulHigh	[%]	22.3	14.1	29.0	15.0	30.0	
SumOfModul	[%]	24.2	15.3	30.8	20.0	55.0	
SignalStrength	[dBmW]	-135.85	-135.85	15.15	-89.0	-20.0	
ReplyRate	[%]	40.3	21.1	46.2	20.0	100.0	
SquitterRate	[pps]	N/A	N/A	N/A	2565.0	2835.0	
Roughness	[Deg]	0.1	-0.4	0.3	-3.0	3.0	
Bends	[Deg]	-0.1	-2.1	0.2	-3.5	3.5	
PhaseCoherency	[Deg]	-1.0	-9.3	6.2	-15.0	15.0	
TxDiff AziErr	[Deg]	N/A	N/A	N/A	-2.0	2.0	
TxDiff DistErr	[NM]	N/A	N/A	N/A	-0.2	0.2	
PolariCheck 1	[Deg]	N/A	N/A	N/A	-2.0	2.0	
PolariCheck 2	[Deg]	N/A	N/A	N/A	-2.0	2.0	
PolariCheck 3	[Deg]	N/A	N/A	N/A	-2.0	2.0	
Coverage	[dBmW]	20.0	-100.0	30.0	-80.0		
ConeOfSilence	[dBmW]	N/A	N/A	N/A	-80.0		

Figure 4: Example of interfacing to Microsoft Office

Printers and other interface devices can easily be accessed by the Windows network mounting mechanism.

Post processing on any desktop PC

CAPE improves the post-processing capabilities significantly. All incoming data is recorded during the flight inspection run. These data can be evaluated or even post-processed as often as necessary.

The operator is able to compare the current run to any previous one, in flight or at home, as he prefers. No dedicated equipment is mandatory for performing post-flight evaluations in the lab. Post-processing can simply be performed on nearly any modern desktop-PC. This brings a great flexibility and comfortable operation to the flight inspector.

Flexible system configuration by customer

The user interface allows for different levels of preferences. As a framework, it is possible to define fleet-setups. Each user can have his individual setup within this frame. The preferences can be edited by windows dialogues.

Common facility data format

For fleet operators it is quite an issue to maintain facility data. Updates and corrections have to be incorporated fluently. This has to be as straightforward and error-proof as possible. Additional problems may occur, if redundant data has to be maintained because different systems require different data base formats.

Operators that have different FI systems to maintain now get the full compatibility of the facility data base storage format which easily allows to use the same database for all aircraft.

Control of oscilloscope and spectrum analyser via operator console

The system fully supports remote controlled operation of oscilloscope and spectrum analyzer. An operators panel appears in the windows GUI that allows full control of these units. The user can set up all required switches like time base, trigger source and -level or center frequency and frequency span, respectively.

In addition to this manual remote control, automatic

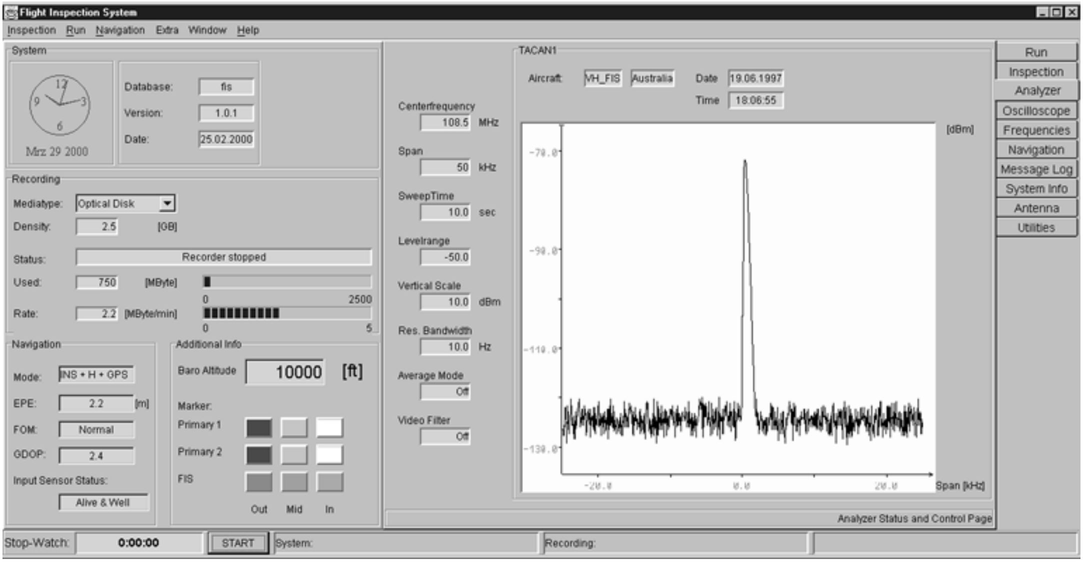


Figure 6: Integration of Spectrum Analyzer

sequences can be driven by the flight inspection application in respect to the requirements of the current calibration procedure.

Output screens of the measurement units are fully integrated into the GUI and can be selected by a simple user action. The outputs can be printed and stored on the mass storage device.

CONCEPT

A CAPE - system in general consists of three parts:

- The real-time-system (RTS) which is responsible to collect the incoming data. It also allows for real-time-critical software parts as aircraft control loops or time critical outputs. It runs under a real-time operating system.
- The semi-real-time-system (SRTS) reads the data via network connection from the RTS and may perform calculations and storing of results. This part will usually run on a PC.
- The third subsystem is built by one or more graphical user interfaces (GUI). The GUI is a client of the SRTS and is responsible for data presentation, printing and control of the measurements. The GUI can run on the same or another PC as the SRTS.

This open concept allows for an easily scalable solution to virtually any needs of data acquisition systems. Options include the usage of an RTS alone for dedicated data acquisition or to use as many GUIs as requested without affecting the system concept.

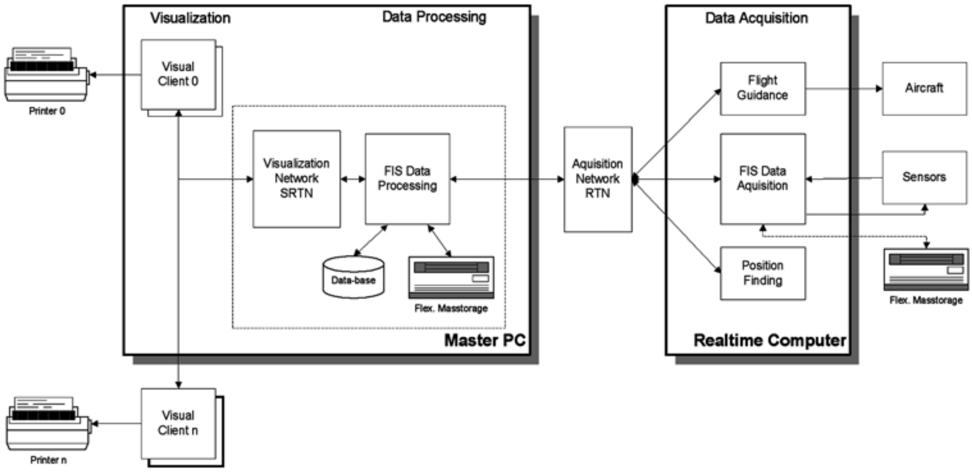


Figure 7: Sample Block Diagram of a CAPE system

CONCLUSION

The new system based on a CAPE core is the next step in flight inspection techniques. It brings in a user-friendly graphical user interface without losing full access to all system parameters that are interesting to engineers. A fully modular design allows for extendibility to nearly any customer needs. Full real-time capability is available by the included real-time system module.

This step is possible only as a joined effort of an alliance of companies. The new system combines the expertise and manpower of all partners. It simply includes the best of all.

It combines the power and the reliability of a real real-time system with the ease of use of the windows world.

John H. Johnson, Sr., Engineering Manager
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INSTRUMENT LANDING SYSTEM (ILS) SOLUTIONS FOR 2000 AND BEYOND

«Directive and Frangible with Modern Specifications and a Renewed Commitment»

March 20, 2000

ABSTRACT

Continued ILS research and development (R&D) has yielded powerful options to meet the needs of the future. Test results of a developmental wide aperture localizer antenna indicate a system capable of handling the future needs for lateral guidance. Extensive modeling results indicate a reduction of the critical area of the antenna system can be achieved while still providing Category III quality signal. Deployment of wide aperture localizer systems can further reduce construction constraints and minimize efficiency limitations that result from large critical and sensitive areas to protect the ILS localizer signal quality during instrument approach conditions.

Frangible and directive glide slope antennas, imaging and otherwise, show promise in providing greater availability of vertical guidance. Frangible construction enables antenna placement closer to the runway with substantial cost savings and a better reflection plane for image type systems. The smaller offset provided by frangible systems permits more directive radiating elements to be employed. Directive elements provide a horizontal reduction in the glide slope critical area and lateral confinement of the radiated energy to minimize multi-path reflections.

PURPOSE

The capabilities of the ILS are by no means at a limit. However, continued development is contingent on a renewed commitment to provide the necessary service with the ILS. In order to reap the full benefit of modern designs and concepts discussed herein, existing specifications should be reviewed to adapt to today's operational requirements without sacrificing safety. Failure to consider revising some older specifications can ultimately make the retirement of the ILS a near-term self-fulfilling prophecy. Adhering to older specifications is limiting development options for new designs, which would ensure that the ILS can meet future needs.

BACKGROUND

For some 15 years or more there has been a move to replace the 50 + year old Instrument Landing System (ILS) with newer technology. The basis for considering such a plan has ranged from perceived limitations of the ILS, frequency spectrum issues, the benefits of curved approaches, and more recently countless applications of the satellite technology. It is true that the application of ILS technology has a limited life cycle. It is not clear, however, what the life span actually is. Many publications and conferences today provide indication that new replacement technology is coming, however, the complexity of making these systems certified for public use results in scheduling delays of unpredictable proportion. This scenario begs the question: ***How shall we proceed during this indefinable interim period?*** Consequently, ILS developments are driven more by the concept of sustaining temporary use rather than more aggressive developments that will allow meaningful long term benefits.

Approximately every 5 - 8 years a new localizer antenna array is available with enough aperture increase to promote replacement of a system near or at the CAT II or III limits. In many cases this provides the desired service but does not provide enough improvement to substantially increase operations or promote construction. Consequently, airport administrators are constantly concerned about replacement technology to minimize their fears regarding losing their CAT III ILS. The incremental upgrading of their localizer antenna is an unwelcome but necessary interruption in airport operations. Substantial long term cost savings can be realized by upgrading to the greatest possible aperture for the benefit of reducing the localizer critical area, promoting construction that will attract business, and avoiding service interruptions caused by incremental replacements of the antenna system.

With the glide slope, requirements for lateral coverage and tower offset criterion significantly increase installation costs, reduce the availability of vertical guidance, and require the use of broad antenna patterns. The merits of frangible systems with narrow-beam radiation are discussed.

SUBJECT

ILS Localizer

Attachment B. of the International Civil Aviation Organization (ICAO) Annex 10 [1] titled, «Strategy of Introduction and Application of Non-visual Aids to Approach and Landing,» subsection ILS related considerations, indicate «there is a risk that ILS Category II or III operation cannot be safely sustained at specific locations». It goes on to indicate, however, that « in most areas of the world, ILS can be maintained in the foreseeable future». The global strategy for the future is identified in part as follows; a) continue ILS operations to the highest level of service as long as operationally acceptable and economically beneficial; and b) implement MLS where operationally required and economically beneficial. Emphasis is placed here on the statement that there is a risk that ILS Category II or III cannot be safely sustained at specific locations.

A detailed analysis requires that sources of error for the ILS localizer be grouped into two categories. ICAO recognizes the two part composition of errors as follows; 1) static i.e. hangers, power lines, parked aircraft etc.; and 2) moving objects herein referred to as dynamic i.e. aircraft, vehicles etc. Further recognition of the two principle contributors is given by the root-sum-square method used determine the size of the localizer critical and sensitive areas:

√ (total error ^2 + static error ^2) = dynamic error permitted

Reductions in the magnitudes of static and dynamic errors are necessary for continued use of the ILS. Three methods are identified to accomplish this goal; 1) Increasing the aperture of the course antenna systems to confine the RF radiation to the greatest extent practicable; 2) In cases where large objects exist with the coverage area, the clearance RF patterns are produced to minimize the quantity of the signal at large angles, i.e. beyond 15 degrees, while still meeting coverage requirements; 3) Consider the benefits in a reduction in the lateral service volume of the localizer.

Computer Modeling

To quantify the contributing components to localizer errors and to evaluate proposed solutions, an extensive computer modeling study was conducted [2], [3], [4]. Two objects were synthesized in various orientations and incremented along the length of the runway. Several different aperture sizes were evaluated to determine benefits and any potential weaknesses of large aperture course antennas. The methodology for the study was to position the multi-path sources so as to intentionally produce the greatest error along the approach path and then to model each localizer antenna in the critical environment. Modeling parameters include a runway length of 12000' (3658m) with localizer setback of 1000' (305m), yielding a tailored course width of 3.08 degrees. A glide path angle of 3.00 degrees was used with a threshold crossing height (TCH) of 55 feet (17m).

The first synthesized object was a flat plate 1000'(305m) x 100' (30.5m) used to represent the effects of a hangar, or static error source, offset only 1200' (366m) from the runway centerline. The hangar was modeled repetitively at 1000' (305m) longitudinal distance increments referenced to the runway threshold. At each location the plate was rotated in 5.0 degrees increments, from +30 to -30 degrees, to identify any sensitivity to the orientation of the structure. Cases were modeled with only the course array signals and then again with the composite course and clearance signals. This method was used as a means to identify the greatest contributor to the overall errors and therefore determine quantitatively which pattern could be shaped to provide the greatest improvements. At each location a centerline approach was modeled and the percentage of error was determined using flight inspection criteria as it relates to each zone. The results are presented below as a percent of Category III tolerances, on a grid representing the location of the structure and its orientation.

The second object was a 747-400 class aircraft at several orientations and various displacements from the runway centerline. The aircraft was modeled parallel to the runway centerline with the tail oriented toward the array and perpendicular to the runway centerline with the tail oriented toward the runway. Only the results from the perpendicular scenario are given in this paper. The aircraft fuselage was modeled as a large rectangular plate, 225 feet (69m) long by 23 feet (7m) high elevated 7 feet (2.1m) above ground. A series of progressively smaller plates stacked vertically represent the tail with an overall height of 63 feet (19m). Results of the aircraft simulation are used to quantify reductions in the critical and sensitive areas, or improved airport efficiency, achievable with the larger aperture antenna.

Increasing the Course Array Aperture

Narrower carrier-plus-sideband (CSB) and sideband only (SBO) radiation patterns are produced by an increase in the aperture of the course array. Course errors, or bends, are produced from reflections of sideband only component of the radiated signal. A comparison of the calculated sideband only radiation pattern from an aperture of 150 feet (45.7m) versus that of a 270 feet (84.7m) aperture is shown in Figure 1. Clearly the larger aperture will provide additional immunity to course bends produced by aircraft or static sources such as hangers. A course width of 4.0 degrees is provided in both cases however, the larger aperture pattern shows a 3.6 dB reduction at the course half-width azimuth angle of 2.0 degrees. The characteristic exists because the carrier-plus-sideband pattern of the large aperture has a half-power beam-width of only 2.65 degrees. The amplitude of the CSB signal is dropping substantially within the half-course guidance sector. The DDM continues to rise linearly in azimuth when the CSB signal decreases slightly faster than the SBO. It is important to note that the 150-feet (45.7m) aperture is fair representation of the most capable ILS localizers in use today. Generally, large increases in the aperture are necessary to provide significant performance advantages.

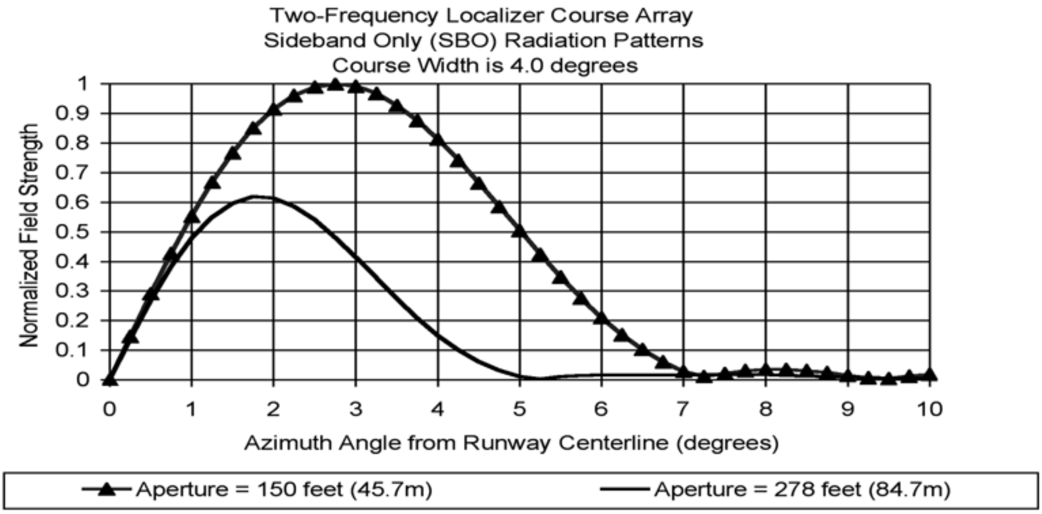

Figure 1. A Comparison of Sideband Only (SBO) Radiation Patters Produced by Array Apertures of 150 feet (45.7m) and 278 feet (84.7m).

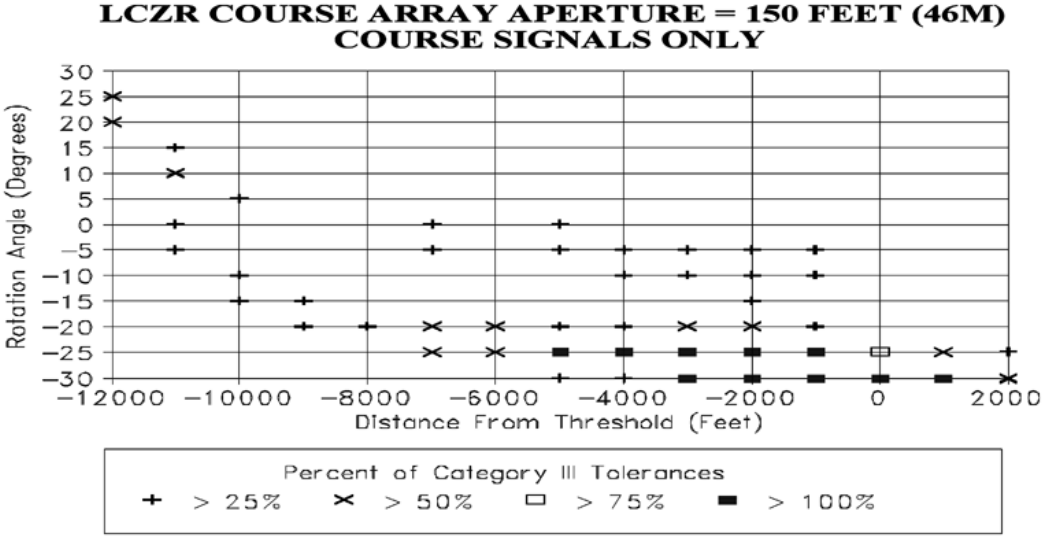

Figure 2. Modeling Results Using a Localizer Course Array Aperture of 150 feet (46m) in the Presence of a 1000' (305m) x 100' (30.5m) Reflecting Object Offset 1200' (366m) from the Runway Centerline. The Grid Identifies Locations and Orientations Sensitive to Course Signal Multi-path and the Percent of Category III Tolerances that Result.

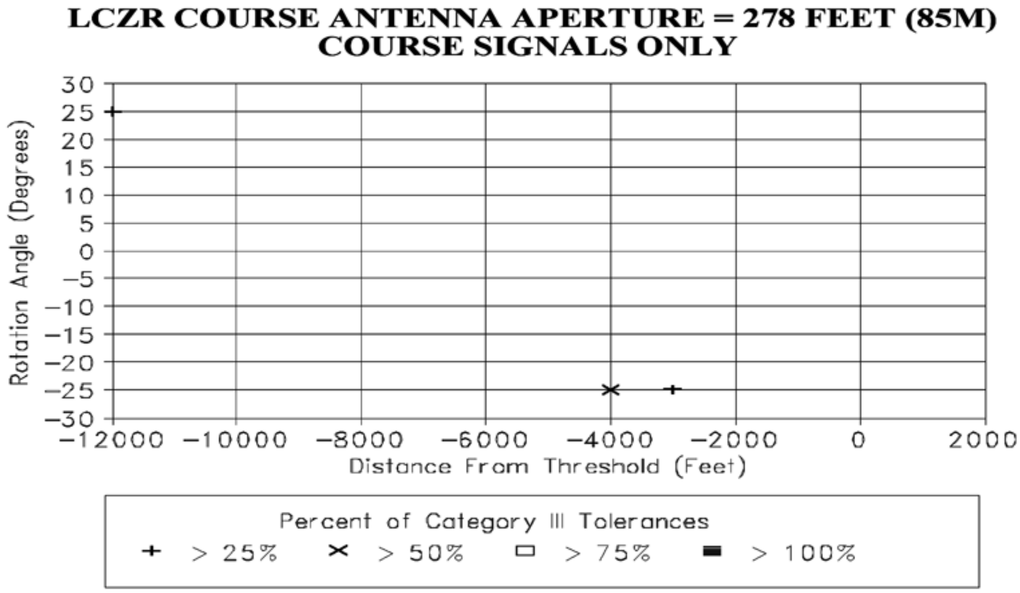

Figure 3. Modeling Results Using a Localizer Course Array Aperture of 278 feet (85m) in the Presence of a 1000'(305m) x 100' (30.5m) Reflecting Object Offset 1200' (366m) from the Runway Centerline. The Grid Identifies Locations and Orientations Sensitive to Course Signal Multi-path and the Percent of Category III Tolerances that Result.

Figures 2 and 3 provide the course errors calculated in the computer modeling simulations of a large static structure with the localizer aperture sizes used in Figure 1. Errors are shown as a percentage of Category III tolerances. As the simulated hanger is rotated in each location the offset is adjusted so the closest part of the structure is at 1200 feet (366m). Only three points are identified as producing greater than 25 percent of error with the large aperture, and no points were identified as being near the tolerance limits.

Another important factor is that the total error on the course line typically is comprised of both course and clearance signal multi-path. As the course aperture is increased, course errors tend to approach zero and the «capture point» where the clearance takes over the receiver moves in toward the course line but still outside of the course sector. With minimal course errors, the total error budget is available for the effects of clearance multi-path, which has additional rejection in the receiver due to «capture-effect» characteristics. A comparison of Figures 4 and 5 shows this clearly. Modeling predictions are shown resulting from the composite two-frequency course and clearance signals with the hanger scenario. In both modeling cases, the same clearance array subsystem was used with the different course antennas. Parameters such as centerline power separation, course width, clearance course width and minimum DDM, were identical in both cases. Clearly the larger aperture provides substantial flexibility to allow additional construction and development on the airport while maintaining CAT II/III quality guidance signals. The wide aperture antenna reduces course errors to a minimum and allows greater levels of reflected clearance signals to exist before reaching tolerance limits.

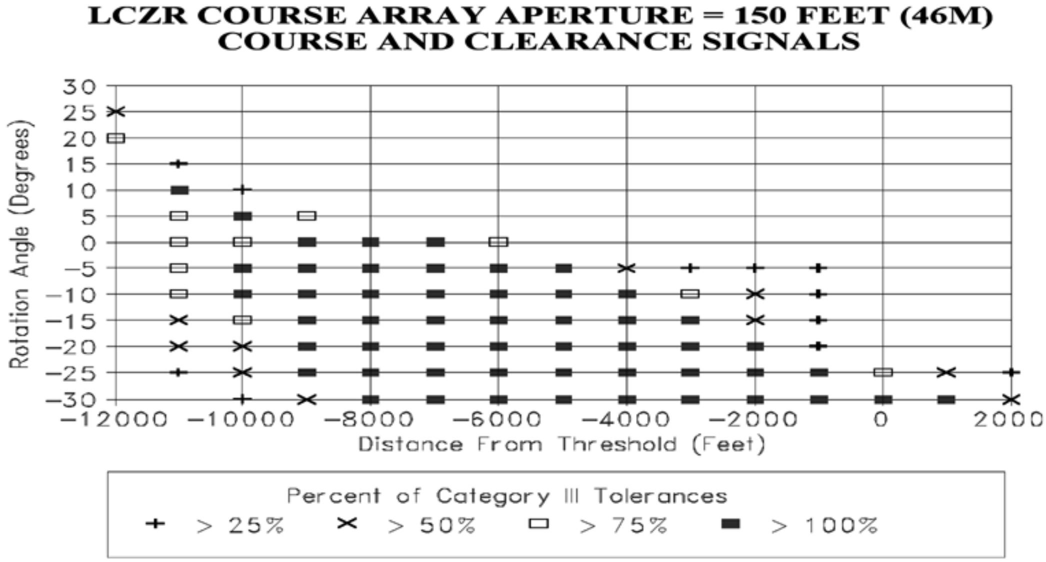

Figure 4. Modeling Results Using a Localizer Course Array Aperture of 150 feet (46m) in the Presence of a 1000' (305m) x 100' (30.5m) Reflecting Object Offset 1200' (366m) from the Runway Centerline. The Grid Identifies Locations and Orientations Sensitive to Composite Course and Clearance Signal Multi-path and the Percent of Category III Tolerances that Result.

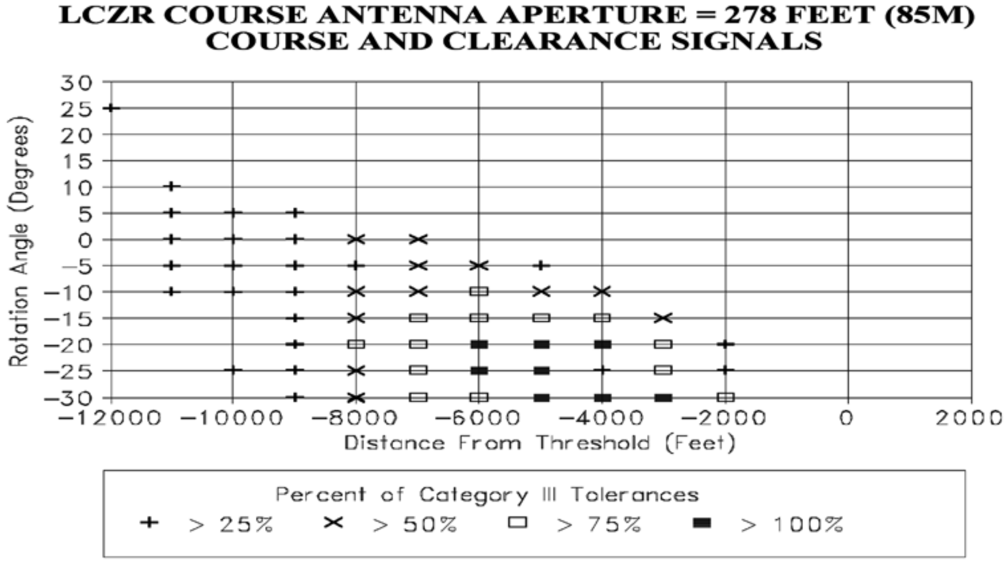

Figure 5. Modeling Results Using a Localizer Course Array Aperture of 278 feet (85m) in the Presence of a 1000'(305m) x 100' (30.5m) Reflecting Object Offset 1200' (366m) from the Runway Centerline. The Grid Identifies Locations and Orientations Sensitive to Composite Course and Clearance Signal Multi-path and the Percent of Category III Tolerances that Result.

Clearance Array Performance VS Coverage

The localizer coverage sector at 31.5 km (17NM) between 10 degrees and 35 degrees from the front course line; and 18.5 km (10NM) outside of plus or minus 35 degrees if coverage is provided; is by far the greatest example of a specification in need of revision. In the year 2000, why are we using very wide azimuth coverage from a landing system to locate the airport? It is self-defeating to expect wide azimuth coverage in the direction of substantial construction without producing multi-path signals. The requirement to maintain this historic specification is a great contributor to multi-path. Comparing Figure 2 with Figure 4, and Figure 3 with Figure 5, illustrates clearly that the majority of multi-path errors result from the clearance signal reflection. Despite the contradictory objectives of wide coverage and minimal multi-path, design engineers have produced clearance antenna patterns that exhibit lower signal levels with increasing azimuth. The goal has been to provide coverage while minimizing the potential for multi-path to the greatest extent possible. In the case of a large source of reflection well displaced from the course line, reducing the level to minimize the effect of multi-path on the centerline creates a problem of meeting the signal level requirements at the 35 degree points. Further, while tailoring the clearance array pattern as described above is a benefit, and generally a requirement to minimize clearance reflections onto the centerline, the low levels at 35 degrees produce three undesirable conditions:

1) The edges of the coverage area are easily disturbed by stronger clearance signal reflection from sources on the same or opposite side of the course line;
2) The requirements for minimum signal level of 40 micro-volts per meter within the coverage area including at 31.5 km, 35 degrees, and minimum altitude, substantially limit the flexibility to reduce multi-path effects on the centerline;
3) Low signal levels at 35 degrees are susceptible to the effects of FM radio frequency interference.

ICAO Annex 10 Attachment C. defines +/- 10 degrees as the minimum localizer coverage area that could be operationally accepted, however, clearance arrays are currently designed for coverage of +/- 35 degrees. Lateral restrictions are imposed when errors exist that prevent full use of coverage area. Operational procedures are established to ensure that the aircraft is within the acceptable area as defined by flight inspection. In the event that sources of multi-path exist outside of the reduced coverage area, substantial signal levels still exist at large angles and may reflect back onto the course line and produce errors. Curve «A» in Figure 6 is representative of a typical clearance pattern tailored to reduce multi-path and provide +/- 35 degrees of coverage. Curve «B» shows a proposed clearance array pattern that will, by design, provide +/- 15 degrees of coverage and greatly reduce multi-path from sources located at large azimuths from the course line. It is also proposed here that the lateral coverage of the localizer be divided into two parts: 1) Lateral Service Volume (LSV) defining a NEW NOMINAL coverage area of +/- 15 degrees; and 2) Extended Lateral Service Volume (ELSV) defining additional coverage, where practicable or operationally required, out to +/- 35 degrees. A new nominal coverage area will allow antenna manufacturers to produce narrower patterns from the clearance array that will substantially reduce multi-path from wide azimuths. Ultimately, the localizer should have the sole purpose of providing guidance for landing the aircraft. The navigation function, used to find the course region, should be provided by some other means.

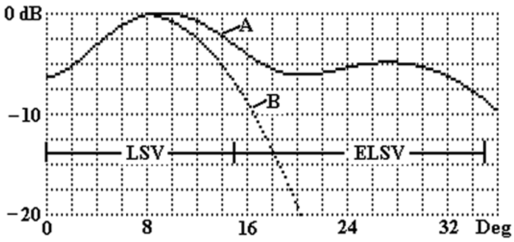

Figure 6. Plot Showing a Typical Clearance antenna pattern «A» providing azimuth coverage to 35 degrees each side of centerline and a proposed radiation pattern «B» providing 15 degrees coverage on each side of the runway.

Critical and Sensitive Area

With the ILS, the size of the critical area is directly related to the beam-width of the antenna providing the guidance information. When comparing two Category II/III capable ILS a significant performance factor is the size of the critical and sensitive areas. The two areas are sometimes combined into simply the «critical area» and will be referred to as such for simplicity. The term «critical area» defines the area that must be kept free of aircraft, vehicles, etc. during Instrument Flight Rule (IFR) conditions in order to ensure course bends are not produced that exceed tolerances. Ground traffic procedures and signage protect this area while another aircraft is on approach to land.

Complex computer models are used to determine the size of the defined area and operational verification is made whenever possible. It is impractical to model all potential geometries for multi-path sources or to simulate them operationally. Computer models are intended to provide a margin of safety for temporary conditions such as the superposition of two reflections. Superposition occurs when two reflections add complementary to produce maximum errors.

The size of the critical area can also be related to efficiency for a given airport. Wide apertures not only provide Category III but efficient Category III capabilities. A comparison of Figures 7 and 8 allow a quantitative analysis of the capabilities of large apertures to reduce the critical area and perhaps allow the use of vital taxiways during IFR. Each scenario shows the percentage of errors produced from a 747-400 class aircraft located at various ranges with the tail oriented toward the runway centerline. Clearly, substantial reductions in the size of the critical area are achievable with the larger aperture. Concerns of superposition or simulation of all operational geometries are diminished. Unrealistic values of aircraft displacement were modeled intentionally to magnify the capability of the wide aperture.

Sources of Measurement Error

There have been many cases of measurement discrepancies between two like receivers processing two-frequency signals. Errors also have been noted between two different flight measurement aircraft. Typically the sources of these errors are identified as the receiver detector and the receive antenna pattern, respectively. In both cases questions can be raised if Category I, II, or III, guidance signals are actually within tolerance for all aircraft that utilize the facility. Measurement variations of these types are indicative of a multi-path rich environment. The source of the problem, excluding reflections from the aircraft itself, is the existence of multi-path signals. The multi-path can then provide numerous results depending on the unique characteristics of the receiver or receive antenna. Antenna systems that minimize the multi-path itself will provide the greatest immunity to measurement variations. Consequently, the probability is increased that all aircraft would, if measurement equipment were connected to the receiver output, find the approach quality to be as verified by flight inspection.

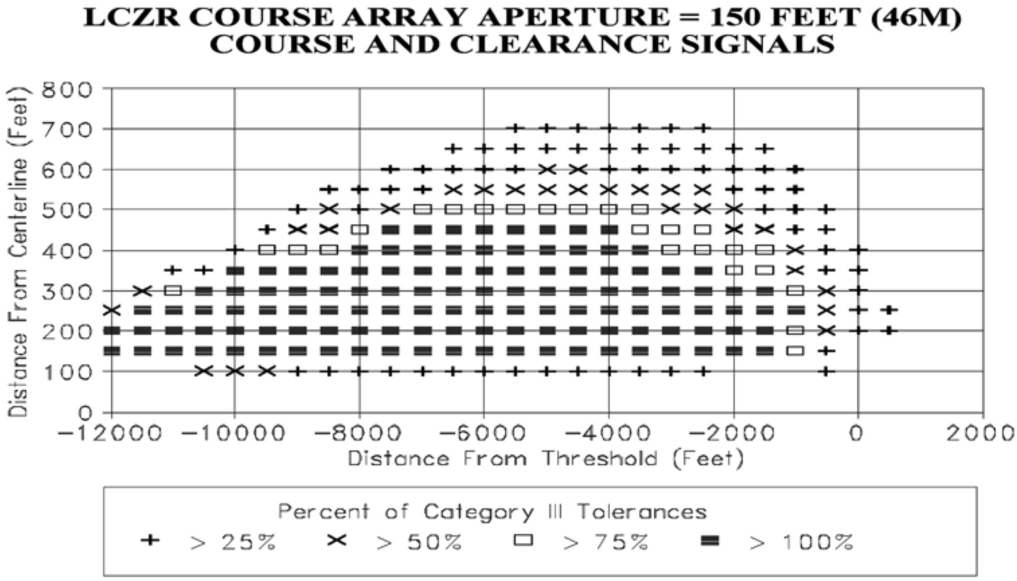

Figure 7. Modeling Results Using a Localizer Course Array Aperture of 150 feet (46m) in the Presence of a 747-400 Class Aircraft Perpendicular to the Runway Centerline with Tail Oriented toward the Runway. The Grid Identifies Locations and Orientations Sensitive to Multi-path and the Percent of Category III Tolerances that Result.

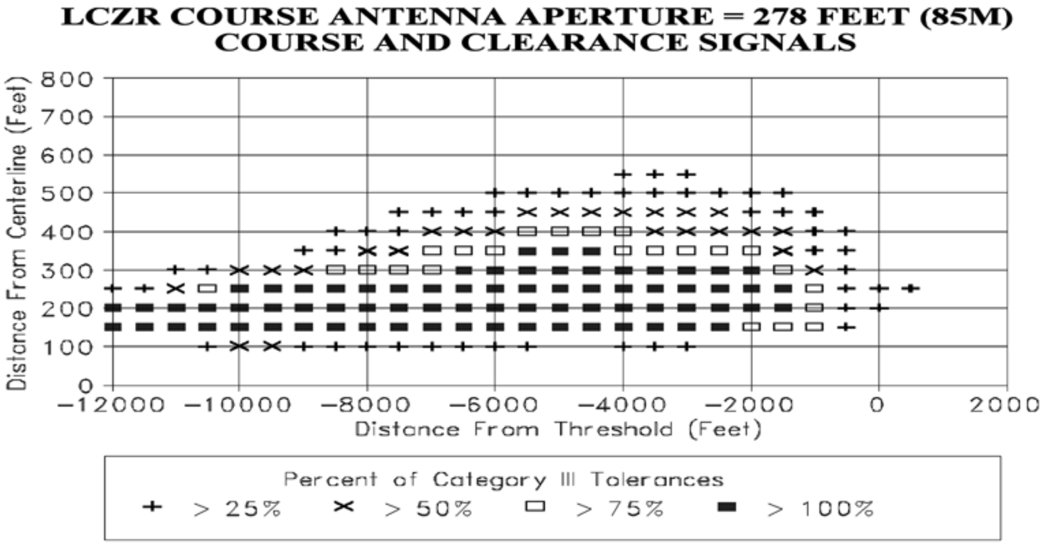

Figure 8. Modeling Results Using a Localizer Course Array Aperture of 278 feet (85m) in the Presence of a 747-400 Class Aircraft Perpendicular to the Runway Centerline with Tail Oriented toward the Runway. The Grid Identifies Locations and Orientations Sensitive to Multi-path and the Percent of Category III Tolerances that Result.

ILS Glide Slope System

Many options exist today for providing Category I glide slope capabilities at new installations. Systems are available, imaging and otherwise, that can be reasonably expected to provide glide slope signals at airports where the local terrain features will permit approval of an approach procedure. Sustaining Cat I/II/III glide slope capabilities at existing facilities is not typically a problem unless; 1) the facility was marginal to begin with; 2) The terrain beneath the approach region is altered i.e. logging or significant development; 3) runways are extended; and 4) development occurs within the horizontal beam of the glide slope antenna pattern. Item number 4 is the least difficult to overcome by utilizing directive glide slope antenna elements or, when possible, to cant the existing elements away from the source of reflection. Providing Category II/ III glide slope signals for new installations is a much more difficult task that will require new considerations for future installations.

The most inhibiting factor in providing CAT II/III glide slope signals with image type antennas is the frequent deficiency of available reflection plane both lateral and longitudinal. Frangible, low profile, non-imaging antennas are useful in these cases if the approach region does not contain rising terrain. Providing CAT II/III quality signals at sites with rising terrain will frequently require the capture-effect image glide slope system, or modified m-array. In this event, lateral ground plane requirements become significant for several reasons; 1) Safety, antenna tower offset criteria defined by Obstacle Free Zone (OFZ) surfaces [5]; and 2) controlling the conical shape of the glide slope to the meet the current lateral coverage requirements. The quality of the reflection plane will, in many cases, degrade rapidly with lateral distance from the runway centerline. The offset criterion will frequently dictate that the tower be placed in areas that require substantial sums of money to adequately prepare the ground. The tower displacement is also a significant factor for considering the minimum beam-width of the radiating elements displaced vertically in the array. Wide-angle radiation is required for a large offsets of 400 feet (120m) to provide coverage to the threshold for Category III operations. Large offsets and wide patterns prevent further reductions in the glide slope critical area and increase the probability of reflections from sources off to the sides of the approach path. Given the lack of available ground plane has been defined as the limiting factor hindering CAT II/III glide slope availability, frangible antenna mast structures are necessary to permit installations closer to the runway centerline. Smaller mast offsets will substantially reduce the cost of ground plane preparation and will permit wide-aperture narrow-beam elements to be deployed. Narrow patterns will reduce the critical area size and minimize the potential for multi-path signals.

Modern Specifications

Many specifications applied to the ILS date back some 40 to 50 years. Principally in the area of coverage, but not exclusively, redefining these requirements consistent with the present operational requirements will yield more capable ILS antenna systems. The characteristics and lateral extent of «coverage» should be redefined to permit modern developments and more capable future developments to be deployed.

Some existing and proposed ILS glide slope systems utilize two-frequency capture-effect signals in the horizontal plane. An illustration of this concept is provided in Figure 9. Narrow course radiation patterns reduce multipath from objects to the sides of the approach region. Proportional vertical guidance is provided by the course antenna array (F1) over the minimum azimuth to meet operational requirements. Fly-up clearance signals (F2) provide coverage outside of these azimuths to +/- 8 degrees and beyond. The result is trough shaped glide slope DDM pattern. An additional margin of safety is provided for corridor type approaches and with image type systems by capturing the receiver at azimuth angles that would otherwise exhibit a low path angle resulting from a ground plane truncation. The characteristics of glide slope «coverage» when displaced from the course line are only vaguely

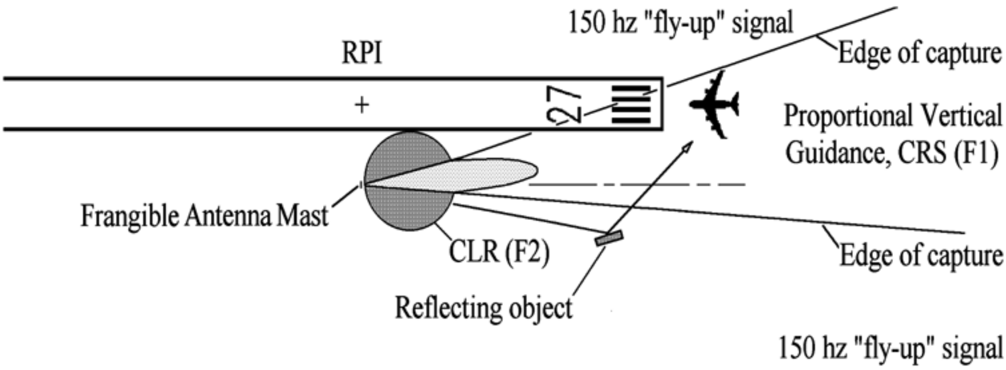

Figure 9. Illustration Depicting the Concept of a Glide Slope with a Narrow Course Beam and Horizontal Capture-Effect Signals Providing Side Clearance.

defined by ICAO. Obviously, linear displacement sensitivity requirements cannot be met in the area dominated by fly-up signals that is outside of the localizer course sector but still inside of the +/- 8 degrees glide slope coverage area. Clarification is required regarding what guidance indications will meet the objectives of providing *coverage.*

Modern specifications should recognize the ILS localizer as a *landing system* and reduce the necessity for providing wide azimuth navigation signals. It is recognized here that, because of many years of providing wide-angle coverage, these signals have been integrated into flight control systems for automated turns onto the course line. The coverage requirements for the localizer should be reduced to a minimum azimuth that will still provide this capability. Ultimately, alternate systems should be defined to serve this purpose, and the coverage requirements for the localizer should then be reduced even further. Note that there is no intention to reduce the accuracy requirements of the ILS.

Renewed Commitment

Replacement of the ILS on the broad scale will not occur in many regions within the next 10 years. It is important that international and domestic decision-making organizations remain intact to evaluate beneficial changes in ILS specifications, system performance, or to evaluate new antenna designs that will permit future operational requirements to be met. Development of new ILS products should be promoted until some defendable schedule can be determined for its replacement. Representative bodies should also consider the benefits of hybrid type systems that can make near-term use of emerging technology without insisting on the impractical and costly near-term replacement of the ILS. Recognizing the role ILS will serve in the future, in conjunction with modern specifications based on today's operational requirements, will allow a new more capable breed of ILS antenna systems to be developed.

CONCLUSIONS

1. Implementing new ILS antenna designs and concepts will provide Category II/III quality signals for the foreseeable future.

2. Wide aperture localizer course antennas substantially reduce multi-path effects sufficiently to permit greater flexibility for new construction and further reduction of existing critical and sensitive areas.

3. Modern specifications are required that promote the design and deployment of more capable ILS antenna systems.

4. A new commitment to the ILS is necessary to maintain services until developing technology has fully matured.

ACKNOWLEDGEMENT

Computer modeling data and figures of such presented herein were provided by the Ohio University, Avionics Engineering Center, Athens, Ohio, USA, under contact by Watts Antenna Company for the study of the benefits of wide aperture localizer antennas. The main titles of the plots were modified by Watts Antenna Company for clarity as related to this paper. The conclusions reached in this report, however, are solely the opinion of the authors. The concepts or quantitative analysis are not to be applied to operational practice without independent verification.

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RECENT ADVANCES AND NEW RESULTS OF NUMERICAL SIMULATIONS FOR NAVAIDS AND LANDING SYSTEMS

ABSTRACT

The Navaids and Landing Systems have to be installed on the airports or in the en-route environment more and more in a potentially electrically adverse environment. A variety of potentially distorting objects or disadvantageous difficult ground conditions are facing the operators of these systems.
The airports and operators are faced often with the case that the decisions for the allowance for the construction has to be made in advance when no object is present.
Also the systematic measurements of the effects of the objects are very tedious and costly. The flight operation is distorted and will create additional costs also.

3D-GTD/UTD-methods(GTD = Geometrical Theory of Diffraction, UTD = Uniform Theory of Diffraction) have been applied successfully for ILS-LOC, ILS-GP and VOR/DVOR and other systems. Due to the fact that the GTD/UTD is an asymptotic method as well as the standard Physical Optics-method (PO), it cannot be applied to a class of objects which consist of wire type elements, e.g cranes, or for objects which are not electrically very large compared to the wavelength or where details are not very large compared to the wavelength or in case of complicated curved surfaces, e.g. aircraft. Principal problems exist also for humped runways for all standard methods.

Newer methods exist which can handle these classes of problems, i.e. the so-called integral equation method solved by the method of moments and the so-called parabolic equation method. The former is well suited for wire type structures and aircraft, the latter can be applied in principal for humped runways. These methods have been adapted and integrated to the system simulation of navaids and landing systems.
Comparisons with measurements are shown also for verification purposes.

INTRODUCTION

The effects of objects/buildings and of the ground on radio systems (radio navigation (so-called navaids), landing and radar systems) have to be analyzed in advance before installing the system or before constructing the object. This kind of technical problem arises more and more on airports and in the en-route environment due to the drastically increasing air traffic which affects the mentioned systems. Also, more and more large and high buildings and objects are constructed close to the airports and close to the navigational and radar systems. These can be e.g.

- real buildings like hangars, terminals on airports
- singular or assemblies of cranes for the construction of buildings
- aircraft in the radiation field
- power generating windmills or high voltage lines in the countryside close to navigational or radar systems

Also, some systems depend on the ground properties in the radiation field and the ground characteristics have to be taken into account adequately, like the so-called «humped runways» or the wet or dry snow layers on top of the ground.

The navigational and radar systems in question are e.g.

- landing systems like the Instrument Landing System ILS (110MHz, 330MHz) and the Microwave Landing System MLS (5GHz); GPS in future (1.2/1.5GHz)
- radio navigational systems like the VOR/DVOR (110MHz), DME/TACAN systems (1GHz).

The pre-analysis of the system performance under the effect of the mentioned objects is a «system simulation» problem where a number of subtasks have to be solved and have to be integrated, namely the antenna problem, the wave propagation, transmitter/receiver problem, signal processing (Fig. 1). In any case the decisive ***«system parameter»*** has to be primarily the final result of the simulation under the realistic system environment effects. The system parameters, e.g.

- DDM guidance parameter in case of ILS
- bearing angle and its tolerances in case of VOR/DVOR and TACAN
- range error in case of DME
- angle error and the filtered parameters PFE and CMN in case of MLS

have to be deduced uniquely from the field quantities. Other quantities can be derived from the system parameter, e.g. in case of ILS: the coverage, the widths, displacement sensitivity. The field quantities themselves may constitute a side result in the best case, e.g. fieldstrength in certain regions or points as the system coverage parameters. Fieldstrength fluctuations in some volume or «field distortions» are more or less meaningless per se for the systems.
However, in the context of this paper mainly the numerical methods and its applied system aspects are discussed.

NUMERICAL METHODS IN SYSTEM SIMULATIONS

The numerical methods used in the discussed system simulations are not basically new, but the generally available ones are adequately selected and adapted to the specific wide range of system applications. The simulation problem discussed here is a three-dimensional one from the beginning. The antennas, the ground and the objects have to be treated and modeled adequately. The objects range from large cubical metallic buildings or aircraft with curved surfaces to wire and skeleton type masts or tower-cranes which may interact with each other or with the exciting system's antenna. The most important condition to be met is that all the methods have to be strictly applied only within their range of definitions and their applicability. Otherwise the results are questionable and speculations - in principle - are worthless.

The preferred methods are the asymptotic ones, e.g. the Geometrical Theory of Diffraction GTD and its derivatives the UTD etc. The first system simulation method developed was the three-dimensional GTD/UTD-method applied for the ILS-system /1/, later for VOR/DVOR and other systems. The GTD/UTD-method was the preferred one compared with the PO-method and derivatives due to the wider range of general applicability and its general asymptotic behavior where the solution is independent of the frequency. For single objects the Physical Optics Method PO with its improvements IPO (rim currents and the extension of the so-called Fock-currents in the shadow) has been adapted and introduced. However, limitations in the GTD/UTD-method and an increasing demand to treat objects not reasonably possible with PO nor with GTD/UTD has led to the introduction of the moment method technique MoM in the applied system simulations. This is for wire type cranes on airports, for electrically medium size objects or for the bistatic scattering of a complete aircraft.
A further recently expanded numerical method has been introduced now and integrated into the entire system simulation, namely the parabolic equation method which can handle in the forward

propagation mode complicated ground and material structures. Extensions for the 3D case and the backward propagation are under way. The 3D-case would include also fields in the deep shadow where the local direction of propagation deviates much from the average one.
A multilayer ground (e.g. dry and wet snow) is treated in this integrated approach by an approximate reflection-refraction transmission line method /3/.

All these methods are combined in an applied novel modular hybrid integrated system simulation approach (Fig. 1 and 3):

- 3D GTD/UTD as the basic method for the 3D scattering of (very) large single and multiple scatterers and 3D ground (Fig. 2)
- PO and IPO method for curved surface objects (aircraft) and large objects (Fig. 7). 3D-ground cannot be treated reasonably.
- Moment method MoM for the antennas and appropriate objects (cranes, masts, wind generators etc.) (Fig. 4,7,10). 3D-ground cannot be treated reasonably. This method is a rigorous method. The mutual coupling between scatterers and between the scatterer(s) and the antenna is taken into account.
- parabolic equation PE for the wave propagation on irregular and complicated 3D ground (Fig. 2 and inserts Fig. 8,9).
- reflection-refraction transmission line method for multilayer problems /3/.

This 3D system treatment, the modular integration of the different methods into a hybrid system simulation has enabled the reliable numerical treatment for a wide class of problems and for systems present on actual modern airports and en-route.
The methods are applicable in principle for landing systems and navigational as well as for radar systems. However, the frequency for the radar systems of interest (ASR,SSR) is generally higher. Primarily the asymptotic GTD/UTD method is the preferred one. Details may be analyzed by the PO/IPO whereas the MoM is in the most cases not applicable due to the required computer storage and/or the computer processing time.

SOME EXAMPLES AND RESULTS

Cranes on airports

Cranes on airports are a particular temporary problem, because they are used during the construction of hangars and terminals and have a large height and large horizontal dimensions, co-polarized to the ILS-Localizers. Usually arrays of such tower cranes are used (Fig. 4). The horizontal jibs are turned according to the constructional needs and also due to the wind conditions which may create dangerous superposed worst case conditions. The jibs have been modeled for the analysis by the Method of Moments MoM. Fig. 5 shows the horizontal scattering patterns when the maximum distortions appear at touch down for a particular geometrical case. The strong forward scattering beam is present and formed in any case. However, these forward scattering components are not pointing to the sensitive region around the centerline above the runway (CATIII) and on the glidepath. Fig. 6 shows the superposed DDM-distortions of an array of 6 closely spaced cranes at Brussels airport in the case of a wide aperture dual frequency ILS-Localizer.

Aircraft on airports

Aircraft on airports (Fig. 2) are potentially dangerous for the landing systems which are serving their guidance for the safe landing even under worst condition in case. The aircraft are taxiing after the roll-off or before starting in the radiation field of the landing systems. Aircraft today can be very large, considering the 747-type or even in future the Airbus A3xx-type (NLA). The critical and sensitive areas should safeguard the landing system. But it should be considered that worst case conditions of arrays of aircraft or the existence of the NLA is not taken into account. The scattering effects of the aircraft are almost impossible to estimate but have to be calculated numerically by the adequate methods having in mind that the aircraft are taxiing close to the ground in the radiation field of the horizontally polarized antenna of the ILS-Localizer. It has been decided to apply an approximate improved Physical Optics method (IPO; see above) which application has to be justified by a more rigorous method, namely the Method of Moments MoM. Fig. 7 shows a numerical calculation of the MoM surface-currents on a 747-type aircraft. The large rim currents as well as the increased currents on the higher tail fin can be nicely seen. It should be pointed out that the ground is included in this calculation in contrast to the standard RCS-treatment (RCS Radar Cross Section) using the plane wave or spherical wave approach. By the knowledge of the bi-static scattering pattern the system impacts can be calculated quite easily.

Humped runways on airports

Humped runways on airports are a particular problem for the landing systems, for the ILS and in particular for the MLS. The specific problem of the humped runway is that that the aircraft are landing in the «shadow» of the antennas of the landing systems. The signal of the landing system is used in the shadow of the hump. Distorting scatterers are located in many cases in the region of the hump and its scattering pattern is affecting much less than the «wanted direct signal». By that the electrical distortions are amplified virtually. The basic task is to calculate numerically the exact direct signal in the shadow of the hump. Fig. 8 shows the adequately optimized application of the so-called parabolic equation PE for the calculation of the fieldstrength in the required height of 4m for the airport Luxembourg. The comparison shows an excellent agreement between the measurement and the calculation. Fig. 9 shows an example of the effects of a hump on the numerically calculated DDM-distortions. In the shadow of the hump and close to touch-down and on the glide-path the DDM-distortions are drastically amplified.

The VOR/DVOR case

The classical VOR/DVOR-system is located on or around airports and more commonly in the open countryside. The distortion effects can be caused by the irregular ground or by nearby objects. The introduced integrated simulation tool is capable of calculating the effects of these factors for VOR and DVOR in 3D environment. Fig. 10 shows the simplified basic geometry of a wind generator in some vicinity to the DVOR-station. The wind generator has been modeled by the MoM and the resulting system parameter, the azimuthal angle error, has been calculated for DVOR as well as for the VOR at the same site. Ideal antennas are assumed. Fig. 11 shows both error characteristics on a cylindrical surface around the VOR/DVOR-station for the generator blades. The error distribution shows the distinct lobing structure due to the electrically large height of the blades. Error maxima are in the low amplitude regions of the VOR/DVOR-station. The wellknown drastic reduction of the angle error in case of the DVOR can be clearly seen.

CONCLUSION

The concept of integrated system simulations has been outlined. Different numerical methods and their optimized application for the system simulations of radio navigation and landing systems have been shown in this paper. By this a wider class of problems can be treated numerically with an adequate accuracy. This is particularly true for cranes and aircraft on the airport for the ILS. The adequate treatment of the humped runway problem has been demonstrated. A further application of this integrated system simulation has been described for the VOR/DVOR-system. A particular target of this paper is to emphasize that the adequate and applicable numerical methods have to be used in the discussed integrated system simulation. The results of all the numerical simulations have to be the decisive system parameter of the treated system. Other non-system parameters have to be justified and have to be referred uniquely to the referred decisive system parameter.

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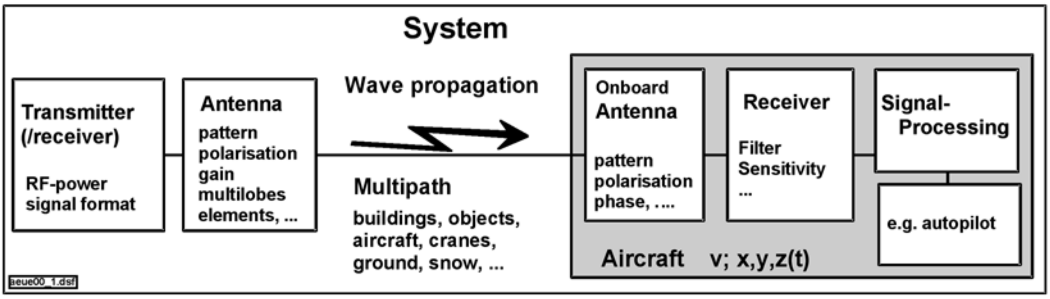


Fig. 1: Principal system components for the numerical system simulations of a radio navigation system; The signal flow may be bi-directional or in the opposite direction as depicted for certain systems.

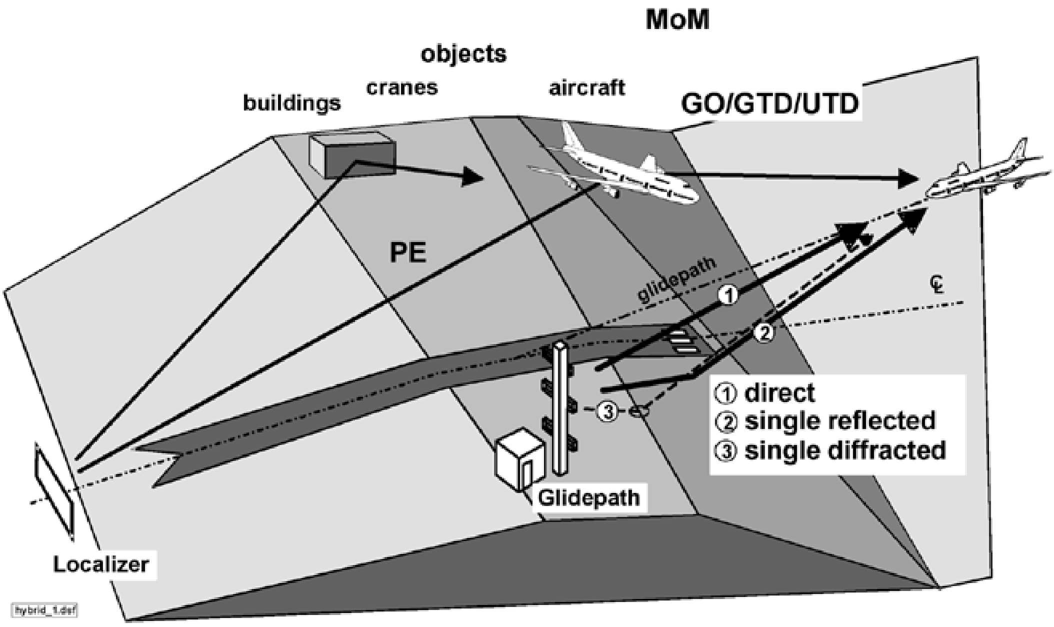


Fig. 2: Principal sketch of a humped runway, the subsystems of an ILS, some distorting objects and a landing aircraft; the distorting mechanism is indicated by some of the existing rays

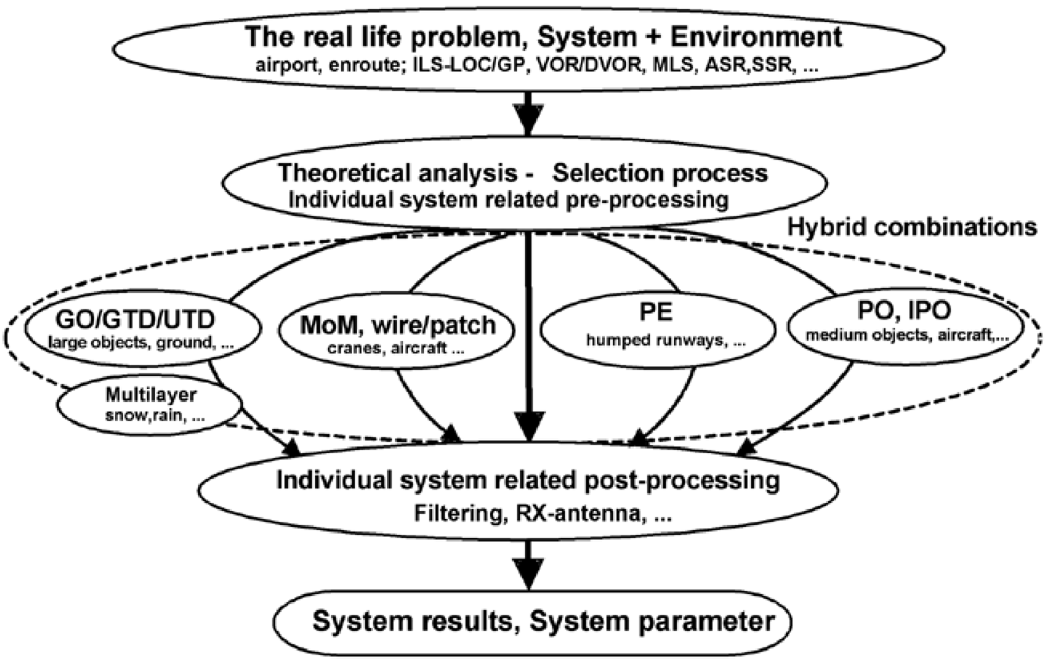


Fig. 3: Signal flow chart of the integrated system simulation process

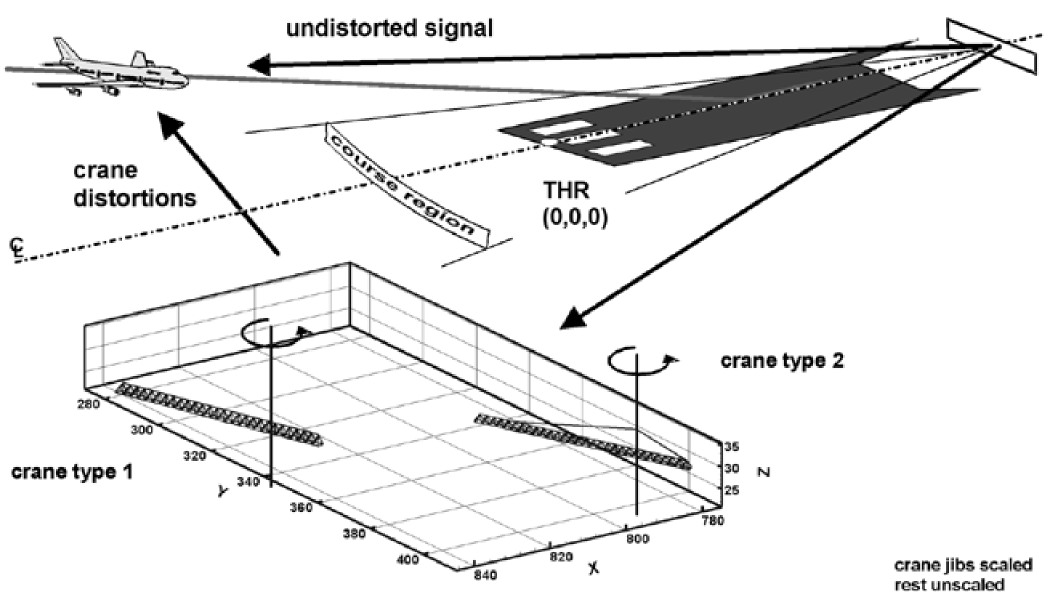


Fig. 4: Principal sketch of single or arrays of revolving tower cranes on airports. The distortion of the ILS landing systems by temporary tower cranes during the construction of buildings, towers etc. is indicated.

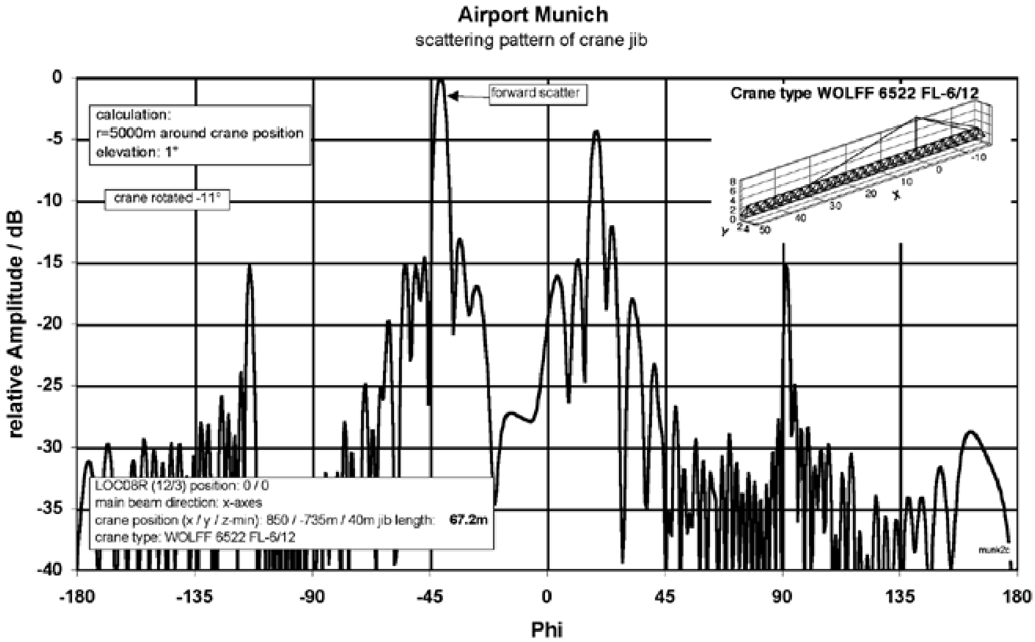


Fig. 5: Bi-static scattering pattern of the jib of a tower crane above ground excited by an ILS-Localizer antenna (horizontal polarisation). The direction of the second maximum is determined by the orientation of the jib. The direction of 0° is the centerline. The maximum beam is the so-called forward scatter beam, pointing in the extended direction from the antenna to the crane.

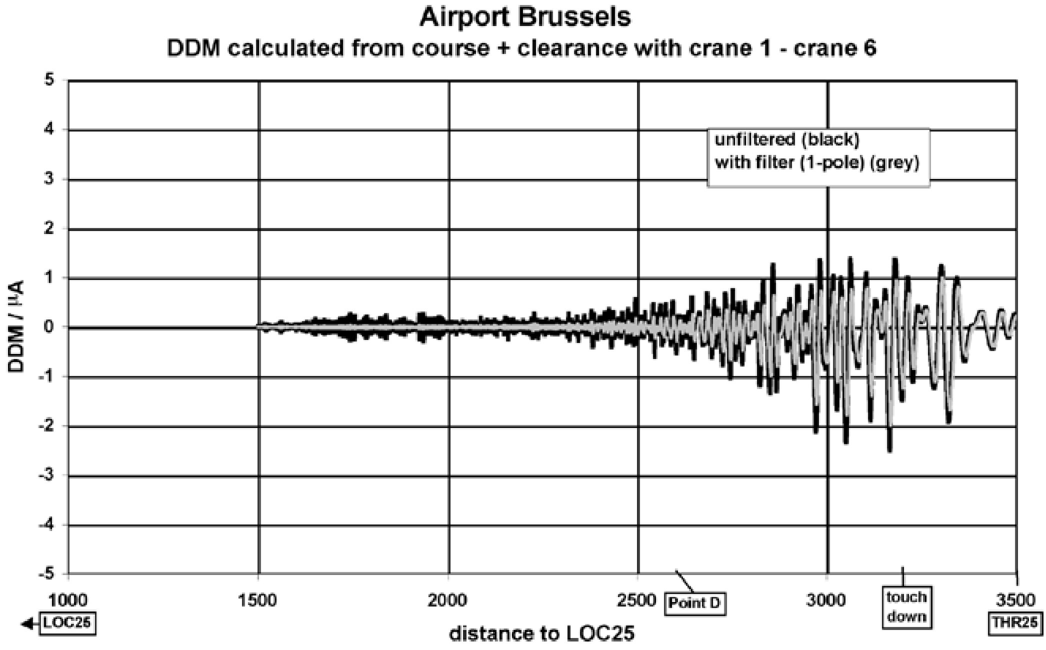


Fig. 6: Numerical calculations of the DDM-distortions (unfiltered and filtered) for an array of 6 cranes on Brussels airport for the given geometry in relation to a CATIII ILS; All the tower cranes are oriented such that the maximum distortions appear in the region of touch-down

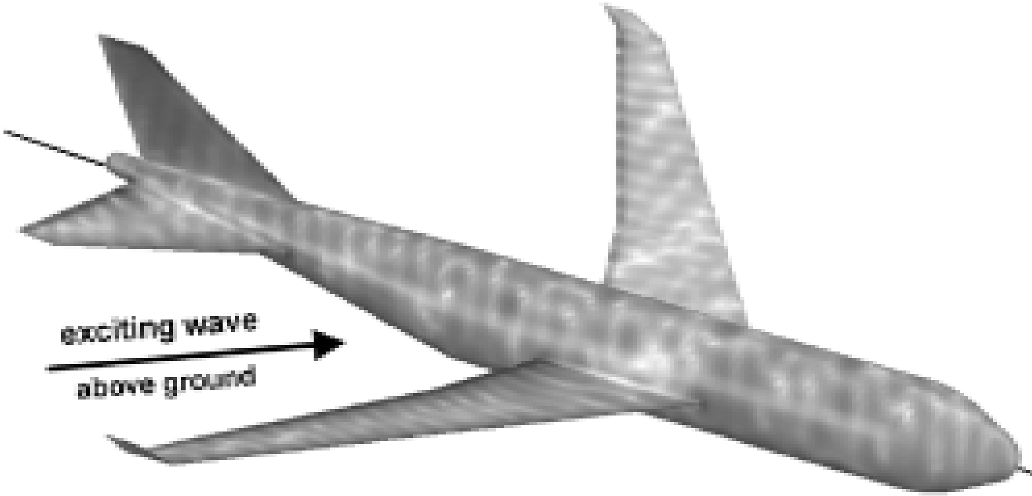


Fig. 7: Color/grey coded current distribution on a 747-type aircraft 3m above ideal ground excited by an ILS-Localizer antenna at 110MHz (horizontal polarisation, direction of incidence 45° to the fuselage axis); (darker «grey» color means larger current)

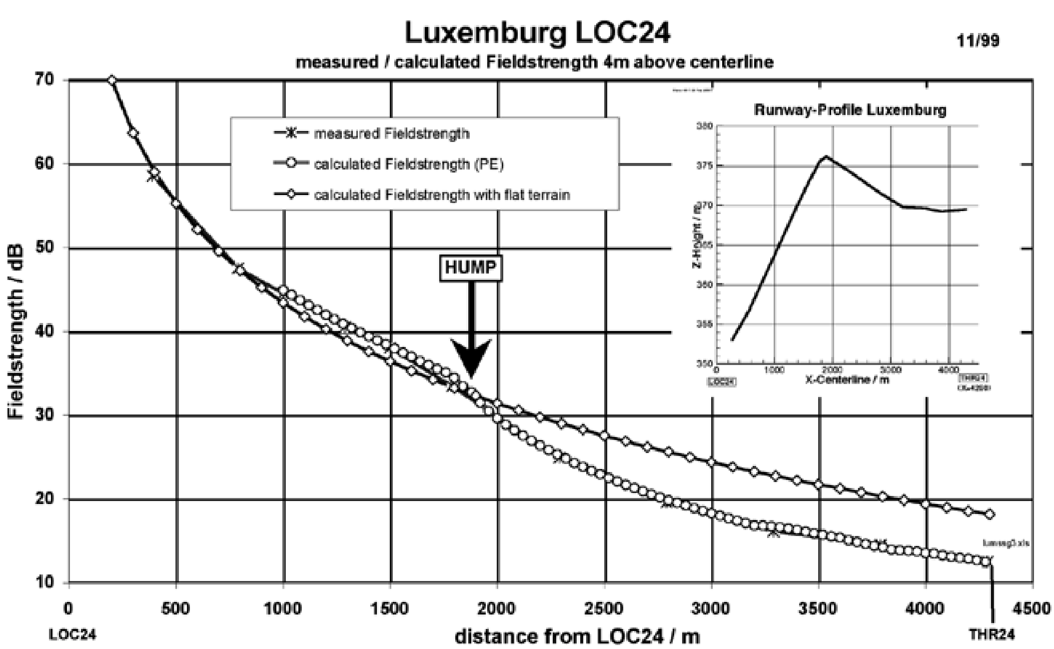


Fig. 8: Comparison of the numerically calculated and measured fieldstrength in the height of 4m above centerline of an extreme humped runway on the airport Luxembourg ; numerical method: adapted and optimized method of parabolic equation

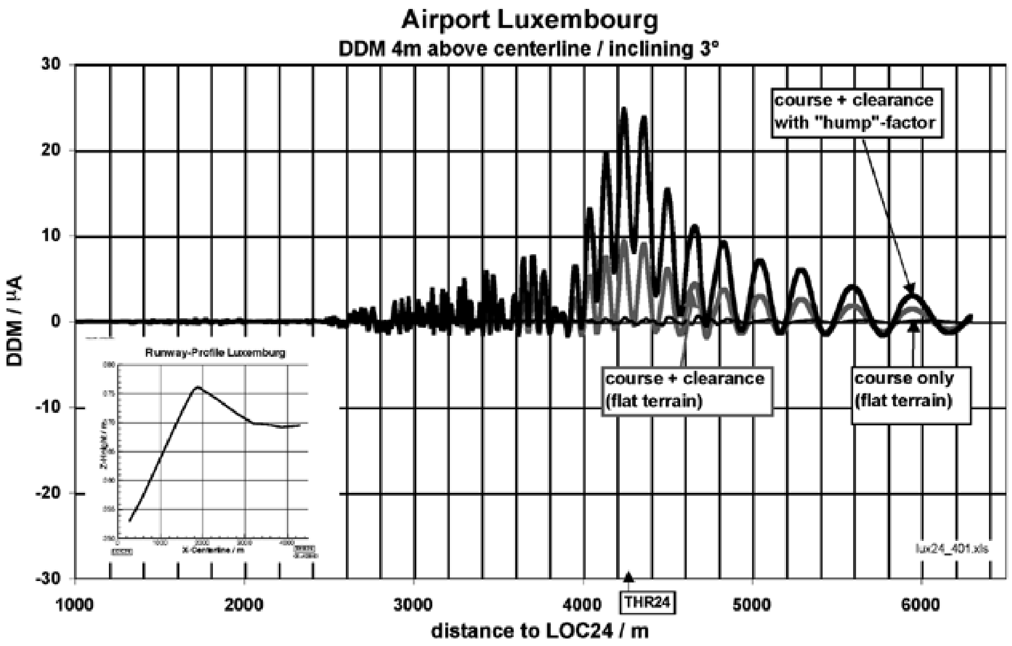


Fig. 9: Numerically calculated DDM-distortions for a worst case metallic hangar under the impact of the humped runway; calculated for the identical metallic hangar for the ideally flat terrain and the hump effect. The ILS-Localizer is a high performance wide aperture dual frequency system.

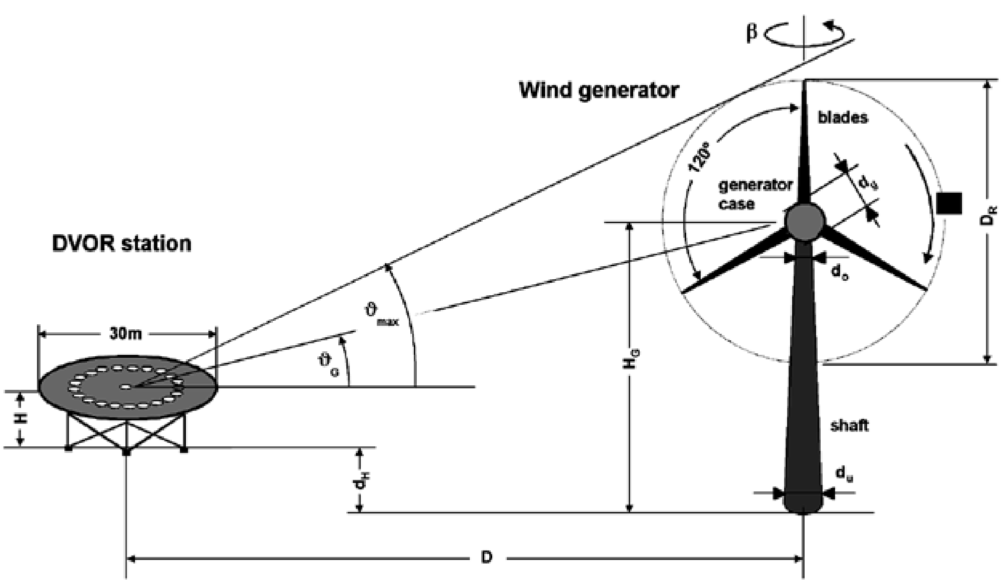


Fig. 10: Geometrical configuration of the DVOR-station and the distorting wind-generator; The shaft is metallic and the blades have a metallic lightning arrestor kernel. The blade-propeller is turning in two axes, the vertical (_) and the horizontal (_) driven by the wind-speed.

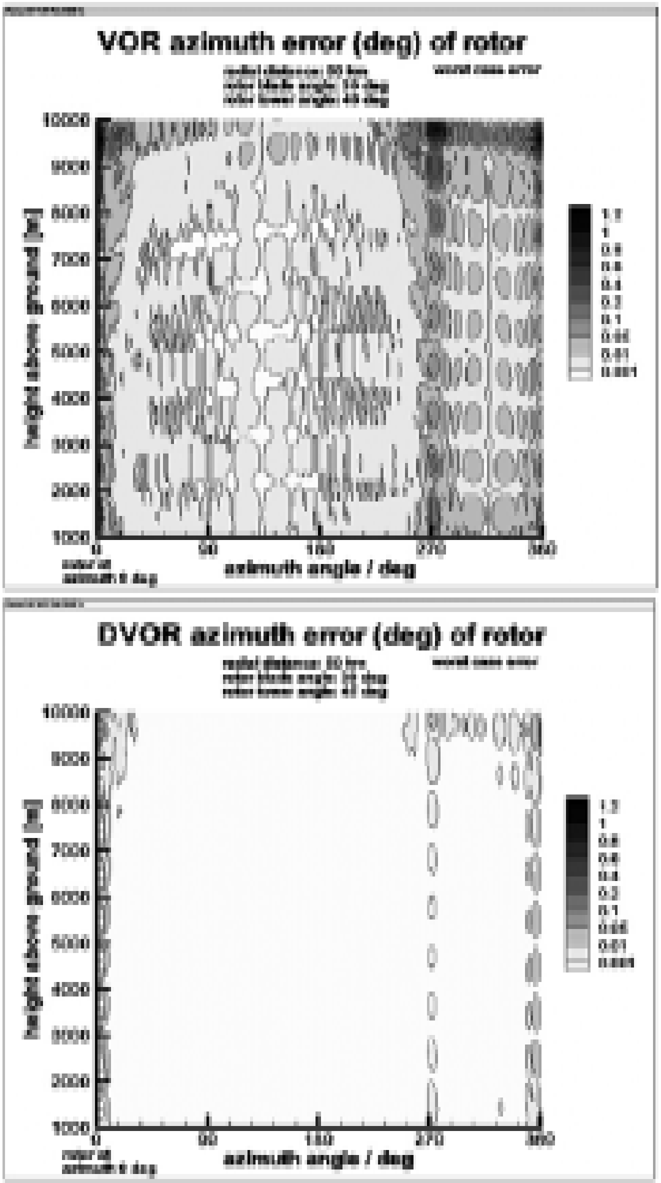
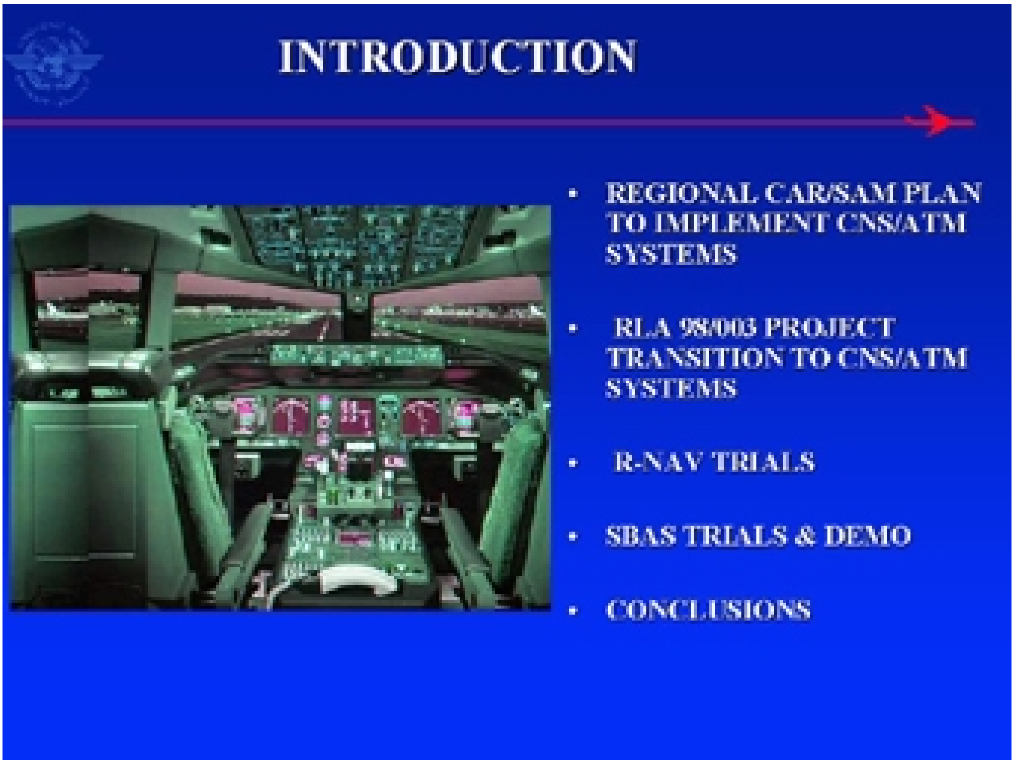


Fig. 11: Comparison of the numerically calculated angle errors caused by the blades of a wind generator for the VOR -and the DVOR-system under the same conditions.

The error grey-coding is identical for VOR and DVOR.


TRANSITION TO
CNS/ATM
IN THE
CAR/SAM REGION
Paulo I. Hegedus
Director
ICAO SAM Regional Office

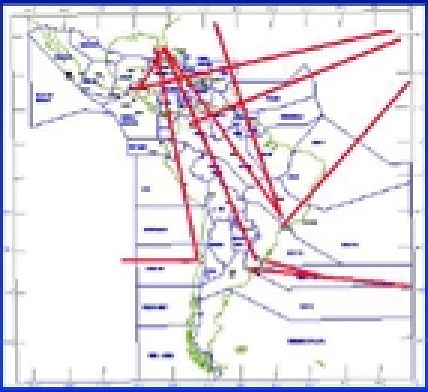

INTRODUCTION
• REGIONAL CAR/SAM PLAN TO IMPLEMENT CNS/ATM SYSTEMS
• RLA 98/003 PROJECT TRANSITION TO CNS/ATM SYSTEMS
• R-NAV TRIALS
• SBAS TRIALS & DEMO
• CONCLUSIONS

REGIONAL CAR/SAM PLAN TO IMPLEMENT CNS/ATM SYSTEMS

- DEVELOPED BY GRPECAS'S CNS/ATM/IC SUBGROUP
- FISRT VERSION APPROVED IN 1995, SECOND VERSION IN 1998
- INCORPORATED INTO THE REGIONAL AIR NAVIGATION PLAN, IN THE THIRD CAR/SAM RAN (Buenos Aires, Argentina, October 1999)

KEY ELEMENTS FOR CNS/ATM PLANNING

- MAIN AIR TRAFFIC FLOW DEFINITION
  - 18 INTRA & INTER REGIONAL FLOWS
- ATM EVOLUT ION ON EACH TRAFFIC FLOW BASED ON USER´S REQUIREMENTS
- AIR TRAFFIC FLOW BASED ON ATM REQUIREMENTS



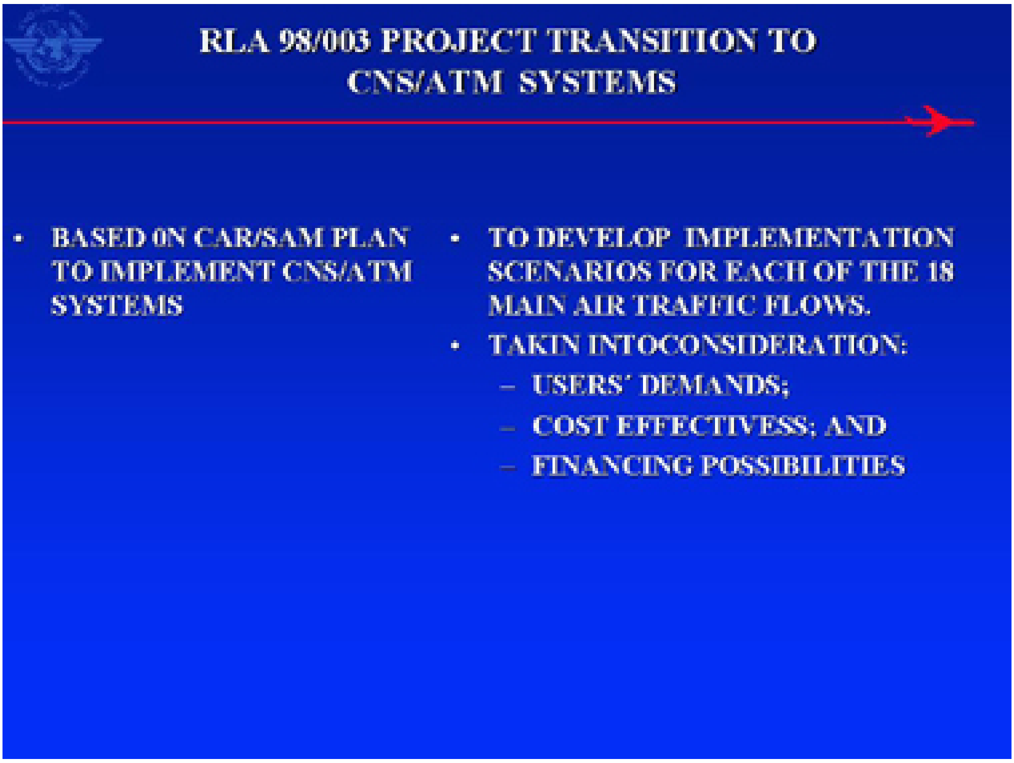
INTRODUCTION

- REGIONAL CAR/SAM PLAN TO IMPLEMENT CNS/ATM SYSTEMS
- RLA 98/003 PROJECT TRANSITION TO CNS/ATM SYSTEMS
- R-NAV TRIALS
- SBAS TRIALS & DEMO
- CONCLUSIONS

RLA 98/003 PROJECT TRANSITION TO CNS/ATM SYSTEMS

- AROSE FROM RAAC/4
- SUPPORTED BY GREPECAS/6 TO EXTEND IT TO CAR/SAM REGION
- BEGAN IN 1999.

STATES THAT HAVE SUSCRIBED TO THE PROJECT
SAM STATES
ARGENTINA
BOLIVIA
BRASIL
CHILE
COLOMBIA
ECUADOR
PANAMA
PARAGUAY
PERU
URUGUAY
VENEZUELA
CAR STATES
UNITED STATES
COCESNA



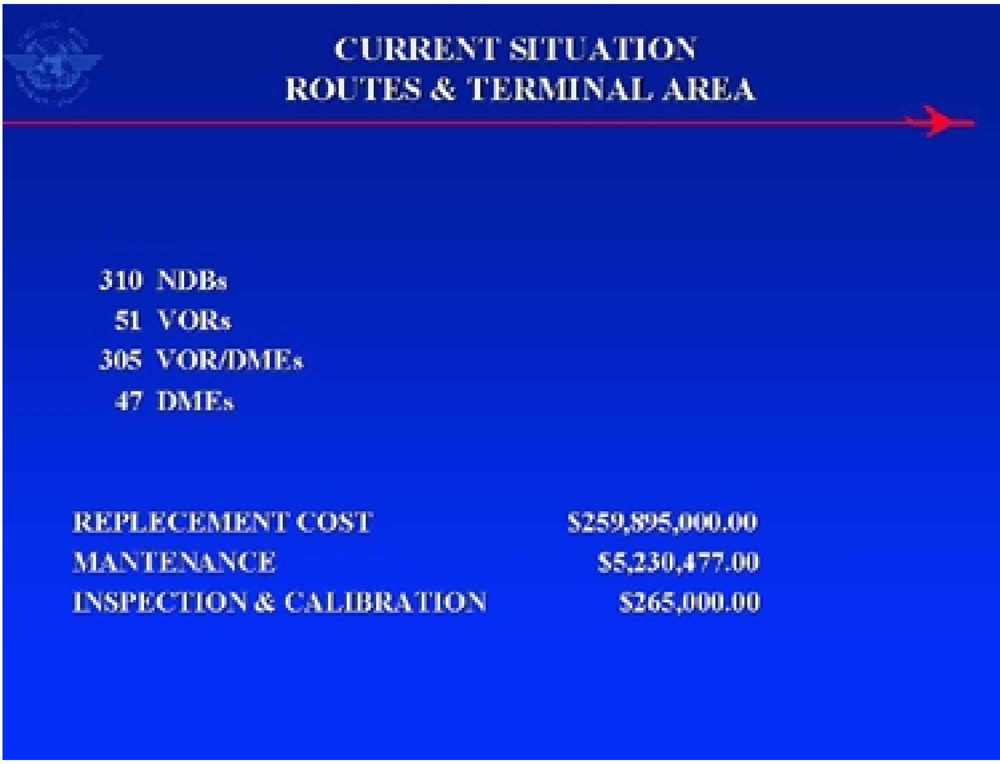
RLA 98/003 PROJECT TRANSITION TO CNS/ATM SYSTEMS
BASED 0N CAR/SAM PLAN TO IMPLEMENT CNS/ATM SYSTEMS
TO DEVELOP IMPLEMENTATION SCENARIOS FOR EACH OF THE 18 MAIN AIR TRAFFIC FLOWS.
TAKIN INTOCONSIDERATION:
USERS' DEMANDS;
COST EFFECTIVESS; AND
FINANCING POSSIBILITIES

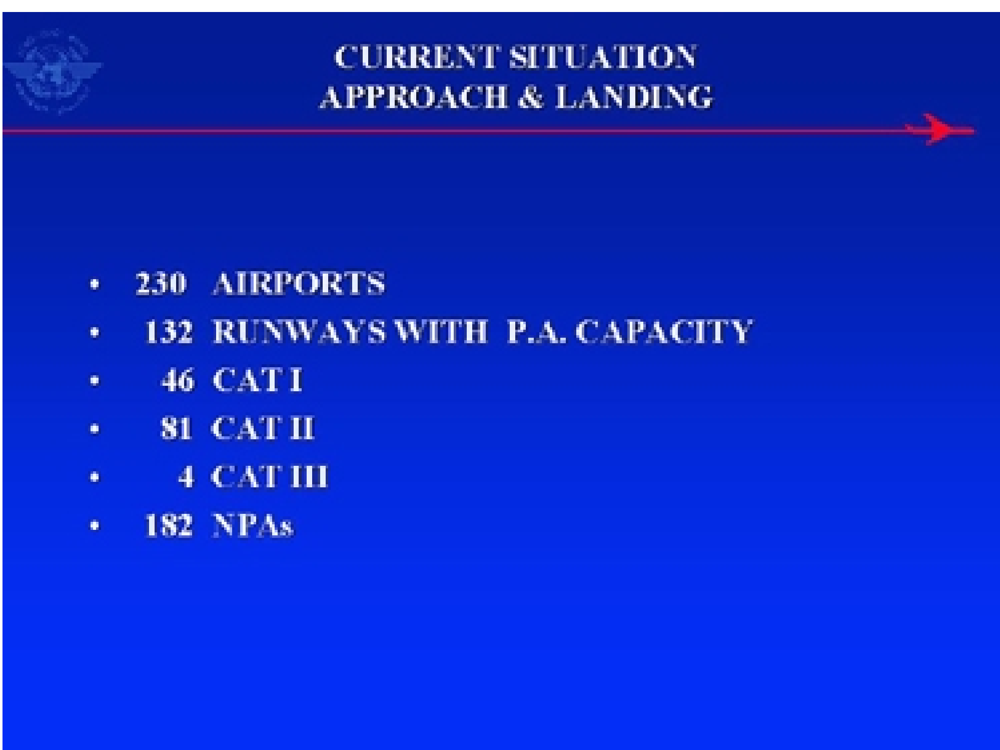
QUANTIFY CURRENT TRAFFIC VOLUMES

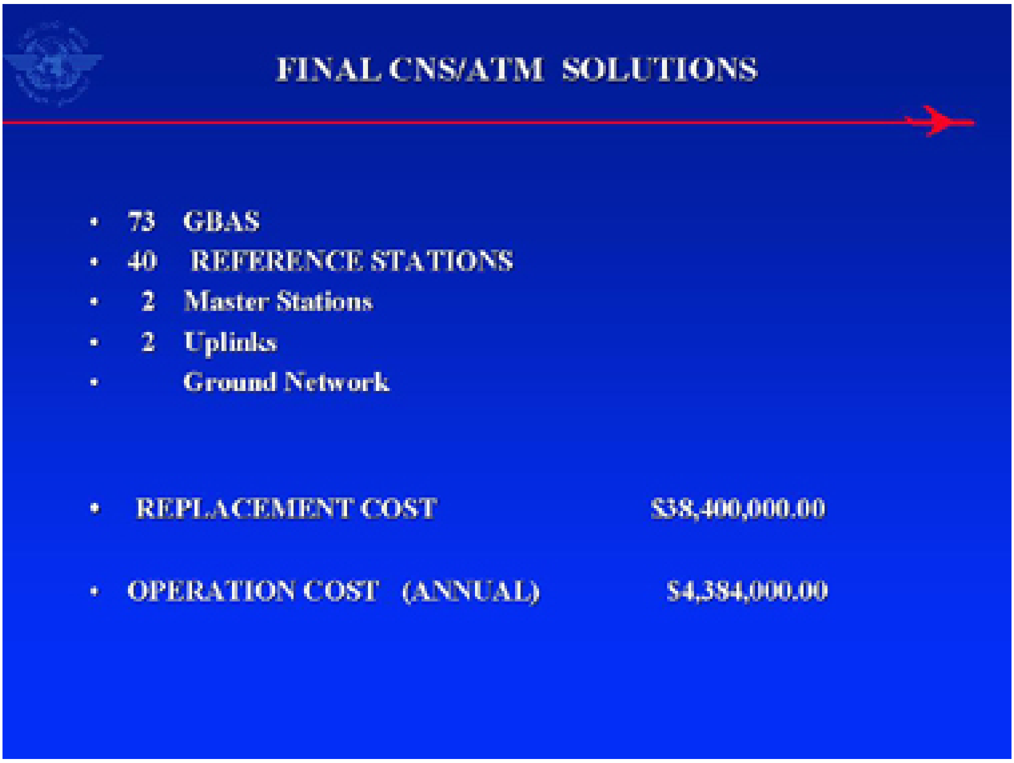
- DEFINE ROUTES TO BE STUDIED
- DEFINE POINTS FOR TRAFFIC SAMPLING
  - TRAFFIC VOLUME PER HOUR
  - TRAFFIC TYPE (PAX, CARGO, OTHERS.)
  - TYPE OF AIRCRAFT (LIGHT, MEDIUM , HEAVY)
  - DETERMINE IF TRAFFIC IS FLYING DESIRED FLIGHT PROFILE

TRANSITION TO CNS/ATM IN THE CAR/SAM REGION

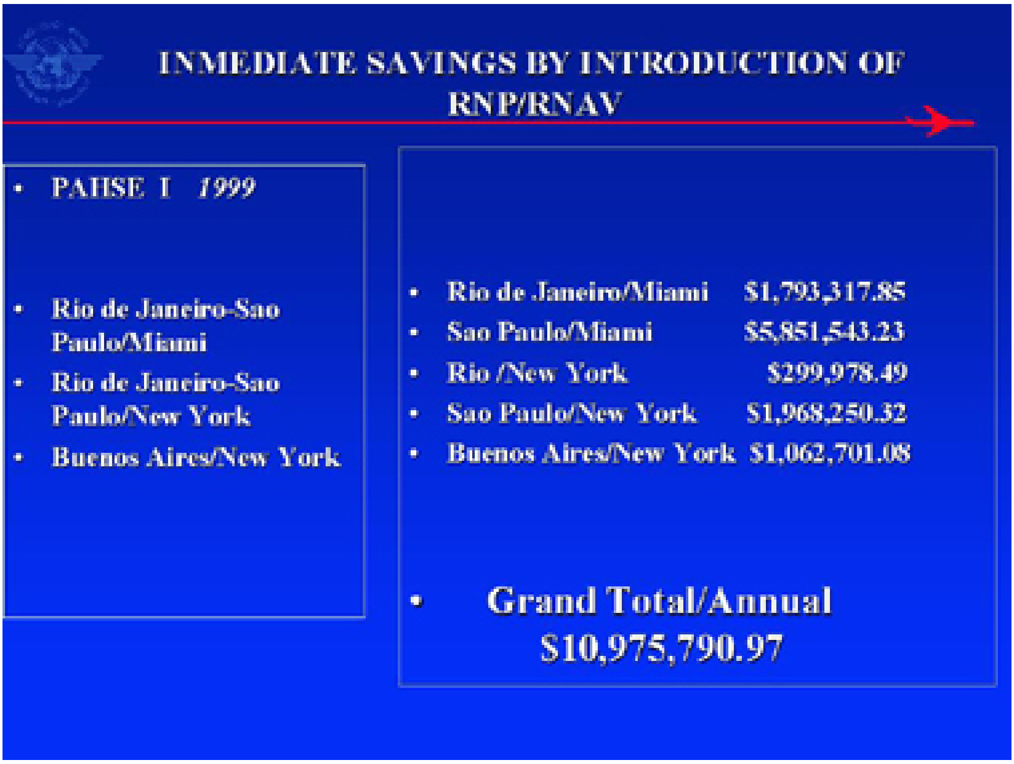
Paulo I. Hegedus
Director
ICAO SAM Regional Office


CURRENT SITUATION
ROUTES & TERMINAL AREA
310 NDBs
51 VORs
305 VOR/DMEs
47 DMEs
REPLECEMENT COST $259,895,000.00
MANTENANCE $5,230,477.00
INSPECTION & CALIBRATION $265,000.00


CURRENT SITUATION
APPROACH & LANDING
• 230 AIRPORTS
• 132 RUNWAYS WITH P.A. CAPACITY
• 46 CAT I
• 81 CAT II
• 4 CAT III
• 182 NPAs


FINAL CNS/ATM SOLUTIONS
• 73 GBAS
• 40 REFERENCE STATIONS
• 2 Master Stations
• 2 Uplinks
• Ground Network
• REPLACEMENT COST $38,400,000.00
• OPERATION COST (ANNUAL) $4,384,000.00


BENEFITS
• OPERATIONAL BENEFITS
– COMPLETE NAVEGATION COVERAGE
– 466 ADICIONAL RUNWAYS COVERED WITH P.A.
• ECONOMIC BENEFITS
– ACQUISITION REDUCTION COST $221,495,000.00
– MANTENANCE REDUCTION COST $1,111,867.00


INMEDIATE SAVINGS BY INTRODUCTION OF RNP/RNAV
PAHSE I 1999
Rio de Janeiro-Sao Paulo/Miami
Rio de Janeiro-Sao Paulo/New York
Buenos Aires/New York
Rio de Janeiro/Miami $1,793,317.85
Sao Paulo/Miami $5,851,543.23
Rio /New York $299,978.49
Sao Paulo/New York $1,968,250.32
Buenos Aires/New York $1,062,701.08
Grand Total/Annual $10,975,790.97

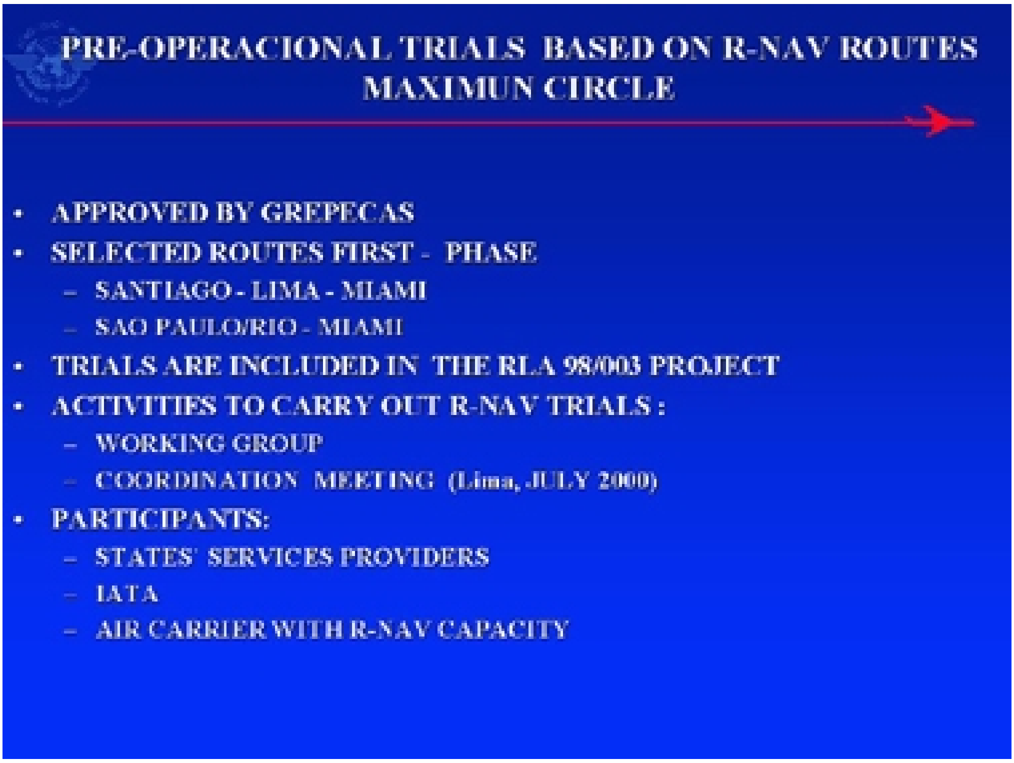

RLA 98/003 PROJECT TRANSITION TO CNS/ATM SYSTEMS
PHASE II (IN EXECUTION)
Sao Paulo-Rio/Europe
Santiago/Lima/Los Angeles
Santiago/Lima/Miami
Sao Paulo-Rio/Los Angeles
Buenos Aires/Miami
México/Dallas
– México/Houston
– México/Los Angeles
– México/Miami
PHASE III (2001)
Buenos Aires/Santiago
Buenos Aires/Sao Paulo-Rio
Santiago/Sao Paulo-Rio
Lima/Sao Paulo-Rio
North South America/Europe
México/Europe
América Central/Europe
South América/South Africa
Santiago/Papeete

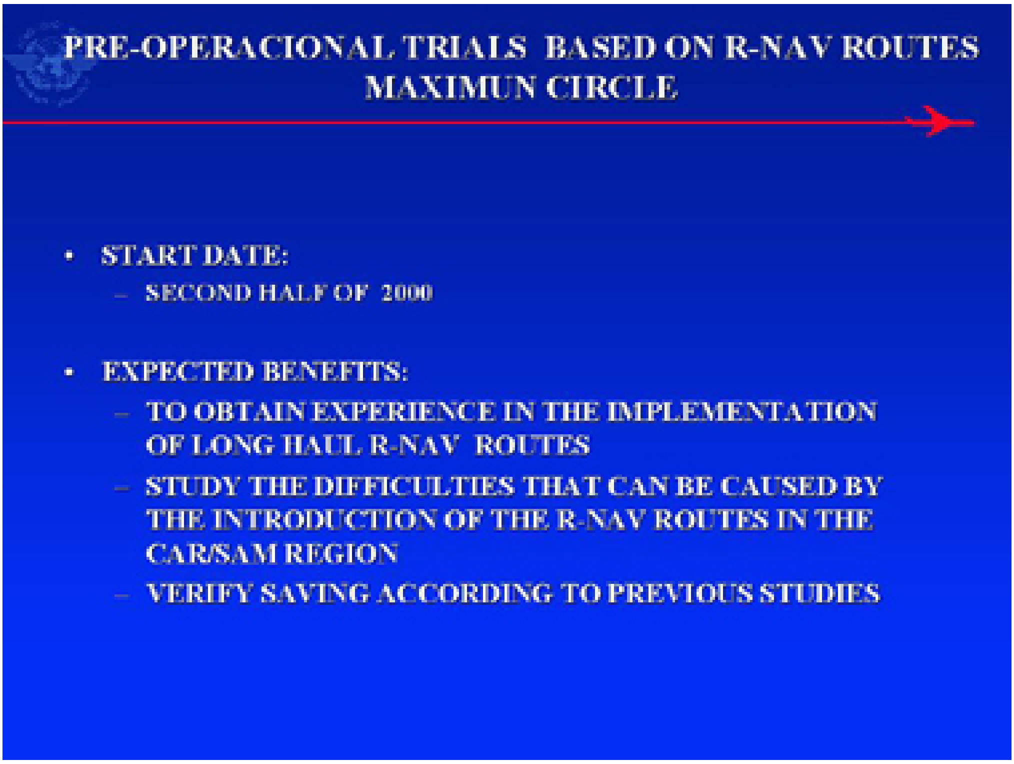
RLA 98/003 PROJECT TRANSITION TO CNS/ATM SYSTEMS

- PHASE IV CONSOLIDATION (FIRST SEMESTER 2002)
  - INTEGRATION OF ALL TRAFFIC FLOW REQUIREMENTS
  - INCLUDING REQUIREMENTS OF THOSE TRAFFIC FLOW OUTSIDE OF THE MAIN ONE
  - DETERMINE THE BEST TECHNICAL & OPERATIONAL OPTIONS
  - DEFINE MORE APPROPRIATE TIMING TO IMPLEMENT CNS/ATM ELEMENTS.

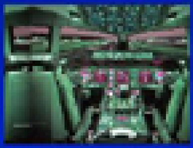
RLA 98/003 PROJECT TRANSITION TO CNS/ATM SYSTEMS

- BASED 0N CAR/SAM PLAN TO IMPLEMENT CNS/ATM SYSTEMS
- TO DEVELOP IMPLEMENTATION SCENARIOS FOR EACH OF THE 18 MAIN AIR TRAFFIC FLOWS.
- TAKIN INTOCONSIDERATION:
  - USERS' DEMANDS;
  - COST EFFECTIVESS; AND
  - FINANCING POSSIBILITIES


PRE-OPERACIONAL TRIALS BASED ON R-NAV ROUTES
MAXIMUN CIRCLE
APPROVED BY GREPECAS
SELECTED ROUTES FIRST - PHASE
SANTIAGO - LIMA - MIAMI
SAO PAULO/RIO - MIAMI
TRIALS ARE INCLUDED IN THE RLA 98/003 PROJECT
ACTIVITIES TO CARRY OUT R-NAV TRIALS :
WORKING GROUP
COORDINATION MEETING (Lima, JULY 2000)
PARTICIPANTS:
STATES' SERVICES PROVIDERS
IATA
AIR CARRIER WITH R-NAV CAPACITY


PRE-OPERACIONAL TRIALS BASED ON R-NAV ROUTES
MAXIMUN CIRCLE
START DATE:
SECOND HALF OF 2000
EXPECTED BENEFITS:
TO OBTAIN EXPERIENCE IN THE IMPLEMENTATION OF LONG HAUL R-NAV ROUTES
STUDY THE DIFFICULTIES THAT CAN BE CAUSED BY THE INTRODUCTION OF THE R-NAV ROUTES IN THE CAR/SAM REGION
VERIFY SAVING ACCORDING TO PREVIOUS STUDIES

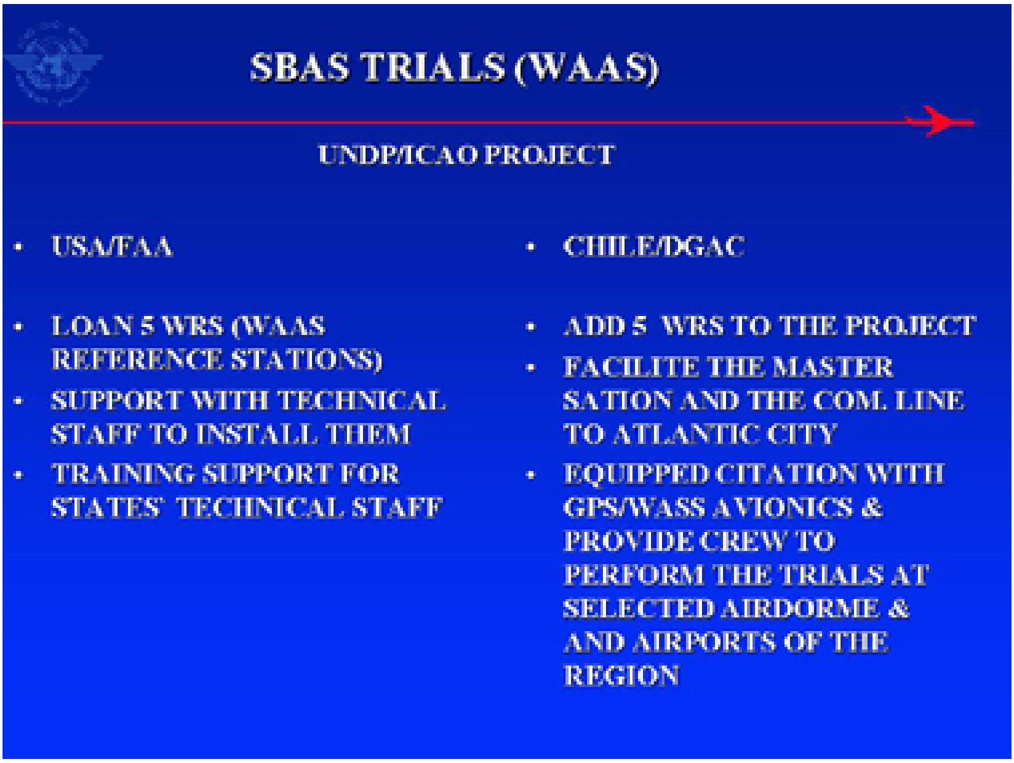
INTRODUCTION

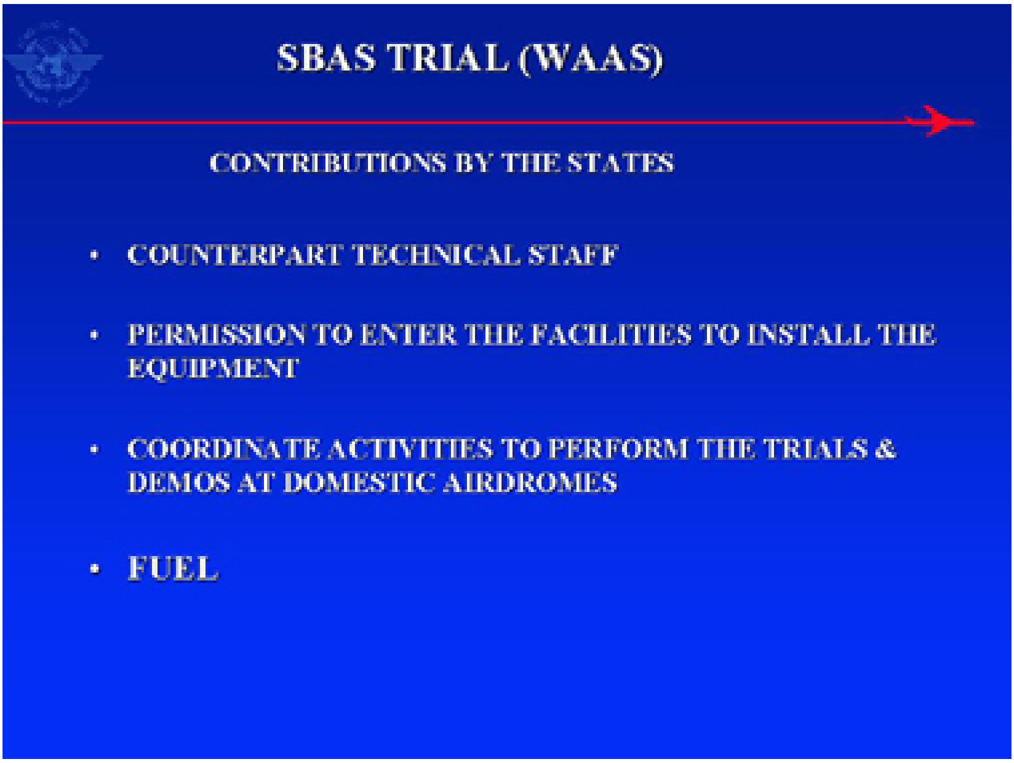


- REGIONAL CAR/SAM PLAN TO IMPLEMENT CNS/ATM SYSTEMS
- RLA 98/003 PROJECT TRANSITION TO CNS/ATM SYSTEM
- R-NAV TRIAL
- SBAS TRIALS & DEMO
- CONCLUSIONS

INTRODUCTION

- REGIONAL CAR/SAM PLAN TO IMPLEMENT CNS/ATM SYSTEMS
- RLA 98/003 PROJECT TRANSITION TO CNS/ATM SYSTEMS
- R-NAV TRIALS
- SBAS TRIALS & DEMO
- CONCLUSIONS


SBAS TRIALS (WAAS)
UNDP/ICAO PROJECT
• USA/FAA
• LOAN 5 WRS (WAAS REFERENCE STATIONS)
• SUPPORT WITH TECHNICAL STAFF TO INSTALL THEM
• TRAINING SUPPORT FOR STATES' TECHNICAL STAFF
• CHILE/DGAC
• ADD 5 WRS TO THE PROJECT
• FACILITE THE MASTER SATION AND THE COM. LINE TO ATLANTIC CITY
• EQUIPPED CITATION WITH GPS/WASS AVIONICS & PROVIDE CREW TO PERFORM THE TRIALS AT SELECTED AIRDORME & AND AIRPORTS OF THE REGION


SBAS TRIAL (WAAS)
CONTRIBUTIONS BY THE STATES
• COUNTERPART TECHNICAL STAFF
• PERMISSION TO ENTER THE FACILITIES TO INSTALL THE EQUIPMENT
• COORDINATE ACTIVITIES TO PERFORM THE TRIALS & DEMOS AT DOMESTIC AIRDROMES
• FUEL


SBAS TRIALS (WAAS)
GPS
WAAS TRIALS
PHASE I
WRS
WRS
WRS
MASTER
WRS
WRS


SBAS TRIALS (WAAS)
WRS
WRS
GPS
WRS
WRS
WRS
WAAS TRIALS
PHASE II

CONCLUSIONS

IMPORTANT INMEDIATE IMPROVEMENTS
SERIUOS STEPS TOWARDS CNS/ATM
DEFINE MORE PRECISE IMPLEMENTATION TERM
ESTABLISH SPECIFIC REQUIREMENTS


CONCLUSIONS
PENDING TASK


TRANSITION TO
CNS/ATM
IN THE
CAR/SAM REGION
Paulo I. Hegedus
Director
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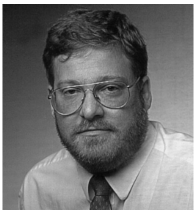

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PREDICTING THE EFFECTS OF STRUCTURES AND LOCATING MULTIPATH SOURCES AT NAVIGATION FACILITIES

ABSTRACT

Ground navigation facilities must perform within flight inspection tolerances, even though the desired clear zones around their antenna systems are continually being encroached upon by new structures. Regulatory and operating authorities are expected to predict the effect of proposed structures and conclusively identify existing structures for removal or modification. Locating individual multipath contributors to marginal facility performance can be difficult if several reflectors exist.

Specialized software tools supporting these modeling and identification requirements have become quite advanced with the advent of highly capable personal computers. This paper presents Instrument Landing System (ILS) and Very High Frequency Omni-Range (VOR) predictive models, and a Fast Fourier Transform (FFT) application for accurate location of multipath sources. Included are a discussion of their technical bases, a brief tutorial on multipath characteristics, and samples of successful use, including confirming flight measurements. The authors have been heavily involved in the development, validation, fielding, and application of the software at numerous navigational aid problem sites.

BACKGROUND

ILS and VOR stations must meet flight inspection tolerances, even though their antenna systems are continually being encroached upon by new structures. When regulatory authorities receive prior notice of proposed construction near these facilities, a requirement exists to predict the effects of the structure, and to endeavor to modify the structure when feasible to lessen its effects. When multipath effects from structures degrade facility performance significantly, a requirement exists to identify conclusively the offending structure(s) for removal or modification. Locating individual reflecting structures with high certainty is usually difficult if multiple reflectors exist, particularly when they are close to one another.

Advanced and specialized software tools, capable of being run on today's powerful personal computers, now support these modeling and identification requirements. Ohio University's ILS and VOR modeling software, capable of providing flight inspection-like graphical outputs predicting the effects of multipath sources, has been developed and is in routine use by U. S. Federal Aviation Administration (FAA) engineering personnel. Recently, a commercially available Fast Fourier Transform (FFT) software package, specially modified for navigation use, has also been introduced as part of the FAA's Navigational Aid Signal Evaluator (NASE) programa. This software makes a straightforward task of separating a complex ILS or VOR crosspointer, modulation, or signal strength measurements file into its constituent multipath components, enabling accurate determination of the location of the reflecting sources from airborne data.

PREDICTING EFFECTS OF STRUCTURES

Over the past 35 years there has been an effort at Ohio University, mainly through the support of the FAA, in developing mathematical models to predict the performance of navigation and landing systems in the presence of large scatterers and terrain. As a result, several sophisticated and accurate models have been developed for the ILS localizer and glide slope, and the VOR. Over the years, new capabilities have been added to the original Physical Optics (PO) model developed by the Transportation Systems Center (TSC) and subsequently modified by Ohio University[2,3,4]. The following sections provide a description of the chronology of model development focusing on unique capabilities, the underlying theory and assumptions, and model applications and validation using actual flight measurements.

Model Development and Capabilities

OUILS (1978 - 1992)[5,6]. This version of the PO model is written in FORTRAN and operates on a large mainframe computer. The localizer model is based on the original TSC development. Ohio University incorporated the glide slope calculations in 1978. This model was extensively used to predict the degradation to the ILS signal, both for localizer and glide slope, caused by various aircraft types. The results were used to determine critical area sizes for the localizer and glide slope systems in the presence of various aircraft sizes.

Additional programs were written to automatically locate or position the scatterer(s) in various locations and orientations, run the scattering model, and automatically process the data. This allowed multiple modeling scenarios to occur without operator intervention.
Additional modifications of the model implemented the existing filtering algorithm and added more antenna array distributions and element patterns.

ILS-MOD (1991 - 1996).[7] This model was developed for Transport Canada and was based on the latest version of OUILS. The FORTRAN code was modified to operate on a compatible IBM Personal Computer (PC). In addition, a DOS based user interface was developed to configure the input data files, run the model, and process and display the data.

Some features incorporated in this model were localizar back-course calculations, localizer clearance sideband scaling and centerline separation, selection and/or modification of the antenna array distribution, and graphical display of simulation results with automatic analysis of tolerances, i.e., structure roughness, and alignment.

ILS2 (1995-Present).[8] The latest version of the ILS Performance Prediction Model, Version 2.07, has incorporated many additional features into the prediction algorithms and the user interface. The FORTRAN version of ILS_MOD was converted to C and the user interface upgraded. These enhancements consistes of: scattering algorithms for long wires such as power lines; both near- and far-field calculations; selection of random distribution errors for antenna currents (phase and amplitude) based on a standard distribution; user definable flight profiles; different receiver processing algorithms; and twelve user-selectable scattering materias.

ILS-PTD (1997 - Present).[9] This model is capable of analyzing rough surfaces and is based on the Physical Theory of Diffraction (PTD). Validation of two types of surfaces, rectangular corrugations and cylindrical bosses, has been completed. Further validation of other non-planar surface types is in progress under FAA support.

VOR (1991 - Present).[10] This model estimates bearing errors caused by reflecting structures in the presence of either a convencional, mountain-top, or Doppler VOR. PO techniques are used to calculate the scattering fields from an object. The direct and/or incident field of the VOR signal is based on the Geometric Theory of Diffraction (GTD) since the ground terrain (counterpoise) is limited in size. The scattering algorithms (PO and wires) are identical to those used in ILS2. In addition, the user interface utilizes many of the same features and options as the ILS2 model.

Underlying Theory and Assumptions

The Physical Optics (PO) Technique. The physical optics approach used in the models consists of calculating the electromagnetic field incident on the scattering (reflecting) object, calculating the current induced on the scattering object by the incident field, and then considering that the induced current gives rise to a scattered (re-radiated) electromagnetic field. The scattered fields from each reflecting object are added to the ideal fields (i.e., those which exist when no scatterers are present) to determine the total electromagnetic field in space. This process is performed for each position of the receiver along a given flight path. The scattering objects may be of any size, as the computer model itself subdivides the plates into areas small enough so that the electromagnetic assumption that the antenna is in the far field of the scattering object applies.

The PO technique assumes that the electromagnetic and magnetic fields at any point on a surface are the same as if that point were part of an infinite tangent plane with the same electrical characteristics, and tangent to the surface at the considered point. The PO technique only approximates the boundary condition on the surface of the scatterer. This is different from Geometrical Optics (GO) which assumes that the scattered field is one reflected from the tangent plane into a single direction determined by the specular point on the scatterer. The scattered field from the PO approximation is not limited to a single direction. In general, the GO predictions will only agree with the PO if the incident wavelength is negligible compared to the size of the scatterer.

The PO technique is the common thread in the development of the OUILS, ILS_MOD, ILS2, and VOR models. The PO technique does have a problem when the physical size of the scattering object is not large compared to the incident wavelength. This deficiency can be corrected to a large extent by using PTD.

The Physical Theory of Diffraction (PTD) Technique. The basic idea of this approach is to account for the differences between the currents used in the PO approximation and the actual surface current on an object with surface discontinuities. These diffracted fields are calculated based on the currents at the surface boundaries, i.e., edge currents. This correction based on the edge currents allows for good approximation of the scattered field when the size of the scatterer is comparable to the wavelength.

Receiver Alqorithm(s). The information contained in a radiated ILS signal is detected by an airborne receiver and processed to provide horizontal and vertical guidance indications. This indication is the difference between the received magnitudes of the two modulated frequencies, i.e., 90- and 150-Hz audio tones. This is accomplished through the use of heterodyne amplitude modulation (AM) receivers.

The ILS signal is coupled from the antenna to the receiver. The receive antenna pattern is considered omni-directional due to the wide range of possible patterns based on antenna type, aircraft size, and location. The signal is a composite of the direct and scattered carrier+sidebands and sidebands-only signals. For dual-frequency arrays, this includes both the course and clearance transmitters. The detected audio tones at the output of the AM detector, typically a linear-envelope diode detector, are directly proporcional to the level of the 90- and 150-Hz signals.

This detected audio is then applied to 90- and 150-Hz filters to separate the frequencies and determine the modulation levels. The signal applied to the crosspointer is directly proporcional to the difference in depth of modulation (DDM) between these two modulating frequencies. The 90- and 150-Hz filter output voltages are summed together to obtain the flag current, or sum of depth of modulation (SDM).

Several factors that affect the received signal, and which must be incorporated in the detected audio signal, are the receiving aircraft's motion (Doppler effects), audio filter crosstalk, and spurious effects that occur in the reception of dual-frequency signals. All these factors are considered in the development of the ILS receiver model.

At present there are four implementations for processing the detected 90- and 150-Hz modulation levels. They are listed below:

Method 1. Analog

$$DDM=(M90 - M150)$$

Method 2. Collins 700, Bendix RIA 35A, Bendix RNA 34AF

$$DDM = (M90 - M150)/(M90+M150)*SM$$

SM = 0.4 LOC; 0.8 for GS

Method 3. Collins 720

$DDM = (M90 - M150) *K$ where:

K = 0.90909

if $M90 + M150 > 0.44$ LOC
or $M90 + M150 > 0.88$ GS

K = 1.0000

if $0.36 <= M90+M150 <= 0.44$ for localizer
or $0.72 <= M90+M150$ for $<= 0.88$ for glide slope

K= 1.1111

if $M90 + M150 < 0.36$ LOC
or $M90 + M150 < 0.72$ GS

Method 4. Bendix Quantum

$DDM=(M90-M150)* K$ where:

K = 1

For $|DDM| >= 0.16$ LOC
or $|DDM| >= 0.18$ GS

$K = SM / (M90 + M150)$

SM = 0.4 LOC; 0.8 GS

Typically, the modulation within the proporcional guidance sector does not vary and is constant throughout an ILS approach. In this case, any of the methods provides similar results. However, Method 2 provides a worse case scenario for evaluation of clearance sectors and is typically used when evaluating the clearances.

A digital filter was implemented that corresponds to the typical RC filter circuit used in ILS receivers. The time constant for crosspointer recording systems for flight inspection work is specified by ICAO as 50/V seconds, where V is the aircraft speed in knots. Modeling simulations typically use 118 knots for the aircraft speed, which corresponds to a time constant of 0.424 second. The digital filter implementation used in the model is:

$$FX(i) = \frac{(SP*(x(i)+x(i-1)) - FX(i-1)*(SP-2TC)}{(SP-2TC)}$$

where SP = sampling period, TC = time constant, x = input signal, FX = filtered output signal, and i = position index number.

The VOR receiver processing algorithm used in the model provides a «bearing error» output, and the implementation is tailored after a typical VOR receiver. The mathematical representation of this receiver process is very complex. In general, the phase discriminator is used to determine the difference in phase between the detected 30-Hz amplitude modulated (AM) signal versus the frequency modulated (FM) components.

Model Applications and Validation.

These models have been used hundreds of times to analyze new construction, upgrade facility performance, or determine the cause of facility problems. In most cases, the models have provided accurate results and valid solutions.

VOR. The VOR model can be used to determine the required counterpoise height and diameter to provide accurate and sufficient coverage in a multipath rich environment. The preliminary modeling used to determine the dimensions for both the COWBOY and RANGER VORs, which support operations at Dallas Fort Worth (DFW) airport, was the first application of this model. Subsequently, it has been used for similar applications at the Northbrook (O'Hare) and Houston VORs.

Critical Areas. The initial critical area validation work was performed at Dallas-Fort Worth Internacional Airport (KDFW) in October, 1982. A 747 aircraft was positioned along the taxiway near Runway 17 in nine different locations covering five different orientations. The predicted results showed excellent correlation with the flight measurements. An example is shown in Figure 1.

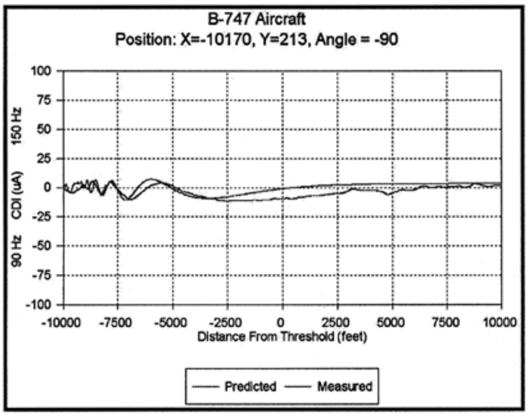

Figure 1. Localizer Performance

Near Field. In the past, difficulties were encountered with accurately modeling structures located close to the antenna system. With the implementation of near-field routines, the prediction accuracy has improved greatiy. An example of this is shown in Figure 2. Both the near- and far-field model predictions are compared to the actual flight measurements. This scalloping is caused by an 8-foot-high security fence approximately 100-feet offset from the capture-effect glide slope mast and located parallel to the runway until threshold. The far-field predictions underestimate the magnitude, whereas the near-field predictions are in very good agreement with the flight measurements.

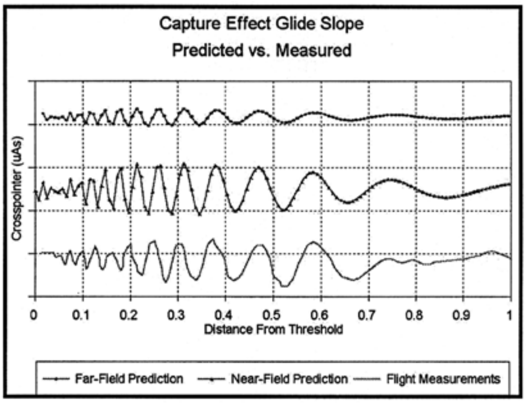

Figure 2. Far-field versus Near-field Predictions

Varying Materials. An additional improvement to the model has been the recent ability to accurately model structures which do not have perfectly reflecting surfaces, e.g., tree lines, terrain, etc. In general, use of perfectly conducting reflectors would over-estimate the amount of degradation. Currently, there are 12 user-selectable materials included in the model. The transmission and reflection coefficients are calculated based on the material's intrinsic impedance and the grazing angle. Figure 3 shows a comparison between localizer flight measurements and model predictions using a perfectly conducting scatterer and trees.

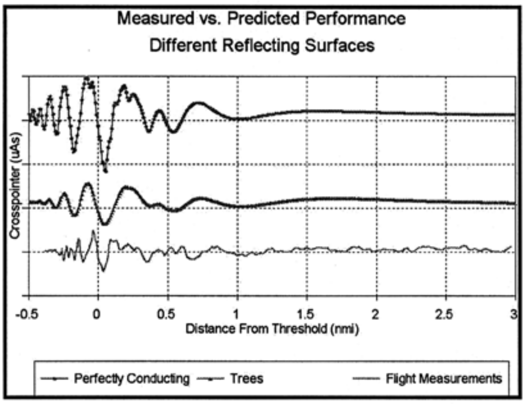

Figure 3. Different reflecting surfaces

In this situation, five tree lines, each with a different length, height, and offset, are parallel to the runway centerline. If these trees were modeled as perfectly conducting plates, the predicted results would significantly overestimate the actual performance. Selecting the reflecting surface as trees, the model results are more representativa of actual performance.

Non-planar Surfaces. The most recent validation efforts have focused on non-planar surfaces using PTD. The validation scenarios examined the benefit of adding cylindrical and rectangular structures to the face of an existing surface causing significant scalloping. A flat surface, 48-feet long and 24-feet high, was constructed to simulate an offending reflecting surface. A 3-element localizer array was used to minimize the required structure size. Figure 4 shows the results of the baseline flight measurements compared to model predictions.

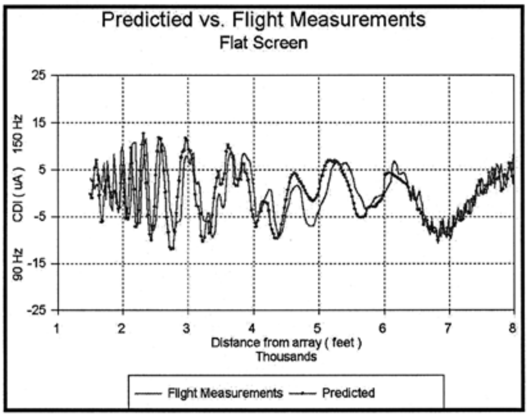

Figure 4. 24x48 foot flat plate

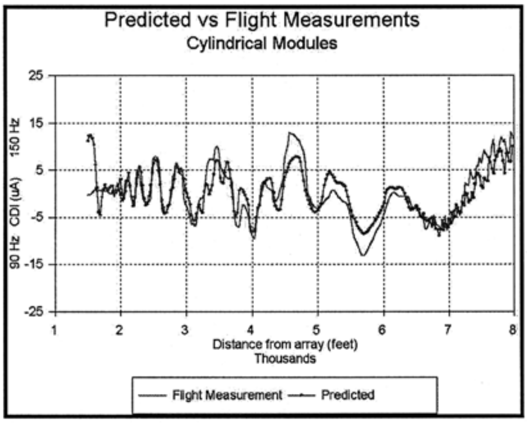

Figure 5. Flat plate with semi-cylindrical bosses

The scalloping from the flat plate occurs between 1500 and 3500 feet from the array.

Roughness and scalloping are also visible at distances beyond 3500 feet, caused by other objects (e.g., power lines, fences) near the test setup. To reduce the scalloping between 1500 and 3500 feet, two 6-foot tall half-cylinders, with a radius of approximately 4-feet, were connected to the flat screen. Model predictions and flight measurements in Figure 5 show a decrease in the scalloping frequency/magnitude.

LOCATING MULTIPATH SOURCES

Determining the location of multipath from airborne measurement data can be simple or complex, depending on the number of sources and their geometry relative to the flight path. Fortunately, multipath characteristics can be related to several straightforward physics principles making analytical analysis of recordings possible. This section of the paper reviews these principles and applies them in severas example cases.

General Multipath Characteristics

For an intuitive sense of the multipath physics, consider a cylindrical reflector close to and directly north of a VOR, with an orbiting aircraft observing the cylinder's effects (see Figure 6). Flat plate reflectors and directional navaid antenna systems are merely special cases of this general problem, with the multipath effects being observable only in certain locations.

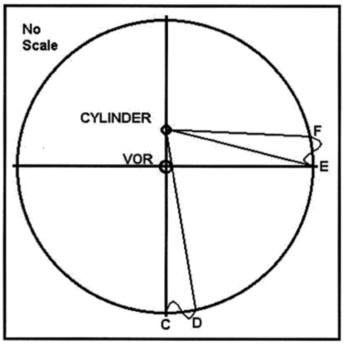

Figure 6. Orbital flight around a VOR, opposite and at right angles to a reflector

The pilot will observe a single crosspointer scallop or oscillation when the aircraft moves sufficiently far that the difference in path lengths, between the desired (D) and reflected (R) signals, changes by a wavelength (λ) at the VOR operating frequency, or approximately three meters. Mathematically, this is describes as a double difference,

$$(R_A - D_A) - (R_B - D_B) = \lambda$$

where A and B are the starting and ending points of the single scallop along the orbit.

Minimum Error Freguency. When the aircraft is directly opposite the reflector (south of the VOR) moving from point C to point D, the desired path length is constant (the radius of the orbit). The undesired path lengths (from the VOR to the cylinder to the aircraft) are longer than the desired path length. However, the length of the reflection path is very little different for an aircraft at point C than it is at point D, since the cylinder is close to, and the aircraft distant from, the VOR. Therefore the aircraft must fly a considerable distance to see a single scallop between points C and D, since the difference between the desired and undesired path lengths is changing very slowly. <u>The frequency of the scalloping is at a MINIMUM (essentially zero) when the aircraft is on the same or opposite radial as the reflecting object.</u>

Maximum Error Freguency. When the aircraft is at right angles to the azimuth of the reflector, moving between points E and F, the undesired path length (VOR to the cylinder to the aircraft) changes quickly due to the different geometry of the VOR and reflector with respect to the flight path. The aircraft must fly a much shorter distance between points E and F than between points C and D to see a single scallop. <u>The frequency of the scalloping is at a MAXIMUM when the aircraft is on a radial at right angles to the radial of the reflecting object</u>.

General Multipath Summary. Figure 7 summarizes the general case of a cylindrical reflector near a VOR. The frequency of the multipath error will be zero on the azimuth of the reflector and its reciprocal, and maximum on the azimuths at right angles to that of the reflector.

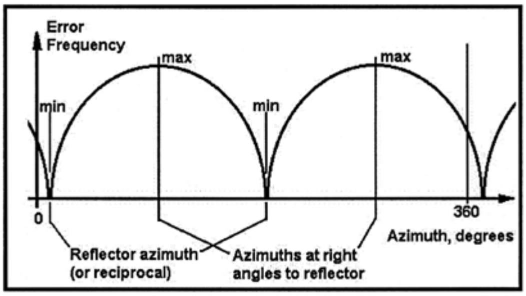

Figure 7. Change in scalloping frequency

Two Methods for Locating Reflectors

Given an intuitive understanding of general multipath characteristics, graphical and mathematical solutions for locating a reflector can be devised[11].

Center of Symmetry. The Center of Symmetry solution provides the azimuth of the reflector, but not its distance from the navigational aid. Again considering Figure 7, the multipath error (e.g., on the crosspointer) is symmetrical on either side of the azimuths of maximum and minimum frequencies. This allows the angle of a reflector to be determined by visual inspection of a flight recording, if these symmetrical characteristics exist. In Figure 8, the scalloping error on the amplitude modulation percentage trace of a VOR goes to zero frequency, and is symmetrical either side of, the reflector's azimuth or its reciprocal. (The ambiguity between these two radials must be resolved by physical inspection.)

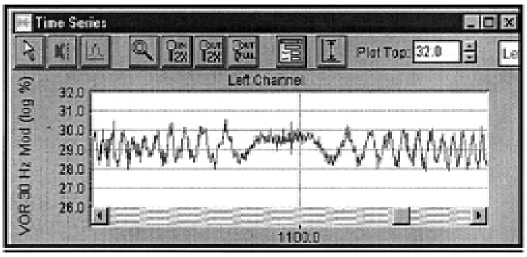

Figure 8. Symmetry of scalloping at reflector azimuth (or its reciprocal)

Scallop Counting. The Scallop Counting method provides both an azimuth and distance solution for the location of a reflecting object. It uses a mathematical solution based on counting the number of scallops per degree of orbital flight. The reflector lies on one of two lines paraliel to the azimuth of the counted observation. The spacing of the lines from the observation radial is equal to (490 x n) feet, where n is the number of scallops per degre[11].

For an example, see Figure 9. Here, a simple software program and line printer were used to draw eight pairs of paraliel lines, based on counting the number of crosspointer scallops per degree of orbital flight at eight different azimuths. The table at the upper left contains the input data, (number of scallops per degree and the corresponding azimuth of observation).
The lines are drawn to scale with the appropriate spacing from the VOR, which is at the center of the plot. The reflector must lie at the intersection of the lines, here at azimuths of approximately 30 or 210 degrees, where seven of the eight lines pass through the hand-drawn circle. This was the location of an air traffic control tower at approximately 2300 feet from the VOR.

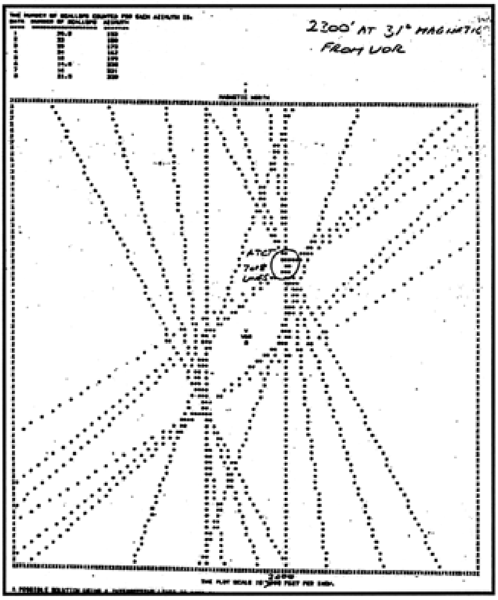

Figure 9. Determining reflector location using Scallop Counting method

Scallop Counting Problem

While the Scallop Counting method is a powerful tool for locating reflectors, it becomes difficult to use when the recording being analyzed does not have cleanly defined scallops. When multiple reflectors are present, the crosspointer error waveform (or other trace being analyzed) becomes complex and non-sinusoidal, and counting scallops accurately becomes very difficult. Even if one reflector is dominant over others, the resulting imprecision in obtaining scalloping frequencies causes the resulting sets of parallel lines to have a poorly defined intersection.

An example complex crosspointer waveform is shown in Figure 10. There is evidence of at least two significant reflectors present, and counting one scallop frequency separately from the other is nearly impossible by manual and simple observational techniques. What is needed is a method to break down the complex waveform containing the desired information into its constituent, sinusoidal frequencies, each of which represents a single reflector.

Implementing such a method is a classic spectrum-analyzer function.

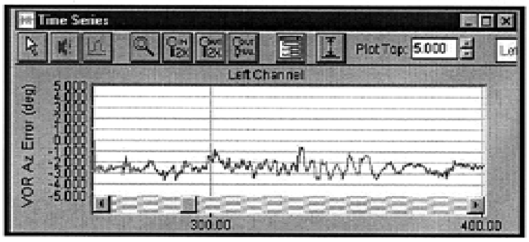

Figure 10. Complex crosspointer waveform

Scallop Counting Solution

Today's personal computer software market offers several software-based spectrum analyzers, intended for use with computerized audio files («wave» files). These programs typically use a Fast-Fourier Transform (FFT) computational engine for high-resolution determination of the component frequencies in a complex waveform. Use of such a spectrum analyzer will solve the problem of resolving a complex error waveform into its component frequencies, enabling high-resolution location of reflectors. An example recording from a VOR in Oklahoma will be analyzed to locate a reflector with high accuracy.

Spectrum Analyzer Software. FAA's Airway Facilities Service has procured one of these audio spectrum analyzer software applications, modified to directly read and process the data files recorded by both the portable engineering flight measurements package (NASE) and FAA's official Automatic Flight Inspection System. The software provides multiple views of an input data file, including a time series view (functionally identical to a flight inspection recording), a frequency series or spectrum view (identical to a spectrum-analyzer presentation), and a spectragram (a spectrum-analyzer presentation versus time).

Time View of Modulation. Figure 11 is a time-series view of a VOR orbital recording's AM percentage-modulation trace. It presents the same information as a typical flight-inspection recording for that parameter, and is merely a computerized display of the sampled data contained in the measurement file. The vertical scale is percentage modulation, and the horizontal scale is time. The figure shows the results halfway through a 1400-second (23 minutes, 20 seconds) orbit. This sample shows two easily-visible error components, indicating that at least two reflectors are affecting this portion of the orbit.

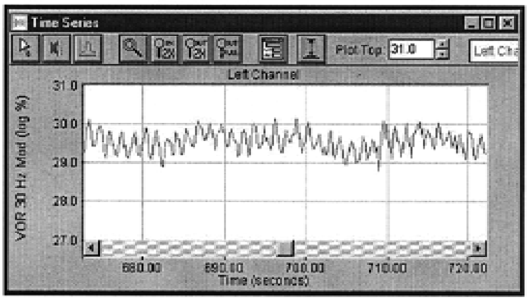

Figure 11. Time series view of AM % modulation

Spectrum View of Crosspointer. Figure 12 is a spectrum view of the crosspointer error from the same recording, computed using the FFT software algorithm for a particular azimuth of the orbit. This view represents an instantaneous spectrum «snapshot» for a particular aircraft location. The vertical axis is signal strength in decibels, and the horizontal axis is frequency of the crosspointer error in Hertz.

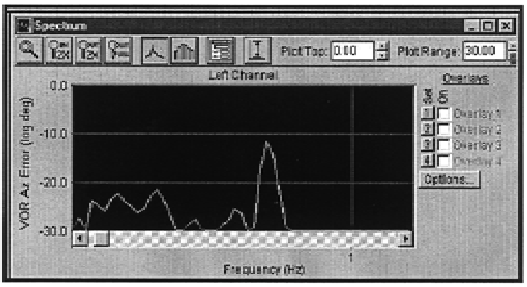

Figure 12. Spectrum of crosspointer error at a particular aircraft location

The spectrum view, because of its logarithmic display scaling, has the ability to display a much larger amplitude range of error components than does the time series display. In this view, one component at approximately 0.75 Hz is substantially stronger than six weaker ones. The individual frequencies of all seven components can be directly read from the software display by using a digital cursor.

Spectragram. The analyzer software combines many individual spectrum computations, taken at successive locations around an orbital flight, into a continuous display called a spectragram. It is this display that can be most readily used to compute reflector locations. Figure 13 is a spectragram of the AM percentage-modulation trace as shown in Figure 11. Figure 14 is a spectragram of the crosspointer trace shown in Figure 10. For each, the vertical axis is scaled in Hertz, and because of the modifications to the software, the horizontal axis is scaled in azimuth or degrees of orbit, rather than time.

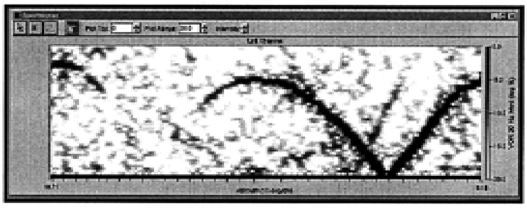

Figure 13. Frequency of AM % modulation error trace vs. azimuth, showing two reflectors

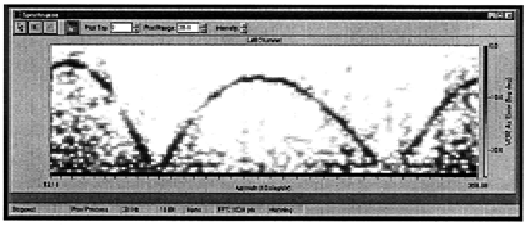

Figure 14. Frequency of crosspointer error trace vs. azimuth

Analysis. Now that the individual frequencies of a complex waveform can be easily resolved by the FFT algorithm in the spectrum-analyzer software, the Scallop Counting method of locating a reflector can provide a high-resolution answer. Note that Figures 13 and 14 both show the characteristic shape of multipath effects introduced in Figure 7. Also note that these two spectragrams are from the same orbital flight, and that both the crosspointer and AM percentage-modulation traces contain the same information for the dominant reflector. (This will also be true of the signal-strength trace, not shown here.)

Azimuth	FFT Freq, Scallops per sec	Seconds per degree	Scallops per degree
126.2	0.27	3.6496	0.9854
166.6	0.68	3.9203	2.6658
244.8	0.49	4.1952	2.0556
32.1	0.86	3.4914	3.0026

Table 1. Crosspointer data for primary reflector

By using the cursor measurement function of the software, the frequency (scallops per second) of the errors can be displayed. Table 1 shows the data extracted from four locations along the heavy line of Figure 14. For each location, the azimuth of the observation and the frequency is obtained (columns 1 and 2). Column 3 contains a conversion factor of seconds of flight per degree of azimuth (taken from the same data file) and column 4 is the desired high-resolution data in units of scallops per degree, for the Scallop Counting method of locating reflectors.

Reflector Location Solution. Figure 15 shows the resulting solution, using a Windowsbased version of the line-drawing program introduced in Figure 9. The range circles are in 100-foot increments around the VOR at center, and the four pairs of lines (corresponding to the four data points in Table 1) can be seen to produce a well-defined intersection at approximately 110 and 290 degrees from the VOR.

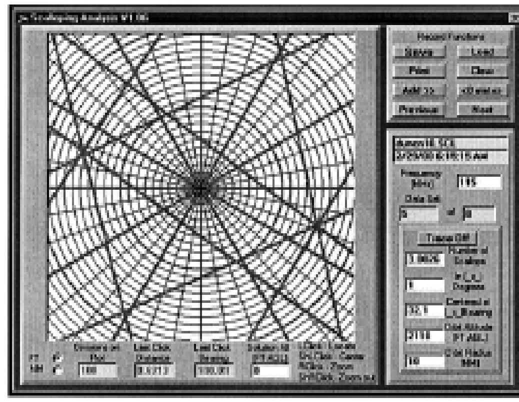

Figure 15. Reflector location from crosspointer error trace

Figure 16 is a zoom view of the intersection at approximately 110 degrees, with range rings now representing only 10 feet of radius. By centering the intersection in the display, the location of the intersection is read from the bottom of the screen, in this case 1508 feet on the 108-degree radial.

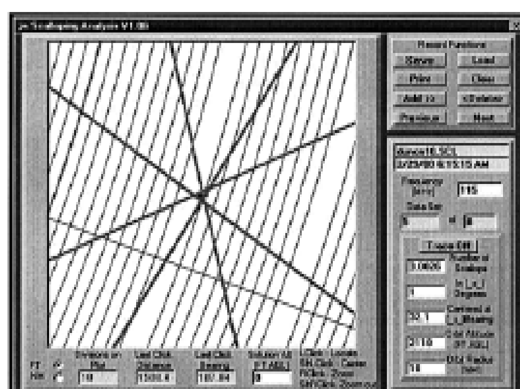

Figure 16. Expanded view of 1080 reflector

Reflector Location Summary. This sample exercise used recordings from a VOR site with a known water tower (cylindrical) reflector. The FFT-derived reflector location of 1508 feet at 108 degrees compares nearly precisely with a topographic map-based solution of 1500 feet and 107 degrees. The effects of individual reflectors (two are visible in Figure 13) can be readily visualized and separately analyzed using a spectragram type display.

CONCLUSIONS

For the navigation and landing system engineer, the ILS and VOR predictive models are cost-effective tools for determining the effects of proposed structures, confirming that an existing structure is the cause of unacceptable degradation, and predicting probable improved performance due to structure relocation, site redesign, or equipment upgrade. Modern spectrum-analysis software and application of straightforward physics can provide highaccuracy identification of existing structures from readily-avaliable flight measurements.

ACKNOWLEDGEMENTS

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AN INTEGRITY CONCEPT FOR GPS PHASE AMBIGUITY SOFTWARE AS A POSITION REFERENCE FOR FLIGHT INSPECTION

ABSTRACT

Over the past few years a trend towards further improvement of position reference systems for flight inspection of approach landing aids such as ILS and MLS can be seen. GPS carrier phase (fixed) ambiguity resolution (also known as a ‘P-DGPS’ solution) represents a ‘state-of-the-art’ technique that provides cm level accuracy, which is adequate for the calibration of approach landing aids.

In addition to accuracy, further parameters are of great importance for a position reference system, namely: availability, integrity, and the probability of detecting false solutions.

The special requirements for Flight Inspection System (FIS) tasks are quite different from those known from TSO-C 129a [1], RTCA DO-208 [2] or RTCA DO-217 [3] which are applicable for online navigation equipment. For a FIS application the accuracy requirements and the probability of detecting wrong solutions are very specific, whereas the alarm time may be much longer than in other applications. Therefore, only a few requirements from these documents are applicable.

This paper gives a short introduction to the Aerodata Flugmesstechnik concept and how the different requirements of integrity and the special needs for flight inspection can be met. It covers special software structures and theoretical analysis, as well as simulator and flight test results.

The concept has proven its reliability during the certification process of the position reference system by the Deutsche Flugsicherung GmbH (Department SNQ) which was officially completed in April, 1999 [4].

INTRODUCTION

Several applications of GPS carrier phase based position reference systems (e.g. [5] et.al.) have demonstrated their outstanding accuracy in general. There should be no doubt that the accuracy is sufficient for ILS CAT III flight inspection. But what about the error behavior of this kind of algorithm? Flight Inspectors must rely on the integrity of the position reference under all conditions and circumstances. Everything may work fine during a snapshot of a few approaches done in one afternoon.

But what will happen the next day with a slightly worse satellite geometry, under multipath conditions, or with a little bit stronger solar activity? Does the system cover satellite health information?

The carrier phase solution depends internally on the selection of a combination of integer values, the so called ambiguities. If the selection picks an incorrect combination due to noisy signals, this may not be obvious to the Flight Inspector and may result in a position error of a few decimeters. Therefore, an important issue is the length of time needed for the system to detect such errors by itself and to inform the operator in a worst case scenario. In addition, it is important to know how and when an individual ambiguity combination can be considered correct and therefore released as valid position reference.

Some existing systems simply wait for a certain time with a constant ambiguity solution. This leads to an extra amount of flying time and may also not help in all cases. If all obtained ambiguity solutions are delivered to the flight inspection system immediately, this may lead to a significant uncertainty.

Because of the importance of a valid solution, and the consequences of an incorrect solution going undetected, Aerodata Flugmesstechnik spent quite a large effort in addressing these issues. Existing requirements for satellite based navigation systems were evaluated for relevance first.

RNP-PARAMETERS

The Required Navigation Performance (RNP) for GPS-based navigation equipment as described in TSO C129a and DO-217 for example for Online Navigation is completely different to the RNP for a GPS carrier phase positioning reference system for flight inspection.

As opposed to online navigation systems, where accuracies of some hundred meters for non-precision approaches (NPA), and down to a few meters for precision approaches (PA) are sufficient, a position reference system requires accuracies in the lower sub-meter range.

On the other hand, online navigation systems dispose of an alarm time of a few seconds, whereas the alarm time of a position reference may be considerably longer. In order to meet the operational requirements for flight inspection tasks, an error of the position reference should be detected before the next approach measurement is carried out. This means, in the case of a normal ILS inspection an incorrect position reference should be indicated to the user within a maximum of 15 minutes time, nominally 5-10 minutes.

In addition for online navigation systems the availability and continuity of service of the position solution are of great importance, whereas these parameters are merely of economic relevance in the case of a position reference system. In any case, the integrity of a position reference is of a special relevance for technical safety.

Therefore test procedures for GPS equipment as defined in RTCA DO-208 or DO-217 are not applicable for the P-DGPS position reference system. Nevertheless, some requirements were taken from these documents.

ACCURACY

As already mentioned above, the accuracy of the P-DGPS solution as a position reference for CAT III ILS flight inspection is of major importance. The development of the algorithms was directed to obtaining a position accuracy of the integer ambiguity solution of 20 cm even under dynamic conditions. Therefore, typical ILS inspection flight tasks were simulated. The accuracy was proven by means of simulator tests with a STR 2760 GPS-RF simulator manufactured by Northern Telecom.

The simulated flights started at Braunschweig Airport (EDVE). After the take-off a 180° turn with a maximum climb rate of 10m/s was simulated followed by a straight flight while climbing up to the maximum flight level.

After a short rectilinear flight, followed by another

180° turn the approach was simulated. After reaching the threshold the simulation finished. The following parameters were modified during the simulation:

- Glide path angles of between 1° and 7° in steps of 1° at a velocity of 160 kts,
- Approach velocities from 120 kts up to 200 kts in steps of 20 kts at an glide path angle of descent at 3°,
- Different take-off times (6:00 hrs ZULU and 12:00 hrs ZULU) for the GPS constellation of GPS week 959 and an idealized 24 satellite constellation from [6].

In case of the flights with the above mentioned parameters a lateral acceleration of 0,3g during the banked turns was simulated. In the following, these flights will be considered as flights under normal conditions. Additionally, flights with lateral accelerations of 0,5g, 1g as well as 2g and a velocity of 160kts and a glide path angle of 3° were simulated. In the analysis these flights will be considered as flights with a higher dynamics.

The program was completed by the simulation of different multipath effects and different setting of the healthbits (signal in space failures) within static tests of a baseline of approximately 4,8 km as well as flights with extreme dynamics.

Differences between the carrier phase solution and the reference data provided by the simulator were computed. Table 1 gives a brief overview of the simulator test results.

Simulated data over 8.5 hrs were analyzed. Only in two simulated flights with increased dynamics, position differences of more than 20cm between the P-DGPS solution and the reference data occurred. These two flights were simulated with a lateral acceleration of 1g, or respectively 2g in the last bank before the approach phase started. In both cases the system clearly annunciated that the solution is unusable. During none of the profiles under normal conditions of almost 5,5 hours of simulated flights a position solution output with a position failure of >20 cm was given (refer to Table 1).

In addition to the simulator tests during July and October 1998 in Hanover (EDDV), Münster-Osnabrück (EDDG) and Bremen (EDDW), several acceptance flights with ILS CAT III with the P-DGPS position reference were performed. The test program was determined in close co-ordination with the Deutsche Flugsicherung (DFS/Department SNQ) and was accompanied by DFS experts. The test program included approximately 30 approaches at each of the three airports. Similar to the simulator tests, the approach velocities were varied between 130 kts and 200 kts and the glide path angles between 2° and 7°.

Table 1: Statistical analysis of the simulator test results for several categories.

	Normal Conditions	Higher Dynamics	High Dynamics	Multipath	Signal in Space Failure
Mean Values (3D-Diff.) [m]	0,075	0,073	0,071	0,066	0,073
Standarddeviation [3D-Diff.) [m]	0,004	0,014	0,002	0,002	0,002
Max. 3D-Diff. [m]	0,120	0,542	0,076	0,079	0,083
Amount of Epochs with Integer Ambiguity Solution	19644	4152	1313	4314	1106
Amount of Epochs with 3D-Diff. <= 20 cm	19644	4140	1313	4314	1106
Amount of Epochs with 3D-Diff. > 20 cm	0	12	0	0	0
Epochs with 3D-Diff. <= 20 cm	100,00%	99,71%	100,00%	100,00%	100,00%
Epochs with 3D-Diff. > 20 cm	0,00%	0,29%	0,00%	0,00%	0,00%

Figure 1 gives an overview of the flight profile and the availability of the carrier phase solution during one part of the acceptance tests. The test program was completed by off-set approaches and approaches with high dynamics maneuvers. For all flight trials a laser tracker was used as an additional position reference.

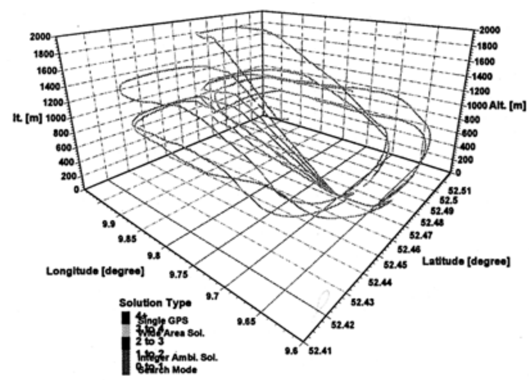

Figure 1: Flight profile of a part of the acceptance tests in Hanover (EDDV).

P-DGPS and laser tracker data were corrected for time skew and laser tracker alignment offsets. By means of the corrected laser tracker values and the extrapolated offline solution the differences for the x-, y- and z-direction were calculated. On the basis of these differences a 3D-difference could be calculated by the square root of the squared directional differences. In a last step the statistical analysis showed how many epochs of the offline solution were within the 3-D tolerance of the inspection system. These values were proportionally calculated at the basis of the existing epochs of the offline solutions. The 3D-tolerance of the inspection system results out of the following formula:

$$Tol_{3D} = \sqrt{TolLT_x^2 + TolLT_y^2 + TolLT_z^2 + TolPha^2 + 5 * TolRP^2}$$

where

$TolLT_i$ are the tolerances of the laser tracker in the x, y and z-directions

TolPha is the tolerance of the phase solution (20cm), and

TolRP is the tolerance of the five used reference points (2 thresholds, P-DGPS reference antenna, 2 points for laser tracker. Survey accuracy: +/-2 cm each).

Table 2: Flight Test Results

	EDDV	EDDG	EDDW	Result
Amount of Epochs	958	2747	1933	5638
Amount of Epochs with 3D-Diff.<=$Tol._{3D}$	954	2730	1907	5591
Amount of Epochs with 3D-Diff.>$Tol._{3D}$	4	17	26	47
Epochs with 3D-Diff.<=$Tol._{3D}$	99,58%	99,38%	98,65%	99,17%
Epochs with 3D-Diff.>$Tol._{3D}$	0,42%	0,62%	1,35%	0,83%

Additionally, the results of the laser tracker and the P-DGPS position reference were compared against the localizer and glide path signal. Identical results could be seen. By using the carrier phase solution a considerable decrease in the noise level could be noticed.

AVAILABILITY

A sufficient availability could be proven at the basis of the data recording of the simulator tests, flight tests and static tests. These tests were performed in replay mode. For the analysis a test shell on a PC was used. The shell contained the same basic modules as the P-DGPS software used in the Flight Inspection software. During the tests, search procedures for the determination of a carrier phase solution at different starting points were performed.

Additionally, a shell was implemented which determined and recorded the necessary times to find a valid carrier phase solution. Afterwards the program once again switched to search mode. If the search process needed more than 90 seconds, a time-out was registered and the parameters for the search were reset. This process was repeated until all data from a batch file, necessary for the setup of the test shell, were processed. Figure 2 shows the statistical results of the average search time for the P-DGPS-solutions.

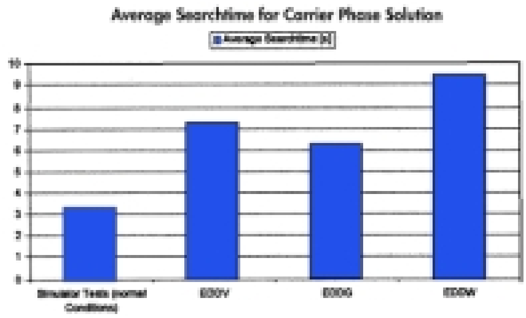

Figure 2: Diagram of the average search time to find a Carrier Phase Solution.

The program automatically compiled a protocol file of all relevant parameters for all processed data records. Afterwards a statistical analysis of the required search times indicated how many of the search modes could be finished within 90 seconds.

Table 3: Results of the availability testing

	Nº. of Carrier Phase Solutions within 90 sec.		Amount of Time Outs (Search Time > 90 s)	
Simulator Tets (normal Conditions)	3694	100.00%	0	0.00%
EDDV	1792	98.62%	25	1.38%
EDDG	1656	98.92%	18	1.08%
EDDW	1514	99.15%	13	0.85%

These results show a probability of more than 98.6% for obtaining a carrier phase solution within 90 seconds.

CONTINUITY OF SERVICE

Because the carrier phase solution is not used for online navigational purposes, continuity of service is not a safety related issue. If the system fails during an approach, it has only economic impact because the measurement run is marked as invalid and has to be repeated.

To avoid problems due to poor satellite constellation, it is possible to use a geometry prediction software based on the current almanac information and then schedule the flights according to the availability and geometry.

INTEGRITY

For over a decade, a significant amount of research has been conducted on the problem of resolving double difference ambiguities as integers. Many methods have been proposed for resolving ambiguities efficiently and reliably (e.g. [7], [8], [9], [10]). These approaches typically involve two steps, namely the identification of potential candidate integer ambiguities and the selection of an integer set that best fits the data [11]. The selection criterion is generally based on a discrimination test, often referred to as the ratio test whereby the smallest sum-of-squared residuals from a least-squares solution using an integer ambiguity solution ($v^T v_1$) is compared to the second smallest sum-of-squared residuals using another set of integers ($v^T v_2$), and is evaluated by computing ($v^T v_2 / v^T v_1$). If the ratio exceeds some threshold, the integers associated with $v^T v_1$ are selected as the true values. Due to the presence of unmodelled multipath and atmospheric errors however, this criterion may allow an incorrect integer ambiguity solution to be selected. Selection of incorrect integer ambiguities can significantly affect the achievable accuracy since for every one cycle of error, this translates into at least 19 cm in the position domain (when using L1 data).

In order to assess the probability of detecting incorrect ambiguity solutions, a series of simulation studies were performed which essentially force an incorrect set of ambiguties to be chosen as the solution. These ambiguity solutions are subjected to a series of statistical tests in an attempt to identify that these integers are infact incorrect, such that the system can self-correct. The following discussion is broken down into two sections, namely the theoretical model used for the simulation scenarios, and then the results from several simulation runs are included which show the impact of the changing satellite geometry and model parameters on the probabilty of detecting incorrect ambiguity solutions.

Theoretical Model

Several statistical tests may be employed to detect incorrect ambiguities. The main test used in this investigation was the measurement residual test. A theoretical model of the residual error for an incorrect carrier phase solution was simulated which accounted for the changing GPS satellite constellation over time. The residual test checks the magnitude of each double difference carrier phase residual with a pre-defined threshold value, *T*, which remains constant from epoch-to-epoch. An incorrect ambiguity solution is detected when the magnitude of more than a certain number of residuals, c_{max}, exceed the threshold value. The measurement residual computation for each epoch is given by the following equation:

$$v_t = A_t \delta_t + n_0 \qquad (1)$$

where A_t is the design matrix formed from the double difference carrier phase equations with known integer ambiguities [12] and n_0 is a noise vector with components varying between ±2 cm. The noise values represent the maximum residuals at the epoch where the ambiguities are fixed. With the use of differential carrier phase GPS methods, existing errors such as residual atmospheric, satellite orbit, multipath and receiver noise are inherent. However, the focus of the simulations was to investigate the effects of changing satellite geometry on incorrect ambiguities. Therefore, the noise factor was introduced to take into account the fact that under normal conditions, the observations are corrupted with errors and there is some initial noise associated with the residual computation. If we assume that all observations are equally weighted, then the position error, δ_t, is denoted by the following equation:

$$\delta_t = -(A_t^T A_t)^{-1} A_t^T w \qquad (2)$$

where A_t is the double difference carrier phase design matrix described above and w is the double difference misclosure vector of length *m-1*, where *m* is the number of visible satellites. It consists of a series of integers which represent the integer offsets in the estimated ambiguities from the true ambiguities. Since there are an infinite number of combinations that can be used for the misclosure vector, only a representative subset was chosen for the simulations. Primarily, the values of the misclosure vector tested ranged from ± 2 cycles, which means that it was assumed that if there is an incorrect ambiguity chosen, it will be within 2 cycles of the true value.

Satellite Constellation

A varying satellite constellation ranging from five to ten satellites was used to assess the position errors under poor to good geometry. A conservative availability criteria of GDOP < 3.5, number of satellites ≥ 5 and elevation masks of 5º and 7.5ª were evaluated in the simulations. All simulations were computed using the reference and user station coordinates for two sites in Germany (located at approximately 52ºN and 10.5ºE and 130 meters in height). The standard 24 GPS satellite constellation available in the Satellite Navigation Toolbox [13] for Matlab was used for all simulations. Over the 24-hour simulation period, the GDOP ranged from 1.4 to 3.3, while the number of satellites fluctuated between six and ten, for the 5º elevation case. Simulations conducted using the 7.5º cutoff elevation angle resulted in a drop in the number of available satellites, which ranged from five to nine with a corresponding increase in the GDOP.

Figure 3 and Figure 4 show the geometry and number of satellites for the 5º and 7.5º elevation mask, respectively.

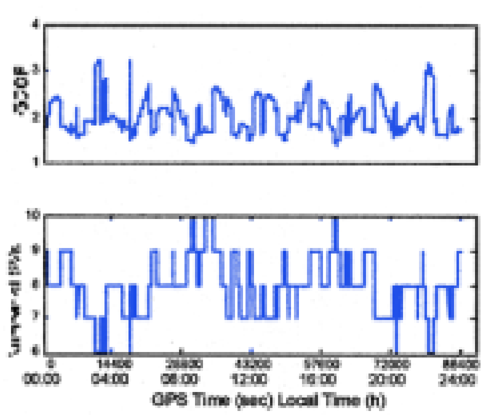

Figure 3: Geometry and Number of Satellites for 5º Cutoff Elevation

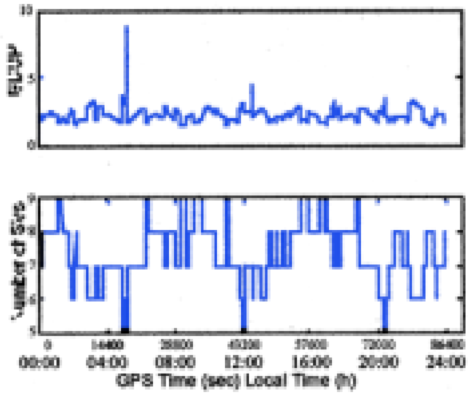

Figure 4: Geometry and Number of Satellites for 7.5º Cutoff Elevation

Analysis of Simulation Results

Several simulations were performed implementing the methodology described previously, over a 24-hour period, checking measurement residuals every 15 seconds with the residual test given above. The 24-hour simulation time provided varying satellite constellations. The simulations conducted herein are aimed at investigating the impact of geometry on the probability of detecting incorrect ambiguity solutions.

The detection capability of the residual test is dependent on two factors, namely (1) the threshold value, and (2) the number of residuals needed for detection. By varying the values of T and c_{max} the probability of detection for each case can be computed. Several simulations were conducted in order to assess the residual test's detection capability. A sample of the results achieved for a simulation at a 5º elevation mask is provided in Table 5.

It should be noted that caution must be taken when choosing extreme values for both T and c_{max} because of the possibility of rejecting correct ambiguity solutions or conversely, accepting incorrect ambiguity solutions. The optimal values are those which minimize these effects.

Table 5: Sample of Detection Percentage

T (cm)	c_{max}		
	3	2	1
3	58%	97.6%	100%
2	94.3%	99.9%	100%

Numerous simulations were conducted by varying the contents of the misclosure vector in order to determine the best and worst case scenarios under the various geometrical conditions. This allowed for an *envelope* of results to be created which contained the results from all incorrect integer ambiguities between ± 2 cycles of the true values.

To demonstrate the behavior of the position errors as the geometry changed over time, the sum of squared residuals, $v^T v$ (m^2), for the upper and lower bounds and the three dimensional position errors, $\delta^T\delta$ (m^2), are shown in Figure 5 and Figure 6, respectively. The lower boundary misclosure vector corresponds to one cycle error on one satellite as follows,

$$w_l = [\ 100K\ ]^T \tag{3a}$$

where the length is the number of satellites minus one, and the upper boundary corresponds to two cycles off for every satellite as follows,

$$w_u = [\ -2\ -2\ -2\ K\ ]^T \tag{3b}$$

This *envelope* of residual and position errors is representative of the minimum and maximum errors computed using the theoretical model. From the plots it is clear that the position error is a function of the geometry and the misclosure vector combination.

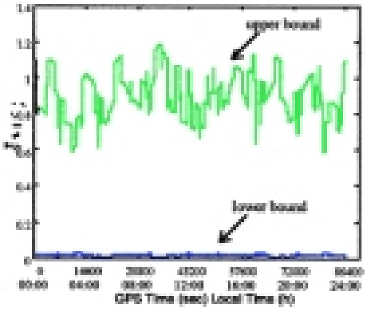

Figure 5: Sum of Squared Residuals Envelope for 5º case

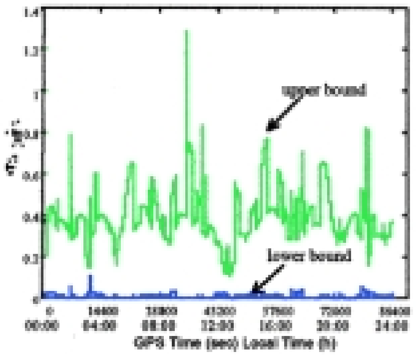

Figure 6: Sum of Squared 3D Position Error Envelope for 5º case

Figure 7 to Figure 9 represent the frequency of detection computed using the results of the 24-hour simulation period with a 5º cutoff elevation. The number of epochs for detection in seconds versus the frequency of detection is shown. The figures represent three cases where the threshold is 3 cm, 2.5 cm and 2 cm, respectively. The values in the graphs corresponding to zero number of epochs for detection refer to the incorrect solution being detected on the first measurement epoch. The plots were created for a 15 minute duration as shown on the horizontal axis. On the vertical axis, the values range from zero to 100 percent, where the percentage represents the frequency of detecting incorrect ambiguity solutions. The shaded region in each figure is bounded by the upper and lower limits in detection frequency for each specific test (see eq. 3a and 3b).

From these figures it is noted that as the number of residuals required for detection and the threshold value are reduced, the detection frequency increases. In the case were the detection frequency is 100% the upper and lower boundaries overlap and appear as a single line in the plots. In all cases, the majority of the incorrect ambiguity solutions are detected on the first epoch. In the most stringent test (Figure 7 for the case where C_{max} = 3), 64% of the incorrect solutions are detected on the first epoch, which slowly increases to 70% after five minutes and finally 80% detection after the full 15 minutes. These detection times are drastically reduced once C_{max} drops to 2. In this case, 98% of the incorrect solutions are detected in the first epoch, with 100% detection achieved in less than 100 seconds. As *T* is decreased, the detection times also decreases. For instance, in Figure 8, a 77% detection rate is achieved on the first epoch followed by an increase to 97% by 15 minutes. It is important to note that in all three figures, the third test (C_{max} = 1) detects incorrect solutions 100% of the time.

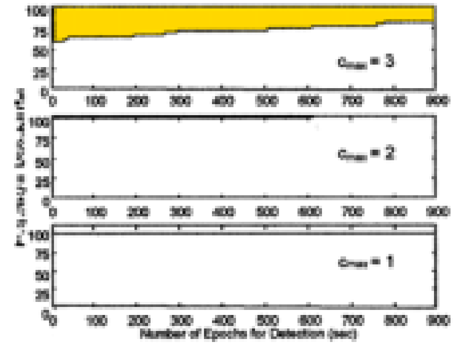

Figure 7: Detection Frequency for 5º elevation mask and T = 3cm

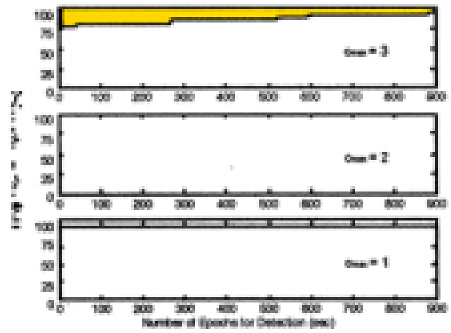

Figure 8: Detection Frequency for 5º elevation mask and T = 2.5 cm

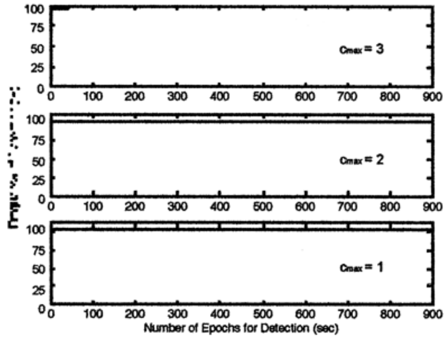

Figure 9: Detection Frequency for 5º elevation mask and T = 2 cm

Simulations were also conducted using a 7.5º cutoff elevation angle. The changing satellite constellation for this case is shown in Figure 4. As with the corresponding change in geometry, the sum of squared residuals and 3D position errors also changed slightly. The detection frequencies achieved using the 3 cm, 2.5 cm and 2 cm thresholds are shown in Figure 10 to Figure 12, respectively. As can be seen, the poor geometry under the higher cutoff elevation results in fewer detections than in the 5º case, which is a direct result of the degradation in geometry. The detection times for the higher cutoff elevation cases also increased slightly, however the change was insignificant for the majority of the tests.

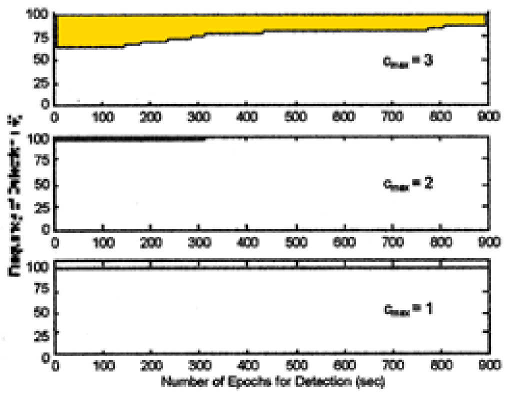

Figure 10: Detection Frequency for 7.5º elevation mask and T = 3 cm

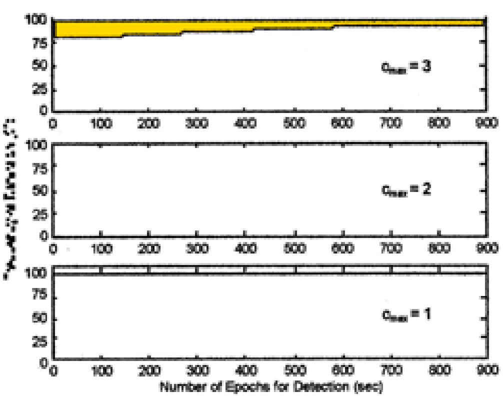

Figure 11: Detection Frequency for 7.5º elevation mask and T = 2.5 cm

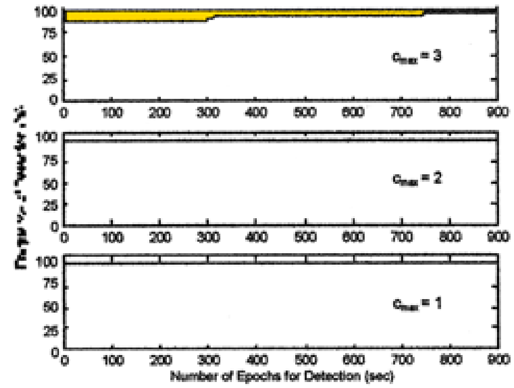

Figure 12: Detection Frequency for 7.5º elevation mask and T = 2 cm

In order to compare the results of both elevation cutoff cases, the same satellites were given incorrect integer ambiguities at each epoch for both cases. That is, the integer offsets introduced in the misclosure vectors were identical, although the length of the vector varied with the number of visible satellites. This provided a valid basis for comparison. By increasing the elevation cutoff angle to 7.5º, the effect of a change in geometry was further assessed. It was found that this change did not significantly impact the results, with the detection frequency being only slightly worse than the 5º case.

As expected, all results revealed that there is a strong correlation between the detection capability of the residual tests and the change in satellite geometry over time.

ADDITIONAL INTEGRITY ASSURANCE

The position reference software has been developed according to RTCA DO-178B [14]. This ensures a development process including robustness testing.

The residuals of all ranges are monitored all the time, as simulated above. Additional structural means provide the possibility of confirming a determined carrier phase solution. This information is clearly indicated to the flight inspector in a traffic-light style. The approximate time for achieving confirmation of the current solution is also displayed.

Table 6: Integrity Indication to the Flight Inspector

Label	Color	Meaning
O.K.	Green	Valid, confirmed P-DGPS-Solution
Preliminary	Yellow	P-DGPS Solution available, but not confirmed
Void	Red	Degraded Operation (not good enough for CAT III)

The system even takes into account, that confirmation of the P-DGPS solution may come **after** the approach was finished. Approach status data from the past are automatically updated from «preliminary» to «valid» after confirmation. All system outputs (graphic, alphanumeric, result sheets) reflect these indications (see Figure 13, Figure 14).

The position reference delivers an estimated position error (EPE) at all times. During a measurement pattern, this EPE is automatically cross-checked against the requirements of this pattern.

Additional information is retrieved be comparing the carrier phase solution of the measurement run to the history.

Executive controls of the received data of the P-DGPS reference station guarantee the integrity of the received data:

- CRC-Check of the data transmitted by the modem.
- Control of the check sum in the raw data
- Further plausibility checks
    - Message Header and Length
    - Receiver Self Test Status
    - Data Contents Plausibility

In the case that one of the described checks is negative, the complete message will be rejected. Computed positions are checked as follows:

- Plausibility of ground station coordinates (GPS vs. given coordinates)
- Comparison of P-DGPS vs. DGPS solution

An indication is shown to the Flight Inspector.

CONCLUSION

Theoretical analysis and simulation have delivered a stable background about error behavior and optimal countermeasures.

Because the entire software development was performed under direct control according to RTCA DO-178B, there were no opaque «black boxes» in the system with unpredictable and non-testable behavior in special cases. All testing was performed in a «white box» manner.

Intense testing with a GPS simulator has proven the accuracy and resistance against satellite failures. Because it delivers the true solution as reference, it is far more precise and reliable than simply comparing position sensors.

The best currently available conventional position reference system, the laser tracker, has been used for comparison during real approaches, as far as its accuracy allowed. During more than 90 approaches with a flight inspection aircraft under different satellite constellations at different locations a variety of maneuvers have been successfully performed. All approaches showed coincidence with the laser tracker.

In addition, several hundreds of approaches have been successfully evaluated from daily routine flight inspection (e.g. Figure 13, Figure 14).

Several layers of integrity measures, including hardware, software and structure ensure the probability of an undetected false solution to be smaller than 10^{-8}. Of course, the availability of correct solutions is still outstanding.

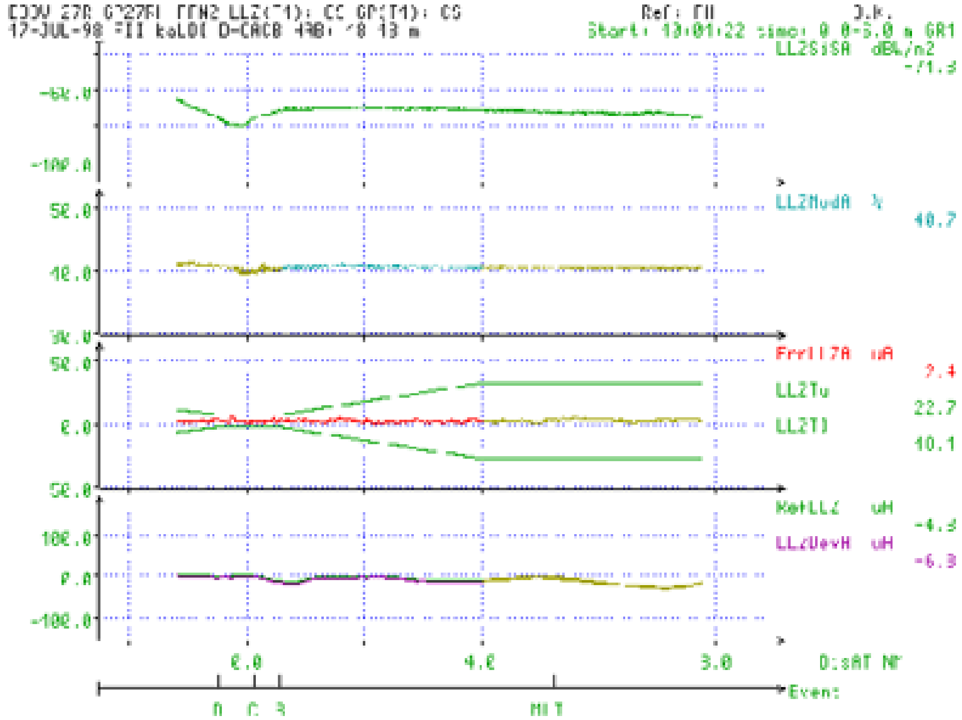

Figure 13: Localizer Calibration Result using confirmed P-DGPS Position Reference

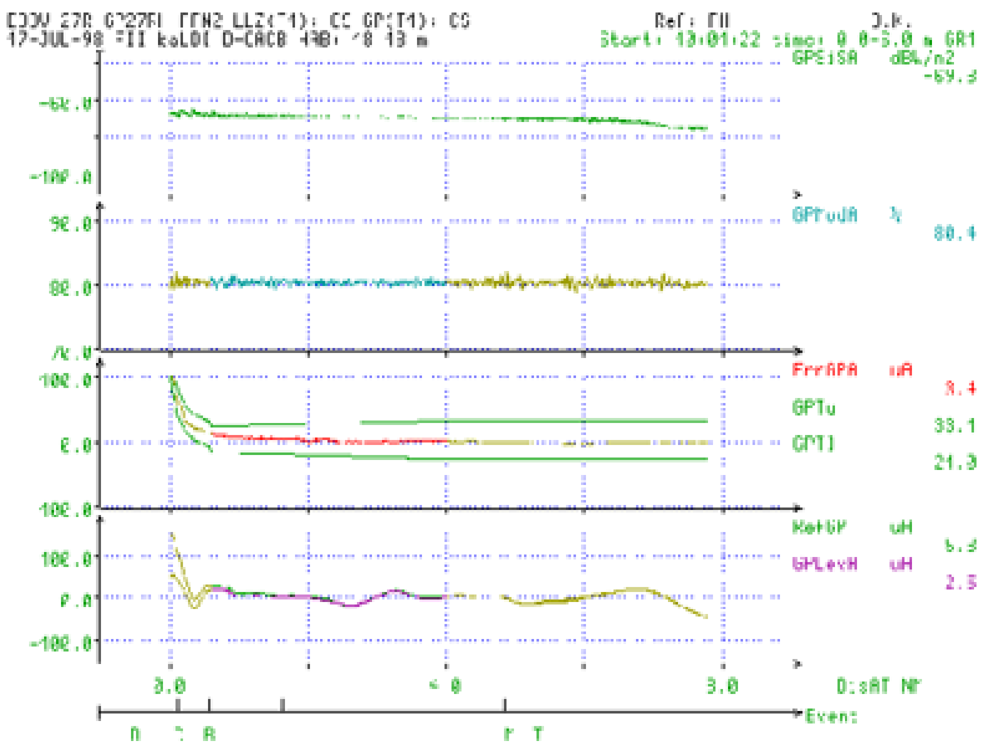

Figure 14: Glidepath Calibration Result using confirmed P-DGPS Position Reference

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Service Technique de la Navigation Aérienne

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FIVE YEARS OF OPERATION WITH VP-DGPS

ABSTRACT

In 1995, STNA performed a study of a new trajectography reference system for flight inspection, based on Very Precise DGPS only, aiming to replace any other system.

The results of this study, very encouraging, were presented at the 9th IFIS in Braunschweig in 1996. Since this date, the system has been used in France operationally for any kind of flight inspection.

This paper summarises these five years of experience, highlighting, encountered problems, their solutions and the major interests of the system.

BACKGROUND

For a long time, STNA has been studying trajectography systems designed for flight inspection. The general purpose was to have a more accurate, a more reliable system and also weather conditions free.

At the beginning of the 90's, studies were oriented toward the D-GPS, a system foreseen to fulfil the requirements as mentioned above.

A system relying on D-GPS hybridised with INS was developed and tested. Unfortunately, the accuracy was limited for some navaids and the infrared tracker was still needed for the last segment of ILSs or MLSs runs.

Meanwhile the studies to improve such a system were running, the GPS receiver technology was running faster!....so, it was decided to develop a new system based on dual frequency phase tracking technique.

During the year 1995, the VP-DGPS system (VP for Very Precise.) (Mainly Ashtech hardware and software.), was tested. The results of this experiment were presented at the 9th IFIS in Braunschweig in 1996.

Generally, the required accuracy for flight inspection depends on the aircraft distance to the navaid. The autonomous solution provided by the GPS receiver, is enough for a VOR, at ten Nm. The floating solution is convenient for an ILS up to 2 Nm of the threshold, according to the standard deviation value computed by the receiver. (Accuracy goes from 1 metre to 20 centimetres, or less), For these 2 last Nm, the ambiguity fixed solution is required, this solution accuracy being some centimetres.

During the two following years, 1996 and 1997, the new trajectography system was brought into operational use. This means that the performances and the consistency of the WGS 84 database were successfully checked.

From 1997 to 1999, the system evolved through the improvement of the equipment and the software, toward more reliability, as the problems arose and were solved.

SUBJECT

Problems encountered, solutions

Data base reliability

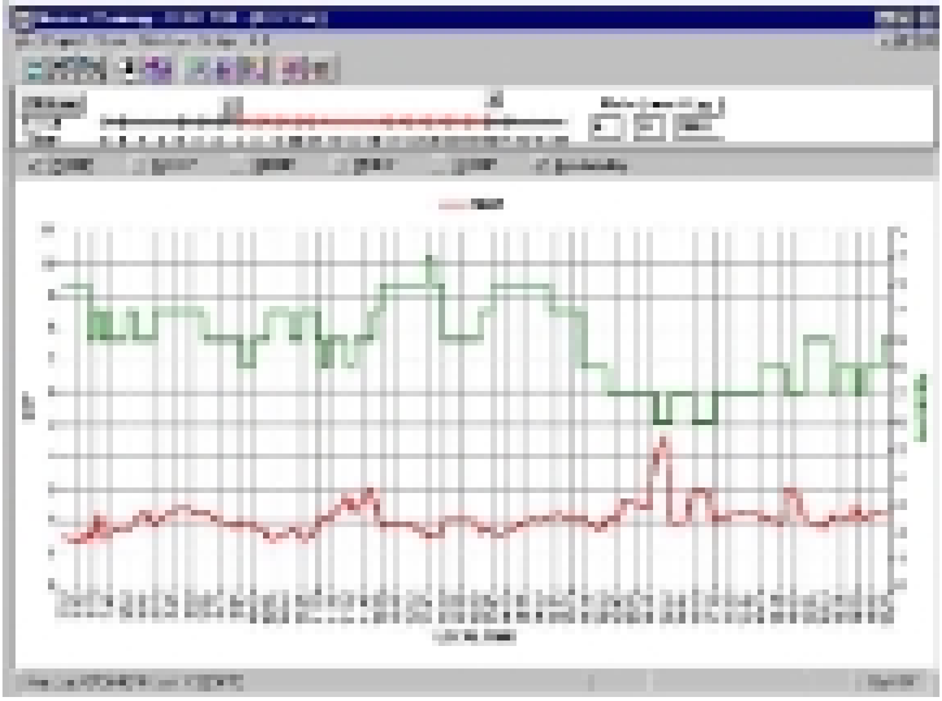
The WGS 84 database for all the airfields was established in 1996/1997 by SIA (French Aeronautical Information Service.) to comply with the WGS 84 ICAO program.
At this occasion, the flight Inspection division asked SIA to complete the WGS 84 ICAO program measurement campaign, with some particular points and some geometrical information required for each airfield, by flight inspection calculations.
It is obvious that an error in the glide path position or in the D-GPS ground station, for instance, will alter the whole system behaviour.
As STNA has to flight check, for example about 100 ILSs, some errors of this type has occurred several times.

So a complete check and a validation of the data base airfield after airfield is necessary. The database is a key element.

Satellite constellation

The experience showed that the satellite configuration could influence the performances of the system. A weak PDOP (greater than 3 or 4), or a poor number of visible SVS damages the accuracy. In these cases, the time to fix the ambiguities increases, and sometimes, the satellite configuration doesn't allow the receiver calculations to fix them.

To cope with this problem, it is recommended when preparing the mission, to use a software tool which predicts the SVS configuration using recent ephemeris. Every GPS receiver manufacturer provides such a software tool. In general, the periods of the day offering a poor satellite configuration are short (a quarter of an hour to an hour. Maybe several time a day) and can be avoided to perform flight inspection.



Example of predictions for PDOP and number of SVS in view.

Data link robustness.

It is easily understandable that to maintain the ambiguity fixing mode working, the data link transmission must be as correct and continuous as possible.

The difficulty comes from some runs performed at low altitude and from some manoeuvres of the aircraft, the turns for instance. In these cases, the data link information can be lost during several tens of seconds and the ambiguity fixing process must be restarted in the receiver.

The choice of the position of the UHF antennas on the aircraft, a new generation of transmitters and receivers allowed at last, satisfactory performances of the data link.

Receiver's software

It was noticed that sometimes, the receiver was suddenly unable to work. The «solution» of the problem was a reset of the receiver Kalman filter or of the receiver itself.

In other occasions, it appeared that the ambiguity fixing was not correct. This phenomena was noticed during flight inspection for five or six runs during all these years. But each time, the effect of the metric error was noticeable and the flight inspector could eliminate the affected runs.
These difficulties were attributed to receiver's software imperfections or «bugs».

Most of these difficulties were overcome through several new firmware releases provided by Ashtech for its receivers.

Despite the information on satellites health provided by the constellation itself, and of the RAIM receiver capability, it happened that bad SVS data entered the system. The effect produced is important enough to allow the flight inspector to eliminate the run.

A solution is to try to get external information about the satellites health, (For instance US Coast Guard web site.), in order to reject the affected SVS through the system, during the unhealthy announced period

An unexpected difficulty has raised since the last years, linked to the solar wind. The sun activity is not the same all the time and is subject to an 11 years cycle. The extension of the «black stains» on the sun surface is a criterion of the cycle evolution. The peak of activity occurred recently and induced stronger solar winds. The «solar wind» influences the ionosphere, and indirectly, the GPS signal when it goes through, so that the GPS receiver cannot fix easily the ambiguities. This phenomenon is more violent in the tropical regions and was experienced by STNA during flight inspection in overseas territories and by ASECNA in Dakar for instance.

Ashtech, the manufacturer of the receivers produced a new firmware version, to counter the problem. The receiver must be set up between half an hour and one hour before the flight, to allow the software to reach a good modelling of ionosphere corrections. Then, the ambiguity fixing works as usual.

New system benefits

Continuous fixing

Compared with optical trajectography systems or INS based systems, requiring an updating above the runway, Full VP-DGPS system offers a great advantage. The aircraft position is computed continuously, not only when the aircraft is in sight or when the INS system is updated. As the system provides help to the pilot through a guidance information, it is very convenient to have this information permanently valid. This allows performing a more precise capture of the beacons for the measurements and reduces the flight time as the runs can be shortened.

Better accuracy

The system error is a «metric error», which has to be converted in «angular error», applied to the measurements. Farther of the navaid you are, fewer the error is. So, compared to traditional position fixing systems, VP-DGPS accuracy is better for most of the run types, except maybe for the last portion of the approaches, where the accuracy is equivalent to that of the best optical system. A better accuracy means of course, more reliable measurements' results.

No weather dependence

Everyone knows, for optical positioning systems, the constrains which are due to bad weather conditions: missed runs, cancelled missions, wasted time, etc. VP-DGPS system is free of meteorological limitations. Its use generates a great benefit for the missions planning and their accomplishment. The only constrains reminding are those of the safety. The pilot must respect the legal minima, according VFR or IFR flight.

Flight time reduction

We have mentioned that a better guidance for the pilot could reduce flight time through shorter runs. Also, the quality of the position fixing induces a flight time reduction because fewer runs are lost, due to a bad or late optical tracking. As there is no need to move the ground system switching from localizer to glide path calibration, wasted time is saved. VP-DGPS being a 3-D positioning system, simultaneous localizer and glide path flight inspection can be performed. This not possible for all the types of runs, but for some specific ones. This is a fine way to reduce flight time significantly.

Equipment simplicity

The total equipment composing the system is very simple, light and cheep. On board, a single GPS receiver with an integrated data link receiver, the self contained software and the associated antennas. At ground a GPS receiver with a data link transmitter and the associated antennas. The total cost can be evaluated to less than US $ 40.000.

CONCLUSIONS

During the past five years, STNA could experience the difficulties linked to the development of the new VP-DGPS position fixing system.

VP-DGPS portable ground station

Most of these difficulties could be overcome with the help of the receiver manufacturer through several enhancements of the firmware, and thanks to technology improvement. At the beginning of the operational use, there were 3 parts on board: GPS and data link receivers and a separate PC, for the ambiguity fixing calculations, performed at a rate of 5 Hz. Now, with the third generation of receivers, the GPS receiver itself performs the calculations, at a rate up to 20 Hz, near free of ionosphere model variations. The second data link generation offers a receiver integrated to the GPS receiver, and secures the whole system.
Gradually, STNA could experience significantly the benefits of the flight time reduction. Another very significant reason leading to cost reduction is that no ground operator is no longer required. There is only one flight inspector aboard with the crew.

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FLIGHT INSPECTION IN THE NEW MILLENNIUM: Change, Challenge, and Opportunity

ABSTRACT

The Twenty-first Century will present a dynamic environment for the global aviation community. Transition from terrestrial-based communication, navigation, and surveillance systems to space-based technology has already begun. The challenge for flight inspection organizations is to be prepared for these new changes. Advanced technologies and the associated flight procedure capabilities present opportunities for new flight inspection methodologies and analysis systems. This paper will address the currently planned changes, the challenges they present, and the opportunities they provide for the flight inspection community.

CHANGE

The most obvious change in navigation technology has been and will continue to be the development and operation of satellite-based navigation systems. Although they have been operational for many years, civil use of the systems is relatively new, especially for the international aviation community.

Global Positioning System (GPS). The changes began almost 30 years ago when the U.S. Department of Defense (DoD) developed the concept and general configuration for the Global Positioning System in the early 1970s. DoD established the U.S. Air Force Space and Missile Systems Organization as the executive agent to manage and implement the system. The GPS Joint Program Office (JPO) was formed for this purpose. The JPO successfully launched 10 GPS Block I developmental spacecraft from 1978 to 1985. This demonstration verified the system's capabilities and DoD subsequently approved the implementation of an operational system, with the first operational spacecraft deployed in 1985. GPS was declared fully operational in April 1995. Total cost of the initial operational constellation was $1.5 billion. [1]

GPS has matured since then, to an operational navigation system of 27 spacecraft serving millions of users worldwide. More than one million GPS receivers have been produced each year since 1997. The rapidly expanding market - including equipment and applications - is estimated to reach $8.5 billion this year and exceed $50 billion in ten years.

The Presidential Decision Directive on GPS issued in 1996 directs that selective availability (SA) will be terminated by 2006 and its effectiveness reviewed annually beginning this year. The accuracy of the predictable civil GPS signal will improve from 50-100 meters to 10-30 meters when the intentional SA is removed. [2]

Global Navigation Satellite System (GLONASS). The former Union of Soviet Socialist Republics' Defense Ministry began the development and deployment of the GLONASS system virtually in parallel with the GPS development. The first

GLONASS spacecraft was in orbit in December of 1982. The full constellation consists of 24 spacecraft. Political and economic changes and the establishment of the Russian Federation have slowed development of the fully operational system. Currently the system contains ten spacecraft, with eight operational. However, the government of the Russian Federation has approved measures to provide GLONASS operations (both military and civil), system improvements, and full international cooperation. [3]

Galileo. The European Union member states have agreed to build and operate a civilian controlled global satellite navigation system called Galileo. The program is in the definition phase at this time. Candidate architectures include an all Medium Earth Orbit (MEO) constellation or a MEO constellation with Geostationary (GEO) spacecraft included. The definition phase will conclude at the end of this year, followed by technology development and design. Deployment of the spacecraft is planned to begin in 2006 with full operational capability in 2008. [4]

Global Systems. In 1991 the International Civil Aviation Organization (ICAO) adopted the Communications, Navigation, and Surveillance/Air Traffic Management (CNS/ATM) concept as a major part of a long-term modernization program for upgraded infrastructures to deal with the ever increasing air traffic demands. The combination of GPS and GLONASS, along with their augmentations, make up the infrastructure of the first generation Global Navigation Satellite System, GNSS-1. The addition of Galileo and other regional augmentation systems will evolve into GNSS-2.

Each of these systems provides a central point for three-dimensional position, navigation, timing, and synchronization for civil safety, security, science, engineering and related applications. In addition, each of these systems has been established with an open architecture. The newer systems will also provide compatibility. The journey toward GNSS-2 will end with an unprecedented open, seamless, continuous service global resource.

The most significant benefit from multiple constellations of satellite systems will be sole-means positioning and navigation. Each system is independent - mitigating common-mode failures. In addition, future improvements in the systems will offer additional benefits. Frequency diversity and additional civil frequencies within each system will reduce the interference susceptibility and separate the interdependency of military and civil signals (Figure 1). Multiple signal transmission will also improve atmospheric errors. Each system will also provide regional and local augmentation, improving integrity, availability, continuity, and accuracy.

Figure 1. GNSS Spectrum

Aircraft-based Augmentation System (ABAS). ABAS integrates the information obtained from the GNSS with information available on board the aircraft. The ABAS function combined with one or more of the GNSS elements must include a fault-free GNSS receiver and aircraft systems to meet the requirements for accuracy, integrity, continuity, and availability.

ABAS includes processing schemes which provide integrity monitoring for the position solution using redundant information such as multiple range measurements. The monitoring scheme generally consists of two functions: fault detection and fault exclusion (FDE). The goal of fault detection is to detect the presence of a positioning failure. Upon detection, proper fault exclusion determines and excludes the source of the failure (without necessarily identifying the individual source), thereby allowing GNSS navigation to continue without interruption. There are two general classes of integrity monitoring: Receiver Autonomous Integrity Monitoring (RAIM), which uses GNSS information exclusively, and Aircraft Autonomous Integrity Monitoring (AAIM), which uses information from additional onboard sensors such as barometric altimeter, clock and inertial navigation system (INS); continuity aiding for the position solution using information of alternative sources like INS, barometric altimetry, and external clocks; availability aiding for the position solution and accuracy aiding through estimation of remaining errors in determined ranges.

Augmentation information may be combined with GNSS information by integration within the GNSS solution algorithm - modeling altimetry data like an additional satellite measurement or external to the basic GNSS position calculation - comparison of the altimeter data with the vertical GNSS solution. Each processing scheme has specific advantages and disadvantages. It is not possible to present a generic description of all potential integration options, including the situation in which several GNSS elements are combined, such as GPS and GLONASS.

Space Based Augmentation Systems (SBAS). SBAS is a wide-coverage augmentation system from which the user receives augmentation information from a satellite-based transmitter. SBAS is made up of three distinct elements: the ground infrastructure, SBAS satellites, and the aircraft receiver.

The ground infrastructure includes monitoring and processing stations that receive data from the navigation satellites and compute integrity, corrections, and ranging data to form the SBAS signal-in-space (SIS). The SBAS satellites relay the data from the ground infrastructure to the airborne receivers, which determine position and time information from GNSS and SBAS satellites. The airborne receivers acquire the ranging and correction data and apply these data to determine the integrity and improve the accuracy of the derived position.

The SBAS ground system measures the pseudorange between the ranging source and SBAS reference receivers at the known locations and provides separate corrections for ranging source ephemeris, clock, and ionospheric errors. The user applies a tropospheric delay model. The ranging source ephemeris and slow moving clock errors are the primary basis for the long-term correction. The ranging source clock error is adjusted for the long-term correction and tropospheric error and is the primary basis for the fast correction. The ionospheric errors among many ranging sources are combined into vertical ionospheric errors at predetermined ionospheric grid points.

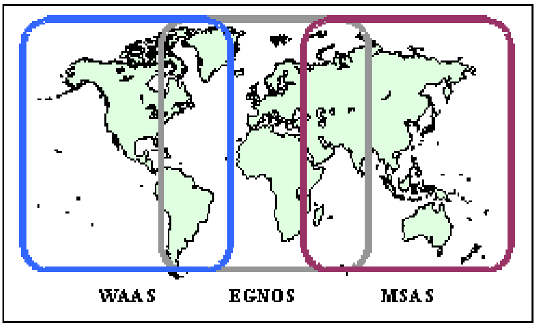

Figure 2. SBAS Systems

SBAS systems currently under development include the U.S. Wide-Area Augmentation System (WAAS), Japan's Multi-transport Satellite-based Augmentation System (MSAS), and the European Geostationary Navigation Overlay Service (EGNOS) planned for interface with Galileo (Figure 2). [5]

Ground-Based Augmentation Systems (GBAS). GBAS is an augmentation system in which the user receives augmentation information directly from a ground-based transmitter. GBAS consists of ground and aircraft elements. One ground sub-system will support all the aircraft within its area of coverage. GBAS will provide the capability for precision landing minima to the Category III level.

The ground sub-system provides the aircraft with approach data, corrections, and integrity information for in-view GNSS satellites utilizing VHF data broadcast (VDB). The VDB transmits with either horizontal or elliptical polarization (GBAS/H or /E), which allows the service provider to tailor the broadcast to their operational requirements and user community. The majority of aircraft will be equipped with a horizontally polarized VDB receiving antenna, which can be used to receive VDB from both GBAS/H and /E equipment. Aircraft equipped with only a vertically polarized antenna are limited to operations supported by GBAS/E only.

The U.S. Local Area Augmentation System (LAAS) is an example of a GBAS. Other systems are under consideration for development to include GLONASS and Galileo augmentation. The Russian Federation is developing and three part differential system as part of the United (State) Differential System (UDS). The plan includes Wide Area Differential (WADS), Regional Area Differential (RADS), and Local area Differential (LADS) systems, with each system providing an increased level of accuracy.

Eurofix. Eurofix is an integrated navigation system that combines Loran-C and differential GNSS (GPS, GLONASS, or future Galileo). Corrections are provided to users by additional modulation of the pulsed Loran-C signal. GNSS reference stations will be located at each Loran-C transmitter facility. Loran-C continues to remain an independent component of the navigation system, operating even if GNSS signals are not available in a particular area. Discussions are ongoing concerning adding this feature to the U.S. Coast Guard chains, Russian Federation Chayka stations and the Northwest European Loran-C System (NELS).

The fully integrated system will provide users with differential corrections for GNSS with an availability of approximately 99.99% and a 2-distance root mean square accuracy of 2-5 meters. Integration with WAAS and EGNOS is under discussion. The system will also provide GNSS integrity messages, emergency messages for the covered area, and coordinated Universal Time (UTC). [6]

Surveillance. Aircraft surveillance for air traffic control and air-to-air situational awareness is rapidly becoming a reality. The use of satellite-based position, velocity and time (PVT) information is under development and testing in the U.S. and other states. The PVT information is being evaluated for oceanic, enroute, and terminal traffic control; collision avoidance; and closely spaced parallel approaches. Results have shown the information more accurate than primary and secondary radar. Autonomous Dependent Surveillance (ADS) will replace ground-based surveillance systems and allow precise air traffic control in the oceanic environment.

The Non-change. Satellite navigation, PVT, augmentations...etc. aside, the flight inspection community must continue to support the traditional systems. The transition to sole-means satellite-based navigation is 10 to 15 years in the future. Instrument landing systems (ILS), microwave landing systems (MLS), VHF omnirange (VOR), distance measuring equipment (DME), primary and secondary radar...etc. will be operational for years to come. Advances in ground-based hardware and software have provided more stable signals and great improvement in system reliability.

In addition, advances in avionics have caused a redefinition of instrument procedures capabilities.

Flight Management Systems (FMS) aided by inertial reference units (IRU), barometric altimetry, rho-theta/rho-rho positioning, and the Required Navigation Performance (RNP) program provide new flight procedure possibilities.

THE CHALLENGE

What will be the role of flight inspection for GNSS? How do we manage the planned changes to the existing GNSS infrastructure? How can we manage sustainment of the ground-based systems while transitioning the new? The challenges we face in the new millennium are many. A thorough understanding of satellite navigation and the associated flight procedures is the necessary first step. What we analyze and how we determine the safety of flight operations will become more apparent with this knowledge.

GNSS Flight Inspection. In 1995, the Federal Aviation Administration (FAA) established a goal to develop a GNSS approach procedure for every qualified runway. We have commissioned approximately 500 procedures per year since that time and are rapidly approaching the goal of over 4,000 GNSS procedures. In addition, we commissioned three Special Category I Differential GPS (SCAT-I) systems and conducted the required periodic evaluations. These systems were early LAAS designs. We began flight validation of the WAAS two years ago utilizing the National Satellite Test Bed and eventually the WAAS during authorized test periods. This involved numerous flight evaluations of WAAS aided approach procedures to Category I minimums. We have also commissioned several special GPS-based airways/routes, departure, arrival, and special helicopter procedures for emergency medical services, law enforcement, and offshore oil platforms.

During these past five years, we have learned much about the flight inspection role in satellite-based procedure evaluation. As with any new endeavor, we began by measuring every possible parameter we could recover through the flight inspection system (FIS), even if we had no idea what to do with the data. Time and knowledge have caused us to reevaluate or requirements. We now believe our methodologies are sound and allow us to deliver a safe instrument flight procedure to both the public and special needs users.

These challenges were not met easily. We have struggled through volumes of documents and flight inspection data. Our aircraft are now equipped with avionics and FIS improvements that allow us to evaluate nonprecision stand-alone GPS, WAAS procedures, and are working on LAAS modifications. As is normally the case, certified receivers are not available early in a new program. We have worked with other organizations within the FAA and DoD to utilize prototype receivers. These will be replaced with certified equipment when available.

ICAO Performance Parameters. The International Civil Aviation Organization recently published draft Standards and Recommended Practices (SARPs) for GNSS operations. Table 1 is a reprint of the performance requirements for various phases of flight and the associated notes. These requirements represent the total system and include the signal-in-space (SIS), aircraft and non-aircraft equipment, and the ability of the aircraft to fly the desired path. In other words, these are Total System Error (TSE) requirements, which include Navigation System Error (NSE) and Flight Technical Error (FTE). [7]

It is important to understand the terminology used. The associated error budget and error allocations are critical to the development of flight inspection standards.

The *control* and user segments provide a signal-in-space and subsequent navigation solution that meets the NSE for the phase of flight operations. The receiver calculations account for satellite geometry (DOP); signal-to-noise and/or carrier-to noise-ratios; and fault detection and exclusion (FDE). Horizontal and vertical protection levels/limits provide integrity monitoring of the navigation solution and will cause a «flag» if the performance requirement is not being met, corresponding to «fail-safe» operations.

Augmentation systems have little effect on the error allocation; rather they provide improvements in accuracy and integrity. The SBAS (WAAS in this case) *ground infrastructure* uses multiple reference stations to receive the data from the GPS satellites. The monitoring and processing stations then compute integrity, corrections, and ranging data for uplink to the GEO satellites using forward error checking techniques. The GEO satellites rebroadcast the WAAS augmentation data and GPS-like ranging signals to the aircraft receiver (*user segment*), which acquires the ranging and correction data and applies the data to determine the integrity and improve the accuracy of the derived position. At the same time, the uplinked corrections and augmented navigation data is received from the GEOs by the ground monitoring and processing stations and cross-checked with the data originally sent, forming a closed monitoring loop. Accuracy and integrity are improved but the error allocation remains the same.

GBAS operates in the same basic manner on a more localized scale. LAAS services include a ground infrastructure comprised of multiple reference stations, a monitoring and processing station, and the VDB. The nominal service area for a LAAS installation will be omnidirectional to a distance of 22 NM. Since the service area is small (compared to WAAS), the augmentation data improves accuracy and integrity to a high precision level - meeting Category III requirements. The correction data, airport data, and approach data are uplinked to the aircraft receiver using forward error correction on VOR frequencies. Again, the error allocation remains the same.

Performance monitoring and data history is recommended in the GNSS SARPs. This data will aid in incident/accident investigations and anomaly analysis. Regions utilizing GNSS services provided by another state are encouraged to implement a monitor and data archive function. The parameters to be recorded are dependent on the type of operation, augmentation system, and core elements used (GPS, GLONASS, EGNOS, etc.).

Table 1. ICAO GNSS Performance Requirements

Typical operation(s)	**Accuracy horizontal 95%** (1)(3)	**Accuracy vertical 95%** (1)(3)	**Integrity** (2)	**Time to alert** (3)	**Continuity** (4)	**Availability** (5)	**Associated RNP type(s)**
En-route	3.7 km (2.0 NM) (6)	N/A	$1\text{-}10^{-7}$/h	5 min	$1\text{-}10^{-4}$ to $1\text{-}10^{-8}$/h	0.99 to 0.99999	20 to 10
En-route, Terminal	0.74 km (0.4 NM)	N/A	$1\text{-}10^{-7}$/h	15 s	$1\text{-}10^{-4}$ to $1\text{-}10^{-8}$/h	0.999 to 0.99999	5 to 1
Initial approach, Intermediate approach, Non-precision approach (NPA), Departure	220 m (720 ft)	N/A	$1\text{-}10^{-7}$/h	10 s	$1\text{-}10^{-4}$ to $1\text{-}10^{-8}$/h	0.99 to 0.99999	0.5 to 0.3
Non-precision approach with vertical guidance (NPV-I)	220 m (720 ft)	20 m (66 ft)	$1\text{-}2\times10^{-7}$ per approach	10 s	$1\text{-}8\times10^{-6}$ in any 15 s	0.99 to 0.99999	0.3/125
Non-precision approach with vertical guidance (NPV-II)	16.0 m (52 ft)	8.0 m (26 ft)	$1\text{-}2\times10^{-7}$ per approach	6 s	$1\text{-}8\times10^{-6}$ in any 15 s	0.99 to 0.99999	0.03/50
Category I precision approach (8)	16.0 m (52 ft)	6.0 to 4.0 m (7) (20 to 13 ft)	$1\text{-}2\times10^{-7}$ per approach	6 s	$1\text{-}8\times10^{-6}$ in any 15 s	0.99 to 0.99999	0.02/40

Notes:

1. *The 95 percentile values for GNSS position errors are those required for the intended operation at the lowest height above threshold (HAT).*
1. *The definition of the integrity requirement includes an alert limit against which the requirement can be assessed. These alert limits are:*

Typical operation	*Horizontal alert limit*	*Vertical alert limit*	*Associated RNP type(s)*
En-route	*7.4 km (4 NM)*	*N/A*	*20 to 10*
En-route	*3.7 km (2 NM)*	*N/A*	*2 to 5*
En-route, Terminal	*1.85 km (1 NM)*	*N/A*	*1*
NPA	*556 m (0.3 NM)*	*N/A*	*0.5 to 0.3*
NPV-I	*556 m (0.3 NM)*	*50 m (164 ft)*	*0.3/125*
NPV- II	*40.0 m (130 ft)*	*20.0 m (66 ft)*	*0.03/50*
Category I precision approach	*40.0 m (130 ft)*	*15.0 m to 10.0 m (50 ft to 33 ft)*	*0.02/40*

A range of vertical limits for Category I precision approach relates to the range of vertical accuracy requirements.

3. *The accuracy and time-to-alert requirements include the nominal performance of a fault-free receiver.*

4. *Ranges of values are given for the continuity requirement for en-route, terminal, initial approach, NPA and departure operations, as this requirement is dependent upon several factors including the intended operation, traffic density, complexity of airspace and availability of alternative navigation aids. The lower value given is the minimum requirement for areas with low traffic density and airspace complexity. The higher value given is appropriate for areas with high traffic density and airspace complexity.*

5. *A range of values is given for the availability requirements as these requirements are dependent upon the operational need which is based upon several factors including the frequency of operations, weather environments, the size and duration of the outages, availability of alternate navigation aids, radar coverage, traffic density and reversionary operational procedures. The lower values given are the minimum availabilities for which a system is considered to be practical but are not adequate to replace non-GNSS navigation aids. For en-route navigation, the higher values given are adequate for GNSS to be the only navigation aid provided in an area. For approach and departure, the higher values given are based upon the availability requirements at airports with a large amount of traffic assuming that operations to or from multiple runways are affected but reversionary operational procedures ensure the safety of the operation.*

6. *This requirement is more stringent than the accuracy needed for the associated RNP types but it is well within the accuracy performance achievable by GNSS.*

7. *A range of values is specified for Category I precision approach. The 4.0 m (13 ft) requirement is based upon ILS specifications and represents a conservative derivation from these specifications.*

8. *GNSS performance requirements for Category II and III precision approach operations are under review and will be included at a later date.*

Flight Inspection Role. The error allocation and navigation processing schemes utilized in GNSS flight operations limits the requirements for flight inspection validations. If we compare GNSS with a typical ILS, we find that standard flight inspection methodologies no longer apply. ILS signals are generated in the ground transmitter and radiated through elaborate phasing and antenna circuits. Monitoring is accomplished at the ground site utilizing integral and near-field antennas. Guidance is recovered from the modulation relationships applied to the carrier by a passive receiver.

GNSS guidance is generated within the aircraft receiver using data received from the satellites and augmentation services. The receivers use algorithms designed and certified to meet the safety-of-life requirements of RTCA Do-178B, Software Considerations in Airborne Systems and Equipment Certification. These algorithms determine position, guidance, guidance scaling, distance information, real-time integrity monitoring, and fault detection and exclusion. All of these processes are certified by a comprehensive set of test programs to meet the TSO requirements.
The role of flight inspection becomes that of flight procedure design validation and anomaly identification. The only signal-in-space analysis required is for the GBAS VDB signal strength/coverage. This has not been an easy transition within the FAA flight inspection program. Flight inspectors are, by nature and training, accustomed to analyzing microamps, ddm, microvolts, structure...etc. Replacing this with procedure design validation and the occasional interference situation is not unlike a trip to the dentist! Value-added analysis, experience, and education help smooth the road.

Flight Procedures. Navigation accuracy of flight procedures is solely dependent on the geographic coordinates used in the design process. International standards for these data is published in ICAO Doc 9674, Airport Survey Accuracy (WGS-84 Manual). Survey system accuracy is required in millimeters and airport coordinates at 1 meter or less.

The coordinates for runway centerline - threshold and stop-end - provide the basis for the approach procedure design. Certified survey data for ground reference stations is another critical element. Reference antenna phase-centers are located to centimeter accuracies.

Flight inspection of the procedure includes design validation, obstacle validation, and flyability. Design validation is performed by entering the procedure waypoints into the GNSS receiver and comparing the bearing and distance between each with the design package. The validation should be done utilizing true bearing. Use of magnetic bearing can cause confusion. GNSS receivers and FMS use different methods to apply magnetic variation - some use look-up tables and others provide real-time calculations. Procedure design is based on the airport magnetic variation, which does not provide accuracy comparable with the receiver technology.

Certified receivers will not operate in the approach mode when waypoints are manually entered, however, the guidance scale-factor can be manually selected. Many FMS manufacturers provide software that allows waypoints and leg-types to be developed in a file and downloaded into the FMS database. This allows the system to function in the full approach mode.

Multiple Approach Minima. GNSS and SBAS approach procedures are being published in the U.S. as Area Navigation (RNAV) approach charts. These charts contain multiple landing minima to accommodate various aircraft/avionics capabilities. Separate minima lines are provided for GLS PA (SBAS Category I precision approach), LNAV/VNAV (lateral and barometric vertical guidance), VNAV, and circling when applicable. In addition, RNP requirements are included for certified aircraft. GBAS approach charts will be published separately.

LNAV guidance may be provided by GNSS or ground-based facilities (DME/DME). This requires flight inspection validation of DME coverage throughout the final segment of the approach at the designed altitudes. DME coverage models are used to generate a listing of probable facilities that may support the procedure.

These procedures require validation to the Decision Altitude (DA) for precision and VNAV approaches and to the Minimum Descent Altitude (MDA) for nonprecision. Obstacle evaluation is based on standard trapizoidal surfaces for all cases except RNP, which utilizes linear surfaces. The approach procedure is flown from initial waypoints through the missed approach segment.
Pilot analysis of flyability must include knowledge of performance capabilities for all categories of aircraft anticipated to operate at the location. This is especially true for arrival and departure procedures to ensure deceleration legs and heading/altitude changes are manageable. Future enhancements such as curved and segmented approach procedures will require careful human factors consideration.

As you can see, validation of the flight procedure can be complicated and will keep the flight crew very busy. But what of the flight inspection engineer/ technician? In addition to the DME coverage and GBAS VDB analysis mentioned above, the FIS is continuously monitoring GNSS parameters. Any loss of guidance will require these data be analyzed to identify the cause. This includes interference, geometry, or receiver failure.

FAA flight inspection systems are being equipped with GNSS passive monitoring capabilities. This system begins archiving specific GNSS parameters at wheels-up. If any of these parameters exceed predetermined levels during the flight, the FIS retains the last five minutes of good data, the data during the anomaly, and five minutes of good data after. The crew is alerted and may decide to re-fly the route or procedure. If interference is suspected, they may fly across and/or around the initial flight path to determine the area affected. Parameters that are monitored are listed in Table 2. If interference is continuously present, a spectrum analysis and interference location aircraft will be dispatched to the location for further investigation.

Table 2. Passive Monitoring Parameters

GPS Sensor (GNSSU)	FIS
UTC	A/C Heading
GPS Altitude (MSL)	A/C Baro Altitude
HDOP	A/C Pitch
VDOP	A/C Roll
RAIM	A/C Ground Speed
Signal-to-Noise Ratio	A/C Latitude
GPS Latitude	A/C Longitude
GPS Longitude	System Time
GPS Ground Speed	System Date
GPS Date	
GNSSU Status	
Measurement Status	
Autonomous Horizontal Integrity Limit	
Autonomous Vertical Integrity Limit	

Interference Detection and Localization. As reliance on GNSS increases, the FAA is taking several steps to mitigate the effects of interference incidents. The program consists of the establishment of an agency-wide coordinated program, fielding of interference localization equipment, and development of traffic management procedures. Performance goals for this program phase are to detect and localize an interference source near a major hub in real time and to eliminate the source in near real time. [8]

A spectrum manager has been established at the Air Traffic Control System Command Center (ATCSCC) to coordinate tactical efforts addressing interference to GNSS signals; collaborate with ATC managers responsible for re-routing flights when necessary, personnel who issue NOTAMS, and flight inspection aircraft utilized in localizing the interference source.

The FAA is deploying GPS interference detection and localization systems for use on five plat-forms: aircraft, portable (temporary vehicle installation), handheld, fixed (ground-based installation), and transport-able (permanent vehicle installation). Portable in this context refers to a unit that can be operated from a moving vehicle, in contrast to the transportable system, which can only be operated when the vehicle is stopped. The five systems have complementary features (range, accuracy, and mobility) and, used in concert provide an integrated interference detection and localization capability.

In many instances, the first reports of interference to GPS will be from aircraft carrying out normal operations. The airborne component of the interference detection/localization system will be quickly dispatched to establish the source position to an accuracy of approximately 1 nautical mile.

The airborne system is based on a direction finding (DF) antenna. DF systems can provide both decreased localization time and increased accuracy by enabling direct homing to and fly-over of the source. The airborne system is deployed on FAA flight inspection aircraft.

After the interference source is localized to within a small area, portable and/or handheld systems will be used to find the precise source position. These units can be easily installed in a passenger vehicle, and are inherently more efficient than handheld units for interference source localization. Handheld localization systems are best suited to conditions that preclude using portable systems - e.g., wooded areas or building interiors.

Fixed-installation multi-band interference detection/localization systems and associated transportable units will be deployed at critical high-traffic airports and surrounding terminal areas. The first operational systems have been installed at Los Angeles International and Chicago O'Hare airports. These systems will protect the aeronautical frequency bands used for current ground-based communications, navigation and surveillance systems, as well as the GPS bands.

A fixed system installation has three or more remote towers, each of which has a DF antenna and electronics unit. Outputs from the remote sites are linked to a base station on the airport, which provides a source location estimate via triangulation and a recording capability. In one recent operational incident involving interference to VHF communications, the source was located in 15 min. The mobile unit consists of a van carrying a top-mounted telescoping tower, a DF antenna, and associated electronics. The van is linked via radio to the airport base station and serves as a real-time deployable sensor. By dispatching the van to a location near an initial estimate of the source location, a stronger interference signal and better DF geometry are obtained, resulting in an improved estimate of the source location.

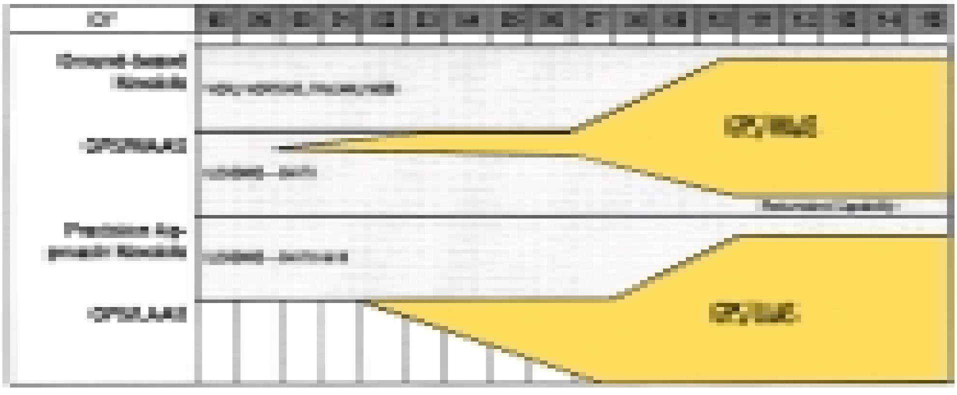

Figure 3. Transition Timeline for the U.S.

OPPORTUNITIES

The new requirements for flight inspection of GNSS and the overlap with traditional navigation and landing aids offers many opportunities for methodology and technology advancements in the flight inspection arena.

Traditional Facilities Inspection. The future implementation of GNSS services and the phase-out of the ground-based infrastructure are depicted in Figure 3. The transition period will increase flight inspection workload dramatically. This situation calls for more efficient flight inspection aircraft and analysis tools.

The increasing use of FMS - utilizing both GNSS and ground-based facilities - coupled with inertial units will expand potential flight operations into new areas. Curved approaches with continual vertical guidance will require validation. Today's flight inspection airframe should include dual FMS and IRU avionics that will facilitate these operations. FMS controlled navigation utilizing the RNP concept provides an additional tool. These systems announce the RNP value for the phase of flight and the actual navigation performance (ANP) achieved in real-time. These two values - with proper calibration - could provide a flight validation of many procedures without external equipment.

Flight Inspection System Advances. There is also an opportunity in incorporate new technologies into the flight inspection system. Reducing the size, weight and power requirements would enhance the selection of available airframes and associated environmental systems to support the flight inspection mission. The incorporation of computer controlled sampling receivers with digital signal processing (DSP) would provide improved performance, higher reliability and lower cost. The entire ground-based navigation spectrum could be analyzed utilizing two receivers of this type - one covering 10 kHz to 30 MHz and the second 30 to 1200 MHz. These receivers can be programmed to scan or sweep one hundred channels per second. They provide data bus interface for ease of integration with ARINC data modules, 32-bit computers, and storage devices.

DSP data provides a direct source for signal analysis algorithms — digital in and digital out - also supporting data archiving and automated report generation. Analysis software modules can provide results both in graphic and tabular formats, in near real-time to the flight inspection engineer/technician. In addition, these data would easily input to desktop analysis tools currently available for multipath analysis and other modeling programs.

This type of system would be the size of a standard desktop computer, weigh 100 pounds, and present an electrical load of 100 watts.

SUMMARY

We have met the enemy, and we are them (or is it they are us?). The changes are upon us and will continue at a rapid pace. Conversely, the traditional systems will be in parallel operation for many years to come. The challenges are many; be prepared for and accept the new, sustain the traditional, and meet the increased demand for flight inspection during the transition. Opportunities abound for new equipment and analysis tools to meet these challenges. It is an exciting time for flight inspection.

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GENESIS OF A NEW SYSTEM WAAS FOR THE TWENTY-FIRST CENTURY
March 17, 2000

ABSTRACT

The first phase of the Wide Area Augmentation System (WAAS) has been completed with the installation of the ground equipment, system software developed, and initial instrument approach procedures designed. One of the first activities in the process of transferring the system to the Federal Aviation Administration (FAA) was to be the completion of a 60 day stability check. During the stability check the FAA was scheduled to concurrently conduct an Operational Readiness Evaluation and Operational Test and Evaluation. In December 1999, the stability check was started in order to identify any new problems that needed to be addressed. Halfway through the check issues arose that necessitated the termination of the stability check, and eventually a reassessment of the program.

This paper reviews the current status of WAAS system development, procedures development, and a detailed explanation of the new instrument approach procedure charts. The new format for satellite derived instrument approach procedures called RNAV will be provided with an explanation of the various fields and improved human factors. The airport infrastructure necessary to support the WAAS precision approach and the generic WAAS approach will be discussed as it relates to the purpose for two types of WAAS approaches. Each of the four lines of minimums will be discussed to provide background, equipage, signal accuracy requirements, and limitations. The final segment will review the John Hopkins University, GPS Risk Assessment Study issues that relate to potential interference and jamming of the GPS signal, and the projects the FAA has implemented to mitigate interference sources.

INTRODUCTION

Two years ago, I presented a paper that outlined the WAAS configuration, capabilities, service availability, instrument approach procedures, and most importantly scheduled commissioning date. Since that paper was submitted, the commissioning date has been delayed from July 19, 1999 to September 25, 2000, and now indefinitely. The problems that caused the indefinite delay were identified during stability testing of the system. In December 1999, the FAA instructed Raytheon to start the 60-day stability test despite knowledge of existing problems. The intention was to run the operational test and identify any other problems that needed to be addressed in addition to the ones already known. Halfway through the stability check serious problems arose and the check was terminated.

Following termination of the stability check the primary question has been what capability can be provided and when. System reviews have been conducted and recommendations have been received from Raytheon concerning the various courses of action that can be taken. The questions that are being asked center around what WAAS capabilities should the FAA commission and in what sequence should this happen. The biggest question is the technical feasibility of achieving a Category I GNSS Landing System (GLS) ILS look alike approach, and at what cost in terms of time and money. To help answer these and other questions the GPS Program Office has established a team of experts to work closely with the FAA and Raytheon to identify the most cost effective and expedient solution to the WAAS problem. The team called WAAS Integrity Performance Panel (WIPP) includes experts in the satellite navigation field from the FAA, MITRE, Stanford University, Ohio University, and the NASA Jet Propulsion Laboratory. Their goal is to provide WAAS technical strategy for the foreseeable future. The WIPP has identified the solution for en route and nonprecision approach integrity and the path necessary to achieve LNAV/VNAV integrity. The precision GLS integrity monitor solutions have not yet been identified and the current path to the LNAV/VNAV may not be applicable to GLS. The WIPP has been tasked to identify the solution and migration path to precision GLS within nine months. These results will then be used to refine the detailed cost and schedule to determine the future of the program.

The FAA is committed to delivering a precision approach capability. Initially this precision capability will be an LNAV/VNAV approach service in the calendar year 2002 over approximately 80 percent of the continental United States. Future GLS service will be determined based on the WIPP recommendations. There are two options for the delivery and commissioning of the WAAS signal in space. The first option provides for an intermediate delivery of the signal for en route and nonprecision approach capability only. Contractor delivery of the level of service would be in the December 2000 timeframe with commissioning of the system in mid to late 2001. This option would delay LNAV/VNAV by one to three months and cost an additional $8 million dollars. The nonprecision approach option provides marginal approach benefits and limited safety applications such as enhanced ground proximity warning system and airport surface movement enhancements. The second option is to go directly to LNAV/VNAV capability. This would entail a contractor delivery time in late 2001 to early 2002 with commissioning in mid to late 2002. This was discussed at the Satellite Navigation Users Group meeting on March 15, and the recommendation of the group was to proceed directly to the LNAV/VNAV capability as soon as possible.

WAAS PERFORMANCE ISSUES

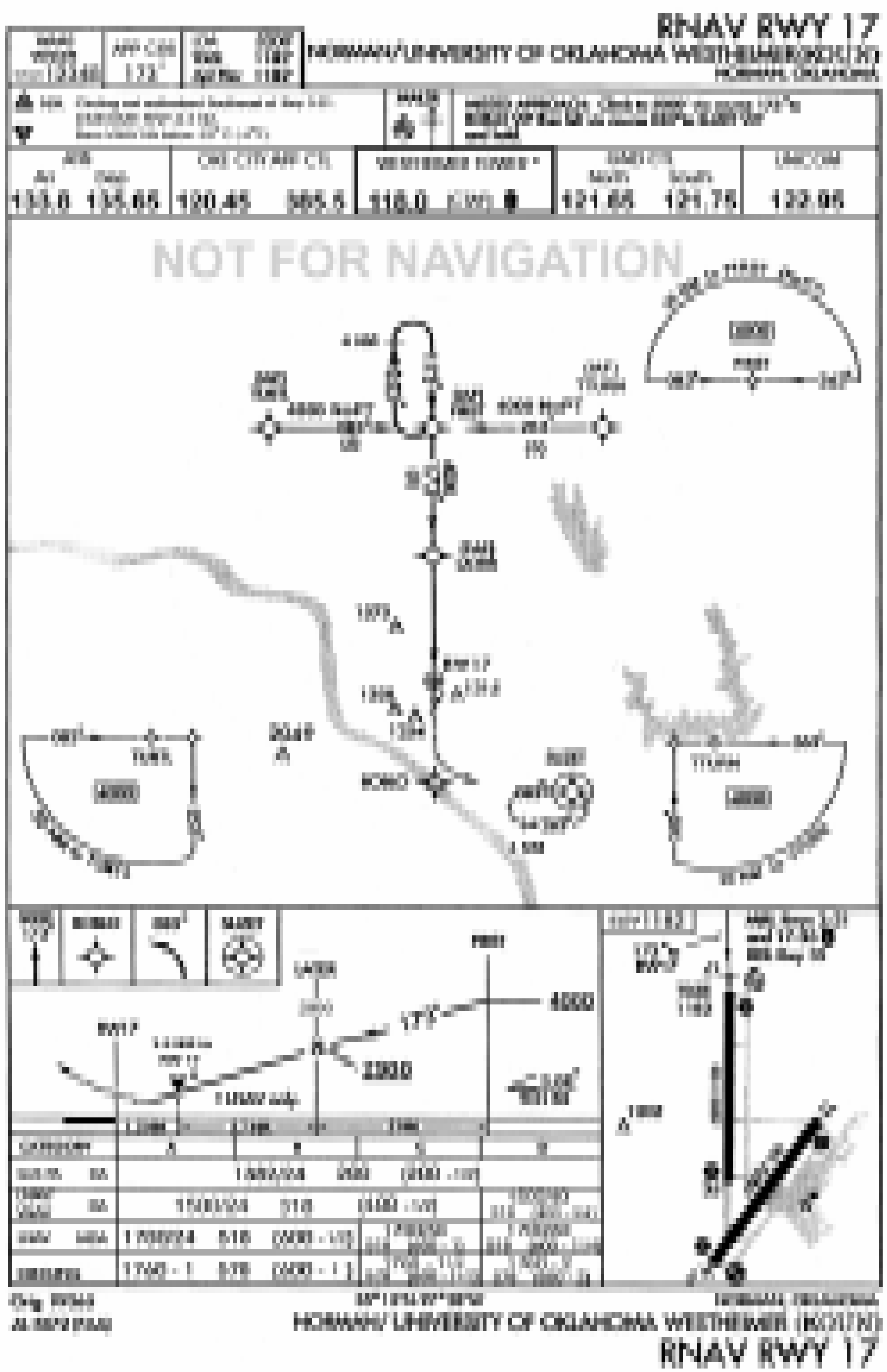
Problems with the WAAS can be divided into two main areas: operational software/hardware issues and integrity issues. Operational software/hardware issues deal with the ground-uplink station errors and problems with frequent alarms due to mulitpath. Multipath causes a false alarm to occur when the signal detects a false satellite signal. This occurs when GPS/WAAS satellite signals reflect off buildings or other objects creating a false signal to be introduced along with the true signal. The integrity issue deals with whether you prove the assumptions made regarding the integrity of the operational system with the existing architecture or with a modified architecture. Integrity is the combination of the probability of broadcasting misleading WAAS or GPS information and the time it takes to alarm the user following such a broadcast so as not to create a flight hazard. The integrity issue has the most serious implications for the certification of WAAS. Horizontal and vertical accuracy was contracted to be 7.6 meters or less. The performance of the system as measured by FAA test flights and flight inspection verification flights appear to be excellent, providing a position accuracy of 2 to 3 meters. To prove system integrity, the WAAS safety processor and computer operating system may need to be held to a higher specification. The current architecture may require a major modification prior to WAAS certification. WAAS as it is currently constructed will not meet expectations and will not be able to deliver precision approach capability at the required availability and integrity. These are the questions the WIPP must deal with.

RNAV APPROACH CHARTS

Basic GPS has been approved as a supplemental means of IFR navigation for domestic en route, terminal operations, and instrument approach procedures. Primary means authorization was granted for U.S. civil operators in oceanic airspace and certain remote areas. There are a number of restrictions to conducting GPS IFR operations. These include requirements such as the receiver must be approved under TSO C-129, the aircraft must be equipped with an alternate means of navigation, alternate procedures for receiver autonomous integrity monitoring (RAIM) warnings, and other basic instrument flight requirements. In addition, with limitations GPS is authorized for use in place of ADF and/or DME for en route and terminal operations. When GPS was initially certified for use in the national airspace system over 3,000 nonprecision approaches were authorized for use as overlay procedures. These overlay procedures were coded into the appropriate databases and renamed as «or GPS» which immediately provided hundreds of approaches that could be flown with a GPS receiver. Development of standalone GPS approach procedures was initiated which took advantage of the unique characteristics of GPS and in some cases lowered minima and provided straight-in approaches that were previously not available. Since 1995, Aviation System Standards (AVN) has developed 2,715 standalone GPS nonprecision approaches, flight inspected 2,485, and published 2,264 approaches. Of the 2,715 developed approaches 1,026 provide new capability to runways that did not previously have a straight-in IFR approach. The chart following the conclusion section shows the yearly production since 1995 through March 1, 2000.

The Interagency Air Cartographic Committee has adopted new criteria for instrument approach procedure charting and depiction. The new GPS approach charts are titled RNAV and provide a new format that groups like information in a more usable arrangement supporting improved human factors for approach data. The RNAV charts display two relatively new concepts. Most new GPS approach procedures are designed using the «T» concept as shown on the next page. The arrival direction of flight determines to which initial approach fix the aircraft proceeds, and eliminates course reversal requirements such as procedure turns and holding patterns. Terminal arrival areas (TAA) provides the pilots and air traffic controller with an easy and efficient transition from the en route to terminal structure. The typical TAA consists of three areas that correspond to the three initial approach fixes (IAF) of the basic «T». These areas are referred to as the straight-in, left base, and right base. The 30 nautical mile boundaries replace feeder routes. When crossing the TAA boundary with an approach clearance or when released by air traffic the pilot is expected to proceed direct to the appropriate IAF waypoint. Minimum altitudes are specified for each area and can be sectorized when necessary to allow for a more controlled descent. TAAs are depicted for each of the IAFs as shown below.

The RNAV charts will provide up to four lines of minimums to avoid duplication and reduce the total number of required charts: GLS PA or GLS; LNAV/VNAV; LNAV; and circling. Each of the approach minimums provide services at different levels of accuracy and augmentation. The approach the pilot selects is based upon the type of equipment in the aircraft and/or the vertical accuracy of the WAAS. The following will describe each minima and reasoning associated with its use.


RNAV RWY 17
NOT FOR NAVIGATION
UNICOM
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RNAV RWY 17

GLS: (Note: A GLS approach will not initially be available when the WAAS system is commissioned. GLS will only be available when the system is certified for a vertical alert limit of 12 meters) A WAAS receiver is required to fly this approach, and is the most precise of the approaches. WAAS may eventually support minimums as low as 200 foot height above touchdown and a $^1/_2$ statute mile visibility (with approach lights). In order to make WAAS precision approaches available to most airports, there will be two levels of service for WAAS precision approaches. The first will be identified as GLS PA. A GLS PA will provide the lowest WAAS minimums available with the PA indicating to pilots that they can expect to see a precision runway environment when they breakout of the weather. To qualify for a GLS PA the airport must comply with all precision requirements contained in AC 150/5300-13, change 6 (in coordination), satisfactory satellite availability, and clear obstruction zones. Most runways do not currently meet the precision runway requirements, but need the added accuracy and safety that WAAS approaches provide. Even though the WAAS receiver may be able to operate in the most capable mode, if the airport does not have the infrastructure required to safely support the lower minima precision approach a PA approach will not be authorized. To support this non-PA type of operation a basic GLS approach will be provided with minimums no lower than 300 foot HAT and $^3/_4$ SM visibility. This approach will be titled «GLS» (note there is not a PA following GLS). Practically all airports will qualify for a GLS approach with minima limitations. At these locations the minima will be adjusted to maintain the required level of safety based on airport infrastructure.

LNAV/VNAV: (Note: This will be the initial level of service that the WAAS system will provide. The vertical alert limit for these approaches is 50 meters.) There are conditions such as poor satellite geometry, atmospheric conditions, or WRS outages that may limit the accuracy of the WAAS receiver. Under these conditions the WAAS receiver may revert to the LNAV/VNAV mode that will provide a vertically guided approach, but not with sufficient accuracy to go to the lowest minima possible. In addition to the WAAS receivers, the TSO C-129 receiver with barometric VNAV may fly this minima. Through special authorization, aircraft with approved IFR RNAV systems may also fly this minima.

LNAV: If vertical guidance is not available, the WAAS receiver can revert to lateral navigation only to fly a nonprecision approach. This approach is identified as LNAV and is identical to the current GPS nonpecision approaches that were published as GPS RWY XX. LNAV approaches can be flown by approved WAAS, TSO C-129, FMS with GPS, and special authorization systems. All of the older GPS approaches will be converted to this LNAV format.

CIRCLING: Like any other type of nonprecision approach circling from an RNAV approach is a visual maneuver initiated by the pilot to align the aircraft with a runway for landing when a straight-in landing from an instrument approach is not possible. Circling minima will only be added to the RNAV charts when approaches cannot be established to both ends of the runway or an operational advantage is available through a circling approach.

AVN has developed the first 50 GLS approaches to support the Operational Test and Evaluation and Operational Readiness Evaluation programs. The WAAS signal was to be available for test flying from October 17, 1999, through January 12, 2000, during the 60 day stability test conducted by Raytheon, but as previously discussed the 60 stability test was terminated. Prior to the commissioning of WAAS as a LNAV/VNAV approach system, AVN will publish the RNAV approaches with the GLS minima line removed from the approach chart. This will provide additional capability for some FMS equipped aircraft and continue to support the TSO-C129 nonprecision receivers. When WAAS certification is complete and provides a precision capability, the GLS minima line will be inserted on the RNAV charts and GLS minimums added.

One of the difficult tasks in supporting the implementation of WAAS procedures into the NAS will be coordinating the geodetic survey requirements and schedule to coincide with the procedure prioritization provided by the regional GPS Implementation Working Groups (IWG). FAA Order 8260.43 establishes the FAA Regional IWGs and the prioritization process they should follow. Current criteria factors include sites having safety benefits, system enhancements, cost benefits, increased capacity, air carrier/commuter support, and requests from State aviation officials. The initial selection of RNAV procedure development locations will require a WAAS availability of at least 80%, RNAV/LNAV availability of at least 95%, and LNAV 100%. Each region IWG provides their WAAS procedure development priority list to AVN and National Flight Data Center for consolidation into a U.S. master list and survey list. This information will be provided to the National Geodetic Survey Office for development of their annual survey schedule. Future changes to the order will include a matrix to score each location in order to determine its priority and greater participation from the state aviation directors, user groups, and airports.

INTERFERENCE

The risks associated with relying on GPS and WAAS as a sole means of navigation and approach capability for the United States National Airspace System have been a major concern. The FAA in co-sponsorship with the Air Transport Association and the Aircraft Owners and Pilots Association selected The Johns Hopkins University Applied Physics Laboratory to conduct an impartial GPS risk assessment study. The objective of the study was to determine if GPS and augmented GPS can achieve the performance necessary to be the only source of navigation provided by the FAA for operations in the NAS. The basic conclusion of the study was that GPS with appropriate WAAS/LAAS configurations can satisfy the required navigation performance as the only navigation service provided by the FAA. It did however point out that interference (unintentional and intentional) poses a significant risk. Unintentional interference was not identified as a major risk factor and will be further mitigated with the addition of a second civil frequency. Intentional interference is the most problematic due to its numerous modes and portability. As a note, the report also recommended that flight inspection measure interference levels at satellite radio-navigation frequencies at airports where GPS approaches are developed and a potential unintentional interference threat may exist.

The Satellite Operational Implementation Team and GPS Program Office are concerned with the threat that interference poses and have established an interference working group to address the problem. Methods to detect, locate, and prosecute anyone who intentionally jams GPS signals must be developed. The FAA Office of Spectrum Policy and Management (ASR) chairs the working group and has overall responsibility for GPS interference issues. It is their policy that reliance on GPS navigation systems requires that the FAA have the ability to quickly detect, localize, and identify interference sources, in order to minimize potential disruptions to the NAS. To support this goal, a three-year interference resolution plan with several separate projects has been established by ASR and funded by the GPS Program Office. These projects provide for the continuing research efforts, frequency planning, receiver specifications, institutional support, and development/deployment of low-cost airborne and ground based systems for detecting and localizing sources of radio frequency interference to the GPS signal.

The first of these projects is designed to study the various interference sources that currently exist. The recognition of the vulnerability of GPS has led several government offices and private companies to develop RFI direction finding technologies. In order to avoid duplication of these efforts, initial evaluation of these technologies and developed systems will be conducted through technical discussions, demonstrations, and field testing. This activity is being conducted by Volpe and the FAA Technical Center. A second project will examine the effects on the performance of two test receivers when potential GPS/WAAS self-interference effects are evaluated along with mobile earth terminals wideband noise and/or other interference sources.

One of the most important projects is establishing an airborne GPS RFI detection and localization system to support initial operational capability of the WAAS. This program has five objectives. The first is to complete research development and testing of the Airborne RFI Localization and Avoidance System II (ARLAS-II), and integrate it on the Technical Center FAA Beech King Air 200 for functional performance testing. A second system call Airborne Interference Monitoring Detection System (AIMDS) will be completed and installed on a flight inspection Beech King Air 300 for functional performance testing. After all testing has been completed the end-state airborne GPS interference detection and location system selected will be installed on the entire flight inspection fleet as time and resources allow. This will be a multi-year project dependent on system cost and available funding.

After an interference source has been reduced to a general geographic area that approximates a half mile radius the search will have to be continued with ground systems that have the capability to further isolate the interference source. Currently there are three projects that are designed to provide the capability to conduct the ground search from the larger airborne identification area to the final location of the interference source. These projects provide different but complimentary capabilities in the location of the interference. The first system is an enhancement of ten interference vans that are available to the regional and center frequency management officers. The interference monitoring vans or RFIM are a transportable RFI detection and location system that use a suite of built-in equipment to detect and locate interference sources at short-to-mid ranges (less than 1 mile to 7 miles). The capability to DF GPS interference will be added through the addition of an appropriate L band antenna and compatible processor. This is a three year project that will modify a portion of the vans each year. The second system is the enhancement of 29 portable direction finding systems or RFID. The RFID is a portable RFI detection and location system that uses a general purpose scanning receiver with conventional antennas designed for the band of interest at mid to short ranges (1 to 5 miles). This also is a three year project that procures and tests the first system this year and modifies the remaining systems over the following two years. The last system is implementation of hand-carried GPS RFI detection and localization systems to identify the final location of GPS interference sources. There are two systems in this project that will provide this capability. The first is referred to as the GPS interference localization system or GILS is a low cost hand-held man-pack device intended for detecting and locating GPS interference sources at short range (less than a mile). Two prototype units have been built and tested and will be refined to provide improved performance and packaging. The second system is an enhancement of existing hand held direction finding system or HIMDS that uses a general purpose scanning receiver and associated antennas for the band of interest at short ranges (less than a mile). The modification will add the appropriate L band antenna and will be completed in fiscal years 01 and 02.

The final project is the implementation of a national test bed for automated GPS RFI detection and localization at fixed locations. There are currently three fixed RFI installations at Chicago, Los Angeles, and Atlantic City. Each fixed platform is comprised of a set of remote sites (3 to 8) interconnected with a base master station. These sets of remote sites use a suite of equipment with conventional antennas designed for the band of interest for detecting and locating interference sources at distances determined by the remote site locations (typically 35 to 70 miles). The fixed locations will be upgraded with L band DF antennas, processors and interconnections for performing the detection and location of GPS interference within the coverage area 24 hours a day. These fixed locations will be linked to the National Operations Control Center (NOCC) in Herndon, Virginia. In FY 01 this system will be established in Atlanta and also connected to the NOCC.

CONCLUSION

The Wide Area Augmentation System has experienced several setbacks over the last two years. This however, does not diminish the potential capabilities that the system will provide in the future. Even with just an LNAV/VNAV capability the large majority of public-use airports in the United States will achieve the lowest minima that they are capable supporting due to a lack of airport infrastructure necessary for a precision runway designation. The adding of vertical guidance to RNAV approaches will support the reduction of controlled flight into terrain safety initiatives. Safety systems such as enhanced ground proximity warning and airport surface movement systems will receive the lateral accuracy necessary to support their operations. Although it is disappointing that we will not be able to commission a Category I capable WAAS in the near future, it should not detract from the immense value that a LNAV/VNAV system will provide to the national airspace of the United States and other nations.

Procedures Publication Chart:

	1995	1996	1997	1998	1999	2000	TOTAL
DEVELOPED*	**310**	**604**	**500**	**531**	**581**	**189**	**2715**
FLIGHT INSPECTED	**135**	**526**	**540**	**528**	**585**	**171**	**2485**
PUBLISHED	**44**	**308**	**585**	**547**	**531**	**249**	**2264**

1,026 of the total developed GPS procedures provide «New Capability» to runways that did not have a straight-in IFR approach.

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GPS SIGNAL QUALITY AND INTERFERENCE MONITORING IN ITALY: EARLY EXPERIENCES AND RESULTS

ABSTRACT

Since its introduction GPS has become a widespread technology for navigation, thanks to the capability to work in those areas outside the navaids coverage, the low cost of equipment, its ease of installation and low power consumption.
Operative experience showed that it suffers from interferences more than it was expected. This led to a general concern and drawn attention on the need to have certain data to evaluate this problem.

Italy has equipped one of its flight inspection aircrafts with a system to monitor GPS signal parameters and to detect interferences. The purpose is to map the country to detect areas that suffer from interferences and possibly to locate and identify the sources. In future this system will be also used to flight inspect GPS procedures.

This paper presents a description of the system installed, the parameters recorded, the methodology used to collect data, the results coming from the analysis of the data so far collected.

INTRODUCTION

ENAV, the Italian Air Traffic Control Agency which is in charge for flight inspection of the Italian navaids, operates three Citation II equipped for flight inspection. These aircrafts are equipped with GPS and DGPS and during the flight inspection missions they reported unexpected losses of GPS signal in many areas of the country. In many cases this was believed to be a consequence of interferences. Hence the necessity of furthers investigations, with respect to the determination of the location and geographic coverage of the interfering sources, amplitude and characteristics of the interfering signals.

ENAV has equipped one of its flight inspection aircrafts with a system to monitor GPS signal parameters and to detect interferences. The purpose is to map the country to detect areas that suffer from interferences and possibly to locate and identify the sources.

The nature and the effects on GPS signal of the interfering sources were not taken in consideration during the first investigation phase covered by this paper. The electromagnetic signal analysis and the interfering source location are part of a future enhancement of the system.

This system will be also used in future to flight inspect GPS procedures.

DESCRIPTION OF THE SYSTEM

The GUARD system consists of two major parts, an aircraft GPS Signal Data Analyser and a ground workstation.
The aircraft GPS Signal Data Analyser collects GPS

data during flight and stores them in a PCMCIA solid-state flash memory card.
The ground workstation reads the data files stored in the memory card, plots them onto a map of Italy, and supply the user with analysis tools to identify and evaluate the presence of interferences.

GPS Signal Data Analyser

The GPS Signal Data Analyser is a stand alone unit, rack-mounted into the aircraft flight inspection console, and it is connected only to a dedicated GPS antenna and to aircraft DC power.
This stand alone unit doesn't need any operator intervention, allowing GPS data collection during everyday flight inspection missions, with no additional workload to the inspector.
The GPS Signal Data Analyser is made of a GPS receiver card, a microprocessor unit, a PCMCIA card interface, a display, a 3 pushbuttons keyboard, and a power supply.
The PCMCIA card is a 44 Mbytes solid state Hard Disk, allowing the storage of up to 35 hours of flight data.
The GPS receiver is a 12 channels unit capable of receiving L1 C/A code and outputting data with 1 Hz sampling rate.
The microprocessor unit is a small computer with I/O interfaces to manage the display, the keyboard, the PCMCIA card and the GPS receiver. Its main task is to format and store the data coming from the GPS receiver to the PCMCIA card. The output data contains one record per satellite received, each second.

Ground Workstation

Hardware

The ground workstation is based on a high end Personal Computer. It is equipped with a 450 MHz Pentium III, a wide 19'' screen allowing the necessary 1024x768 resolution, a PCMCIA slot to read the memory cards where the GPS Signal Data Analyser stores data, a CD recorder for archiving purpose. An 8.5 GBytes SCSI Hard Disk and 128 Mbytes of RAM complete the configuration.

Software

The GUARD software plots the position data collected during flight on a map of Italy, drawing the complete track flown by the aircraft.
The user can choose to plot the track onto a geographical map of the country or onto an aeronautical map. In this case, the user is given the choice of the level of details to display between towns, RWYs, VOR, and NDB.
The map can be zoomed in and out to show the interest area from the whole country down to a 2 by 3.5 NM area.
Using software pushbuttons similar to a video recorder an aircraft symbol can be moved to any point in the track to read the current data associated to that position, while flight playback is possible at any desired speed to observe the parameters evolution with the position. For each point in the track Latitude, Longitude, Height, Ground Speed, Track Angle, PDOP, and Time are presented. A little tag aside the aircraft symbol shows one of VDOP, HDOP, PDOP, Number of satellites in view, Number of satellites used.

The colour of each point plotted can be yellow or red, depending on the type of alarm chosen and the alarm level set by the operator.
The alarm can be triggered by one of the following conditions:

- PDOP greater than a set level,
- Number of satellites lesser than a set number,
- No Fix condition,
- High Interference Probability (HIP) greater than a set level.

All the missions' files are stored on the workstation hard disk, to form a mission database. The database filters allow data retrieval, to find files pertaining to the same geographical area and collected in different times. An interference detected in one area can be monitored to see if it is still present in the following flights.
The embedded database engine can export the data files of each mission to ASCII format to interface with external applications.

Analysis tools

Several analysis tools allow the user to evaluate the quality of the GPS data collected.

The Sky Plot window and Satellite Info window are the main tools. They present, in different graphic formats, the satellites positions and Signal to Noise Ratios for the current aircraft position on the map.

The Sky Plot window shows a polar chart of the satellites in view, with azimuth and elevation respect to the aircraft antenna. The colour of each satellite plotted indicates the signal quality: black for unusable satellites, red for SNR below the 35dB, blue for good signal reception.

The Satellite Info window presents a table with SV ID, Azimuth, Elevation and SNR for each satellite in view. A blue bar graph of the SNR is drawn aside each satellite, with a red colour for a SNR below the 35dB threshold.

Both windows are updated as the aircraft flies along its track, so that the user can monitor the SNR variations during the flight. It is typical to observe a sudden decrease of the SNR values for all the satellites at the same time in those areas affected by interferences.

Other tools include:

- A graph for each satellite where SNR, Azimuth and Elevation are plotted vs. Time. This allows the user to explain SNR decay with the satellite setting below the horizon, or with the presence of a known screening obstacle such as a mountain.

- A bar chart presenting the usability of every satellite in view versus the entire flight time. This allows the user to identify at a glance, for further investigation, the time intervals where many or all the satellites became unusable for the position fix.

- A graph presenting the aircraft Track Angle and the average SNR of all the satellites in view versus flight time. This allows the user to explain a general sudden SNR decay with aircraft manoeuvres shading the GPS antenna.

PARAMETERS RECORDED

The GPS Signal Data Analyser is capable of storing the data received from all the satellites available, with 1 Hz sampling rate.

Mission data are recorded on a separate header file for data retrieval and includes, among the others, date, time start, time stop, location ident.

Every second, for each satellite available a record is composed and written in the flight data file using a compressed format. The fields of each record are: Epoch, Latitude, Longitude, Height (geodetic), Track Angle, Ground Speed, HDOP, VDOP, PDOP, Number of satellites used for position fix, Fix quality, Identification numbers of the satellites used for position fix, Positioning mode, Number of satellites visible, Current satellite ID number, Current satellite Elevation, Current satellite Azimuth, Current satellite SNR.

Usually 7 to 9 satellites are received and the system writes about 30,000 records per hour of flight on the data file, using about 1.2 Mbytes of memory per hour.

METHODOLOGY USED TO COLLECT DATA

The data so far available amounts to 43h 8' 4" of recordings, collected during 28 flights.

For each flight the data collection was started before the take off and stopped after the landing.

As the GPS Signal Data Analyser does not require any user action during the data acquisition, all the data were collected during usual aircraft activities, normal VOR inspections and transfer flights. This allows obtaining GPS signals monitoring at no additional flight cost.

The data collected cover different flight profiles, from very low altitude during take off climbs and approaches, to enroute altitude during transfer flights, while most of the time was spent at the minimum reception altitude of the navaids inspected.

The missions covered most of the Italian territory with latitudes ranging from N 36° 45' to N 45° 50' and longitudes ranging from E 7° 22' to E 13° 28'.

ANALYSIS OF THE DATA SO FAR COLLECTED

Scope of the analysis

In Italy, in normal conditions, seven to nine satellites can be seen from an aircraft flying en route, for most of the flight time. A lack of usable satellites for a good fix can be due to operative conditions or to interferences.

The effect of interferences is decay in the Signal to Noise Ratio, which can make the affected satellites unusable, with consequent poor or definitely wrong position solutions.

Several operative conditions can result in SNR decays or in the loss of one or more satellites. Aircraft manoeuvres with attitude changes can partially hide the sky to the GPS antenna, obstacles such as mountains can hide part of the sky to an aircraft flying at low altitude, while SNR decays can be due to satellites setting on the horizon.

Scope of the analysis is therefore to discriminate explainable SNR decays and poor position solutions that are inherent to the GPS navigation, from unexplainable ones that are to be considered as an indirect sign of the presence of interference, intentional, unintentional or multipath.

Analysis methodology

After the downloading of the data files collected in flight, the first part of the analysis job is to identify those areas that are suspected of being interfered. These areas can be identified at a first glance watching the aircraft track on the map. In high interference areas is very common to observe cross track jumps in the aircraft trajectory, while along track a reasonable flight path is plotted. In these cases, it is easy to see that the few satellites left for position solution are nearly aligned in the direction of flight, giving bad position solutions across track.

A more systematic approach is to set alarm levels for PDOP or for the satellite number and watching the part of the track plotted in red.

Another approach is to watch the SNR of each satellite or the average SNR of all satellites versus flight time. The time intervals where a significative decay is observed can be subsequently correlated to the positions on the map.

The second part of the analysis job is to try to explain SNR decays and satellites losses with operative conditions, using the software analysis tools.

An increase in PDOP could be explained with a temporary configuration of the constellation, which can be predicted using many commercial software tools, or due to the lack of data from some of the satellites in view.

A low number of usable satellites could be explained with a low altitude flight within a valley, or with a steep turn.

A very useful analysis tool is the High Interference Probability alarm. This parameter takes in account for SNR, number of satellites, aircraft manoeuvres, trying to do automatically the analysis job. The user can set the HIP alarm to a greater or lesser level of probability, directly obtaining the interfered parts of the flight plotted in red on the map. However, the user should carefully verify the results, as the human expertise still plays a determining role in the analysis job.

Last part of the analysis job is to correlate the flight data coming from the same area in different times, discriminating temporary interferences from permanent ones. This is a long-term job, which poses some challenge to the actual hardware platform due to the dimensions of the database to process.

The decrease of the average of each satellite S/N ratio was used to evaluate the intensity of each interference.

Usually interferences do not affect all the satellites with the same intensity. Depending on their position in the sky and on the direction of the source, some of the satellites could be not affected by the interference while some others could be heavily affected. Therefore, the decay of the average SNR is a rough indicator of the strength of the interfering source.

The availability of a position solution depends, in each moment, on the geometry of the usable satellites. This depends on the position of each satellite with respect to the aircraft, on the direction of provenance of the interference, on the received interference level, on the signal level received from

each satellite. The received interference level depends on the power irradiated from ground and on the aircraft altitude; the signal level received from each satellite depends on the aircraft altitude and the satellite elevation above the horizon.
Considering all these variables, the study of the interactions between the interfering signal and the satellites is of little interest, because the results obtained would be valid only for that point in space, that altitude, that time. This is the reason for using the decay of the SNR average as an approximate measure of the interference level, because we are considering the detection of the interference sources and their effects on the calculation of position solutions. It is therefore an indirect detection of interferences from their effects. A spectrum analyser would make a direct analysis of the interfering signals possible, but this would be interesting only for a subsequent localisation of the sources.

Results

The data available for analysis were collected during 28 flights, for a total of 43h 8'4" flight time. 27h 23'28" were spent at low altitude, during take offs, landings and flight checks. 15h 44'36"were spent en route during transfer flights.
During the analysis 80 interferences were detected for a total of 4h 52'33", which makes the 11.3% of the total flight time.
The aircraft spent 36.5% of its flight time en route (>6000 ft) detecting 20 interferences, that is 25% of the total number, while it spent 63.5% of its flight time at low altitude (<6000ft) detecting 60 interferences, that is 75% of the total.
This relatively high number of interferences detected, especially at low altitudes, is in part due to the flight profiles required for flight inspection. During the flight checks it is required to pass several times along the same path, thus increasing the number of interferences detected, as the same source is therefore counted more than once.

En Route, 15h 44'36" flight time, 20 interferences detected:

- 18 interferences detected with SNR decay between 3 and 12 dB. In these cases a pilot would not be aware of the interferences. Total time 1h 43'53".
- 2 interferences detected with SNR decay of 21 dB and >45 dB, both with a no fix condition. Total time 3'40".

Low Altitude, 27h 23'28" flight time, 60 interferences detected:

- 20 interferences detected with a SNR decay between 5 e 13 dB. In these cases a pilot would not be aware of the interferences. Total time 1h 19'2".
- 11 interferences detected with a SNR decay between 7 e 17 dB, with a 2D fix or with position jumps due to the receiver switching between different constellation. Total time 1h 14'34".
- 29 interferences detected with a SNR decay between 11 and >45 dB with a no fix condition. Total time 31'24".

As foreseeable the intensity of the interferences is much higher at low altitude. This is because the aircraft is closer to the interfering source and because approach procedures and landing paths are located in the nearby of major towns, where the electromagnetic environment is densely populated by emitting sources.

From the above data we can see that

- Interferences below 6dB did not cause any problem to the navigation;
- Interferences between 7 and 17 dB produced different effects on the position solution, from no effect to no fix;
- Interferences above 17 dB always caused a no fix condition

An important point is that the RF level of the interference cannot be considered as the only cause of a no fix condition. In different situations, medium strength interferences could just raise the PDOP without affecting the navigation capability of the receiver, or they could cause no fix conditions and position jumps, if the affected satellites have a critical position in the constellation in use.
Furthermore, in some cases the GPS Signal Data Analyser considered most of the satellites unusable,

with a resulting no fix condition, even when they were subject to moderate interference levels. It is possible that in those cases the GPS signals were made unusable by the spectral content of the source, rather by the RF level.
This indicates that the RF level is not the only parameter to take in account, but the type of modulation plays a role too in disturbing the GPS signal.

Another result is that we have two different scenarios:
An aircraft flying en route would not have problems navigating with GPS during 97% of the interference time (11.0% of its flight time), while only during the remaining 3% (0.4% of its flight time) it would suffer from a no fix condition.
At low altitude there is a different scenario, where an aircraft would not have problems navigating with GPS during 43% of the interference time (4.8% of its flight time), it would experience a 2D positioning mode during 40% of the interference time (4.5% of its flight time) and it would suffer from a no fix condition during the remaining 17% (1.9% of its flight time).

An interesting result is that the total interference time was the 11.3% of the total flight time and the same percentages were found both for low altitude, where the interference time was the 11.2% of the flight time, and enroute, where the interference time was the 11.4% of the flight time. This means that in both scenarios an aircraft would be exposed to interferences for the same amount of time, but with different effects.

CONCLUSIONS

Flying en route a complete GPS signals disruption is an unusual event (0.4% of flight time) and nearly all the interferences are only able to make the SNR worse for the satellites in view, eventually increasing the PDOP.
At low altitude, during approach procedures and landings, about two thirds of the interferences (4.5% of flight time) can make GPS unsuitable for navigation.
This should be taken in account when implementing GPS procedures and experimental differential GPS landing systems.

FUTURE DEVELOPMENTS

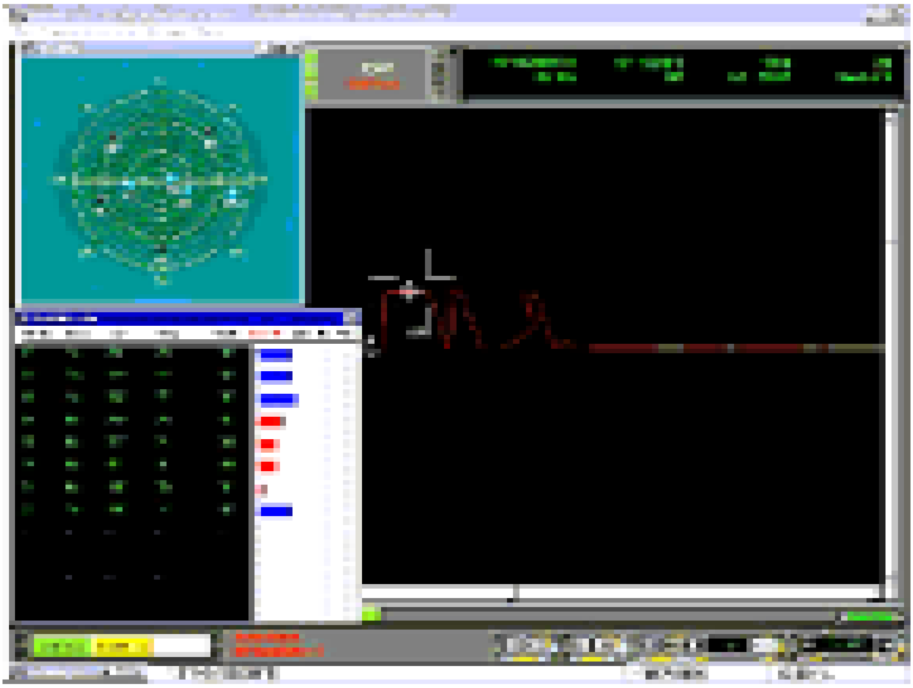
Future developments of the system will include a 3D electronic cartography to correlate interferences with natural obstacles such as mountains that can produce multipath.

During the second half of this year, a spectrum analyser with analysis software will extend the system capabilities to investigate the electromagnetic spectrum of the interfering sources.

In the future the GUARD system will be further developed to inspect EGNOS and Galileo signals.

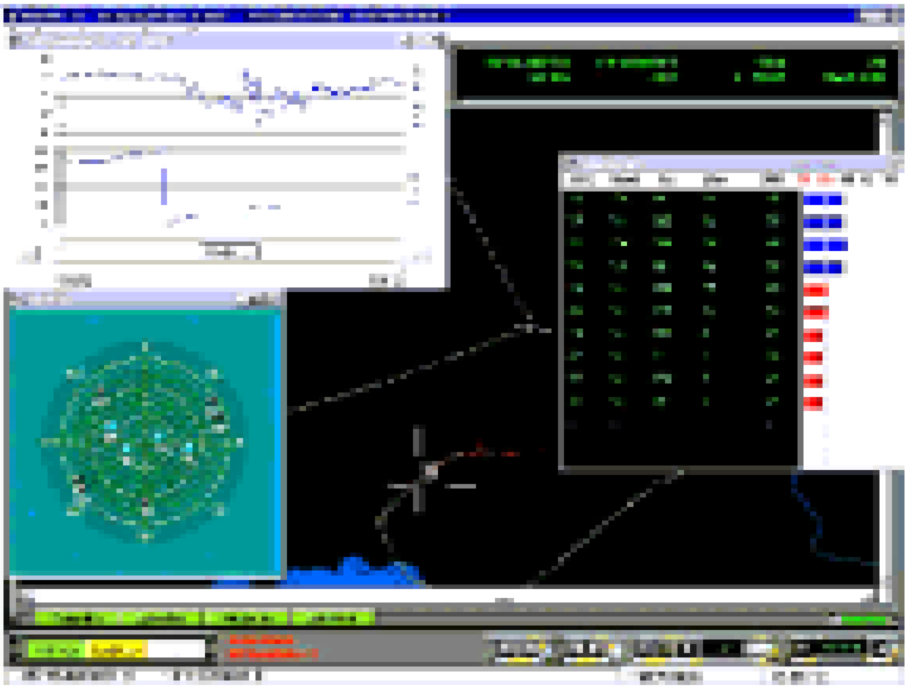
Data file	Total Flight Time	Enroute Flight Time	Low Alt Flight Time	Interfer. detected		Enroute Interf. Time (sec).		Low Altitude Interf. Time (sec).		
				Enroute	Low Alt	OK	no fix	OK	2D	no fix
CATANIA - 1	7446	2459	4987	1	0	133	0	0	0	0
CATANIA - 2	8283	3851	832	1	0	0	160	0	0	0
CATANIA - 3	2390	1920	470	0	0	0	0	0	0	0
LOTTO1 - 1	3914	0	3914	0	7	0	0	20	97	221
LOTTO1 - 2	382	0	382	0	0	0	0	0	0	0
LOTTO1 - 3	10126	2884	7242	1	7	689	0	292	206	158
LOTTO1 - 4	13389	0	13389	0	5	0	0	189	153	0
LOTTO1 - 5	4671	2175	2496	0	1	0	0	114	0	0
LOTTO2 - 1	4754	3813	941	1	0	716	0	0	0	0
LOTTO2 - 2	2912	1491	1421	1	0	232	0	0	0	0
MILANO - 1	11211	6506	4705	1	4	222	0	134	0	224
MILANO - 2	4575	3955	620	2	0	216	0	0	0	0
MILANO - 3	0	0	0	0	0	0	0	0	0	0
MILANO - 4	2611	1806	805	0	0	0	0	0	0	0
napoli - 1	4033	0	4033	0	6	0	0	0	1900	713
napoli - 2	2179	1152	1027	0	1	0	0	351	0	7
napoli - 3	2773	1682	1091	1	1	685	0	0	8	0
NAPOLI - 1	21	0	21	0	0	0	0	0	0	0
NAPOLI - 2	2753	1703	1050	3	1	553	0	0	115	52
NAPOLI - 3	13906	1662	12244	1	11	1080	60	2002	1773	213
NAPOLI - 4	2611	0	2611	0	2	0	0	714	0	36
NAPOLI - 5	6776	1465	5311	1	2	410	0	147	0	0
OLBIA - 1	4109	2774	1335	1	1	168	0	90	0	0
OLBIA - 2	1344	0	1344	0	0	0	0	0	0	0
OLBIA - 3	5894	0	5894	0	0	0	0	0	0	0
OLBIA - 4	4157	3514	643	1	0	110	0	0	0	0
Venezia - 1	5255	0	5255	0	2	0	0	0	94	179
Venezia - 2	10616	6706	3910	1	5	358	0	315	77	56
Venezia - 3	12552	2956	9596	2	4	340	0	374	51	25
Venezia - 4	3241	2202	1039	1	0	321	0	0	0	0
TOTALS	**158884**	**56676**	**98608**	**20**	**60**	**6233**	**220**	**4742**	**4474**	**1884**

TABLE 1 - Summary of flight data



Picture N.1 - Position jumps due to constellation switching

Picture N.2 - Interferences in correspondence



Picture N.3 - Satellites unusable in spite of a reasonable SNR

Picture N.4 - The effect of a steep turn