Monitoring a NAVAID'S True Signal-In-Space

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ABSTRACT

Today, flight inspection relies on typical navigation receivers modified to deliver a few more parameters of a particular NAVAID's received Signal-In-Space (SIS). Although the signal information obtained in this manner can be influenced or even falsified by the receiver's Radio Frequency (RF) behaviour, flight inspection results are based exclusively on such single sources, neglecting unknown RF characteristics.

For example, the AGC voltage is only well suited to give a relative indication of the received signal strength in case of undisturbed reception. However, interference in the same or an adjacent frequency channel could significantly falsify this voltage and therefore suggest an insufficient field strength, possibly leading to unnecessary additional flight inspection and maintenance actions, while remaining unaware of the true cause of the problem.

A complementary, more sophisticated approach is to evaluate the SIS directly at the antenna's output both in time and frequency domain. This new system called "Signal-In-Space Monitoring System" (SISMOS) is currently under development. Its main component is a downconverter with well-known large-signal characteristics, a widely selectable bandwidth and attenuation to generate a defined IF signal that can then be sampled for analysis completely independent from specific avionics receiver implementations. This allows a much better assessment of the true service quality of a NAVAID.

With the use of DME as a back-up or baseline RNAV sensor and in view of additional GNSS services to be offered in the DME band, optimizing the navigation service provided by DME system-wide becomes increasingly important. Consequently, the DME application was chosen to be the first functionality to be implemented with SISMOS. This paper shows some results from ground and airborne tests with SISMOS/DME and demonstrates the benefits of such a system.

INTRODUCTION

Current Flight Inspection mostly uses slightly modified standard aviation DME devices. Their major measured quantities to be fed into a Flight Inspecton System (FIS) are:

- distance
- peak level
- pulse rate

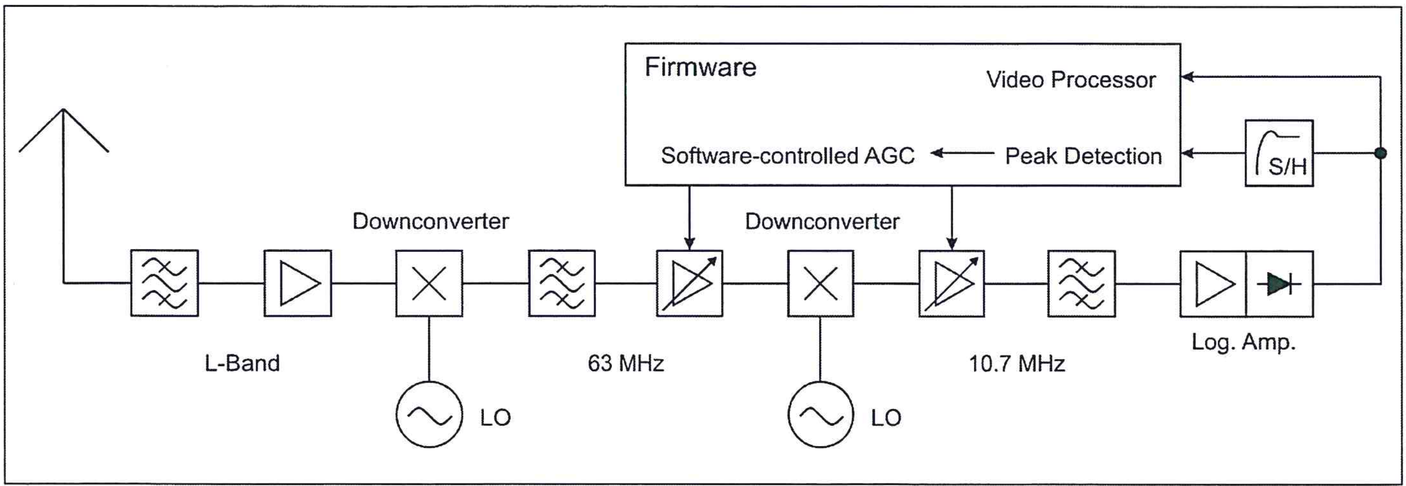

Figure 1: Typical DME aircraft receiver

Figure 1 gives an overview of the superheterodyne architecture of such a typical DME aviation receiver, which is not state-of-the-art but still in widespread use [1].

The DME signal in the L-band (962 to 1213MHz) is pre-filtered, amplified and mixed down to an intermediate frequency (IF) of typically 63MHz (corresponding to the up/downlink channel spacing) to a single local oscillator (LO) for both interrogation and reception purposes. Further amplification and mixing provides a second IF of e.g. 10.7MHz to allow using steep crystal filters originally designed for VHF radios. Most of the input power range (typically from -90 to -20dBm) is compensated by an Automatic Gain Control (AGC), while a logarithmic amplifier captures the remaining dynamics (typically an additional 30dB) and its detector provides the baseband video.

The video processor attempts to extract valid DME pulse pairs that are suitable for ranging from the steady stream of pulses present at the detector's output. The shape of the two pulses are checked in their 50 percent amplitude (-6 dB) points to determine whether a valid distance measurement can be made. This works best if gaussian-like pulses occur as defined in ICAO Annex 10 [2, section *3.5.1, figure 3-1*].

As proved in some measurements below, this method is susceptible to multipath effects. Furthermore, the software-implemented AGC adapts to detected DME pulses only but neglects various effects in connection with radio field anomalies like multipath propagation and spurious emissions.

To reveal all those radio field-related aspect it's absolutely necessary to visualize in how DME pulses are deformed. This results in a design of a new receiver/detector which has to be experimentally tested. However, the purpose of SISMOS/DME is not to replace a standard aviation receiver as a major flight inspection system (FIS) component for NAVAID checking but to supplement flight inspection if severe radio field anomalies appear.

RECEPTION AND DETECTION OF DME PULSES

The DME as a pulsed-based system consequently radiates a non-CW signal. Carrying out a transformation to the frequency domain is not applicable because of the only 5μs lasting pulses which would lead to an insufficient frequency resolution. This implicates that all further investigations regarding the DME signal structure are confined to the time domain.

A simplified block diagram in figure 2 depicts the main components to record DME pulses in the time domain without any gain control: An adequate L-band filtering and pre-amplifying precedes a down converter whose IF result is filtered again and fed into a LogAmp. Like in figure 1, the LogAmp contains an implicit rectification that provides directly the baseband at its output.

The use of low noise amplifiers and DME pulse-adapted IF filters (400kHz) results in an input volume range from -90dBm to -30dBm. This covers all expected levels received either on ground or airborne. The major advantage over an AGC receiver as described above is that the output voltage instantaneously delivers the true baseband of the signal coming directly from the antenna including transient effects.

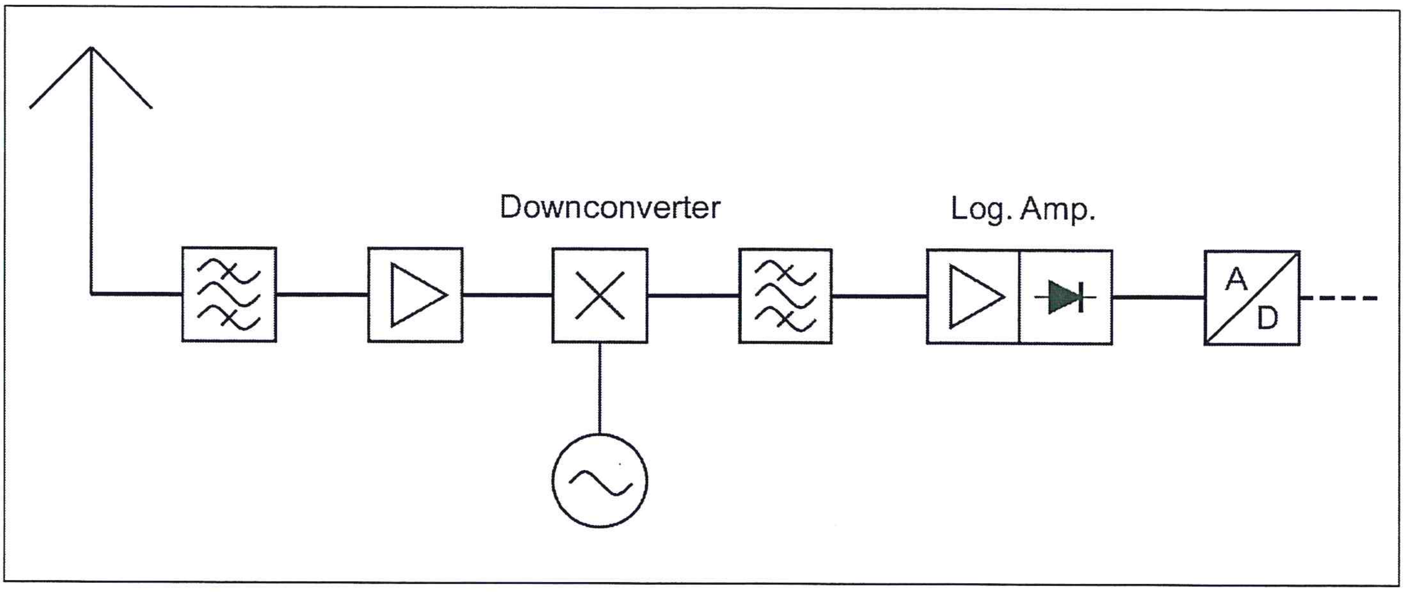

Figure 2: DME Receiver without AGC

In order to assess multipath propagation, a reflection's amplitude as well as its relative frequency need to be evaluated. Just recording the steady stream of baseband sampled data would result in a large amount of data (several MByte / s) which mostly consists of redundant noise that cannot be handled in real-time.

However, for each single pulse and its reflected portions to be considered a special mechanism is necessary. This is implemented by calculating the correlation between sampled data and a model pattern. Figure3 demonstrates this process:

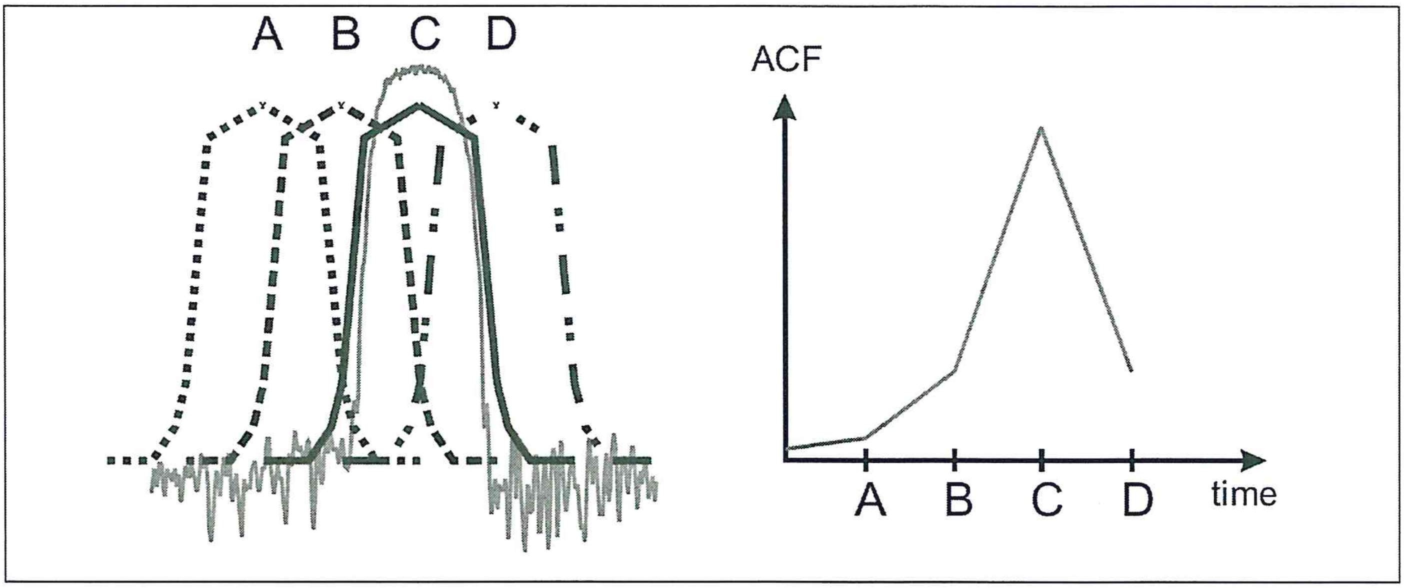

Figure 3: Autocorrelation of a single DME pulse

The pattern is continously shifted over the incoming baseband video stream (left figure) and, for illustration, captured at four different moments A, B, C, D. This results in an autocorrelation function (ACF, right figure), which delivers a steep maximum at moment C, indicating a detection and triggering a time stamp. Succeeding weak reflections would cause a smaller maximum but can still be discovered if the recognition threshold is well chosen. Applying the ACF function provides a sharp maximum that allows to trigger the capture mechanism more precisely than just regarding the pulse video itself.

Hence, the system acts as a real-time correlation pulse processor and yields the following values:

- 5µs of video data to visualize distorted pulse shapes
- time stamp
- pulse peak level

These are collected and transferred via a TCP/IP network to a computer which saves all the data.

A typical result of an undistorted DME Mode-X pulse pair's correlation is shown in figure 4. The continuous baseband video (left figure) displays a DME mode-X pulse pair with a spacing period of 12µs. The ACF processor then saves both pulses and 5µs of each shape (right) with a reduced bandwidth of 400kHz.

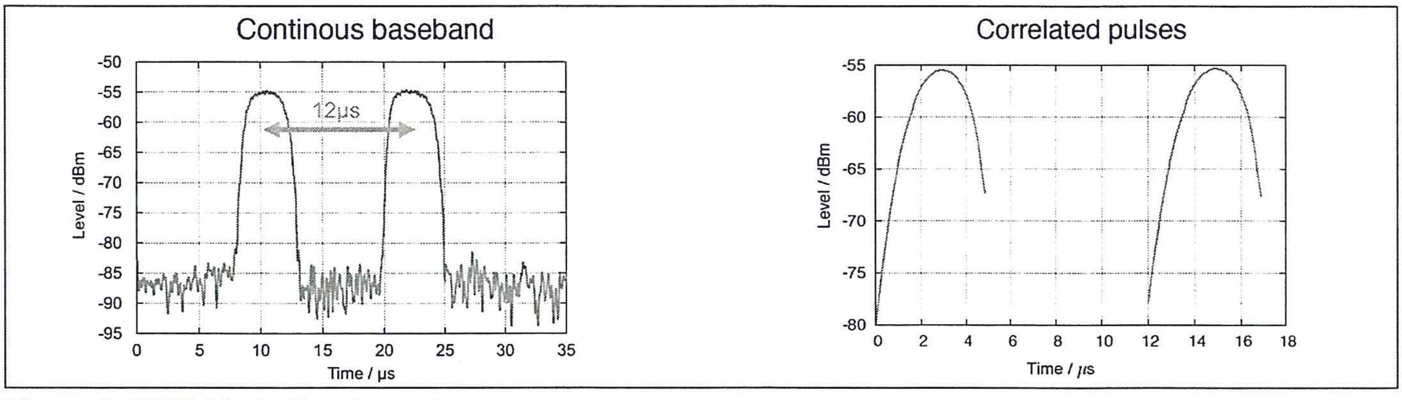

Figure 4: DME Mode X pulse pair

GROUND VERIFICATION MEASUREMENTS

The first field tests with SISMOS/DME were carried out at the Institute of Traffic Engineering (Technical University of Braunschweig) close to Braunschweig airport. This site is located within the coverage of DME Hehlingen (HLZ) so it is likely to receive strong aircraft interrogations on the associated channel 120X (1144 MHz).

Figure 5 shows DME interrogation pulse pairs with their relative levels as received from different aircraft. Pulse pairs with similar power levels appearing in close proximity can be assigned to one DME interrogator as pointed out in the diagram. The horizontal axis is not continous in time because of the statistical occurrence of interrogations. Depending on the time of day about 50 to 200 interrogation pulse pairs per second and additional reflections were detected on the site.

In close vicinity to the receiving site there are buildings which exceed the height of the L-band antenna used for SISMOS. Some of them even have aluminum front sections so it is probable that strong signal reflections reach the antenna. As expected, some distorted pulse pairs are shown in figure6. In the upper diagrams, interrogaton pulses being received by aircraft were affected by reflections from a long distance. The spacing between the peak values in picture (1) is about 5µs which results in a propagation path delay of 1500m while picture (2) reveals multiple reflections. The diagrams below contain additional reflections reaching the antenna via short propagation delays. They result from the buildings right next to the site and induce strong distortions. In (4), the reflection is actually much stronger than the direct signal.

While the reflections and distortions of interrogations received in this verification test do not correspond to a real scenario of a DME ground station, it does illustrate the utility of SISMOS for site performance verification - if SISMOS is connected to the DME ground antenna with a splitter, it can be used to look at the ground signal environment in order to identify possible false transponder replies triggered by reflections.

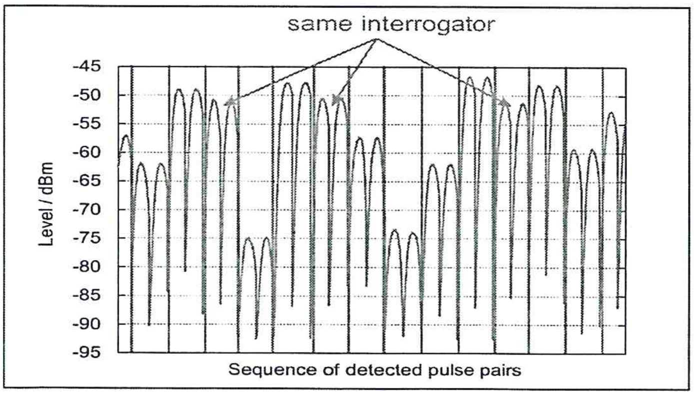

Figure 5: Aircraft interrogations to DME Hehlingen (HLZ)

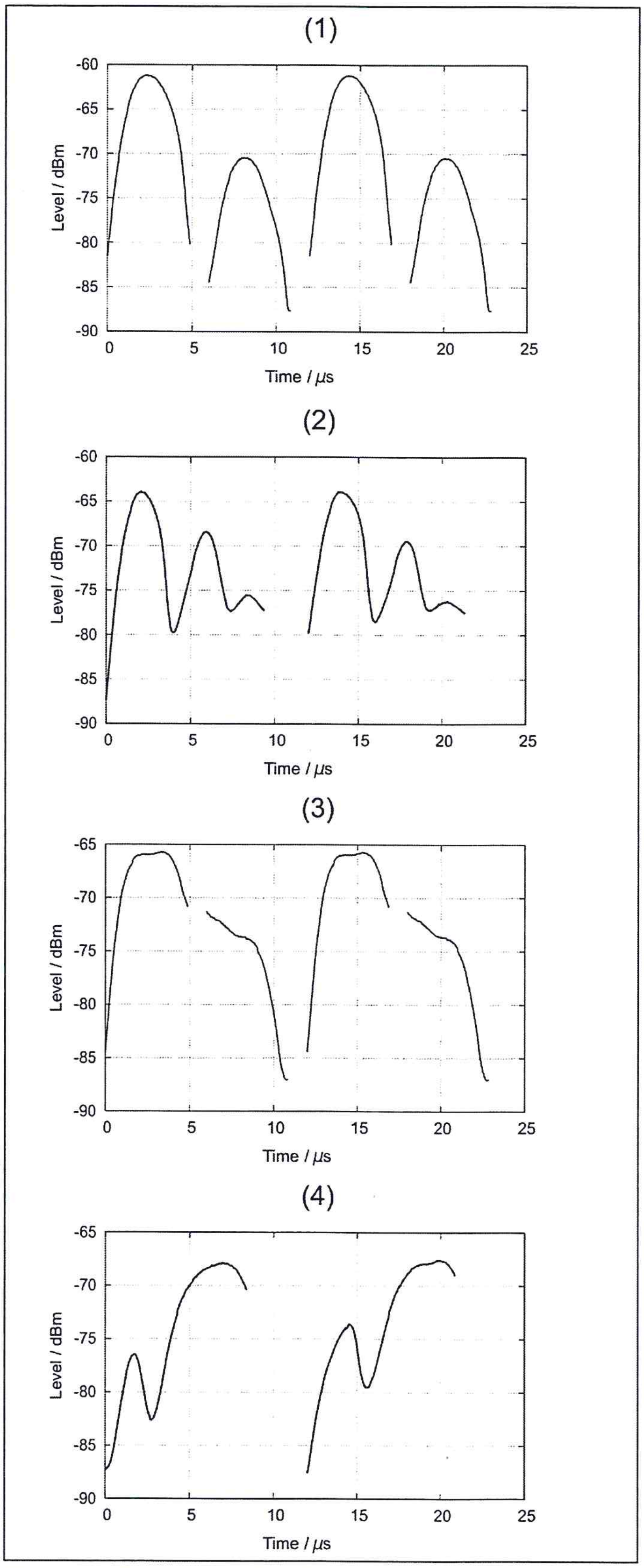

Figure 6: Deformed DME pulse pairs received on ground

IN-FLIGHT VERIFICATION MEASUREMENTS

On March 04 2004, a first flight test with SISMOS/DME was performed. The receiver was connected to a TACAN antenna at the bottom of D-CFMB (Beech KingAir350). In addition to DME pulses the computer also recorded the real time-synchronized flight path data from the FIS with an update rate of 10Hz. Two excerpts from measurements taken during flights around the en-route beacon Leine (DLE) will be presented. Its replies are radiated on channel 99X (1186 MHz). In Germany, most DME transponders operate at a transmission rate of 800 pulse pairs per second, and so does DLE.

Radial to DLE

The path of a radial flown at 6000ft inbound to DLE is illustrated in figure 7 in WGS84 coordinates. The four diagrams in figure 8 show 1s snapshots of the received power levels at various points on the radial. The times given in the titles correspond to the elapsed time labels of the map: Flying at at large distance (1) shows a nearly smooth curve at constant levels. While approaching closer than 6NM, increasing effects of ground reflections occur (2) which result in a 5dB .. 10dB amplitude modulated (AM) fading due to the aircraft's motion.

At a range of 2NM or less to DLE, strong reflections are detected (3) which cause valid pulse correlation results above the ACF threshold (compare: figure 6). Therefore, the amount of reflections increases the total number of pulses. Regarding the last example (4), the number of counted pulse pairs per second rises up from nominal 800 to 1200 (+50%). This represents the real radio load that the receiver is exposed to.

Vicinity of DLE

Coming from another direction and crossing DLE at the same altitude (6000ft) as shown in figure9 some different effects appear.

From an aircraft antenna's point of view the interferences due to multipath propagation induce an artificial amplitude modulation. Its frequency depends on the ground speed and the aircraft's distance and angle towards a reflector.

At a radial distance of 4NM and speed of 75kts this AM is displayed in figure 10 (1). This is a good example to show in how propagation effects could potentially interact with a NAVAID's nominal modulation: Imagine Leine DME being a TACAN beacon providing bearing information (realized by two superimposed modulation frequencies 15Hz and 135Hz with a depth of 20% (approx. 2dB) [5]). The diagram reveals an artificial AM of 5dB (60%) near 15Hz which would superimpose over the TACAN's nominal AM and falsify the bearing. Future flight tests of real TACAN transponders could reveal critical areas during approach.
As the following two subfigures show, different AM frequencies and modulations depths are tuned which all result from the aircraft's motion. In example (2) a higher frequency AM of about 40Hz / < 5dB is encountered. Flying in close vincinity to the beacon (1NM) much stronger fading is detected (3). In this case the modulation depth even reaches 100% at a low fading frequency of 2Hz. High frequency fading could lead to a DME receiver's loss of lock because its AGC cannot adapt to the signal dynamics quick enough.

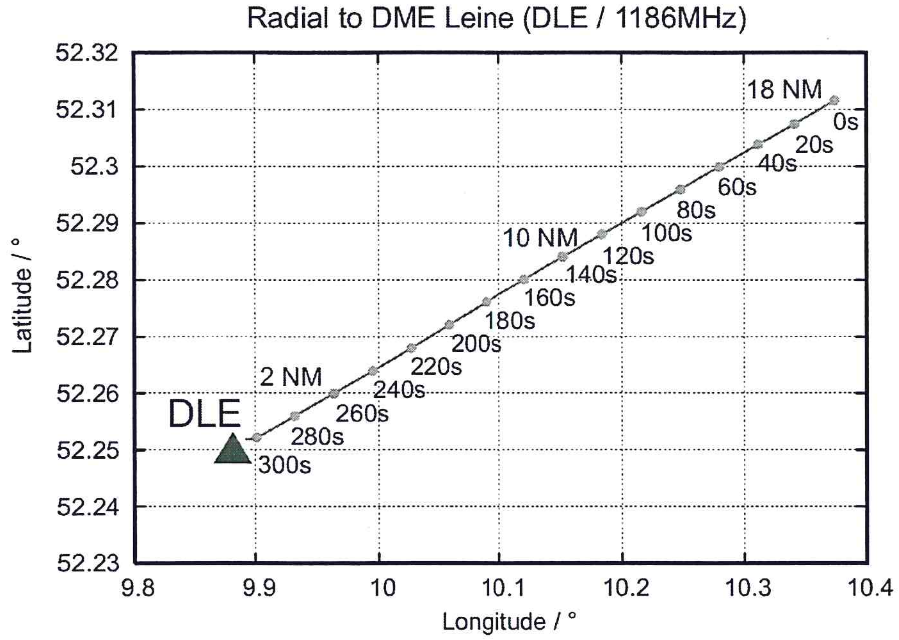

Figure 7: Radial flight path and moments of measurements

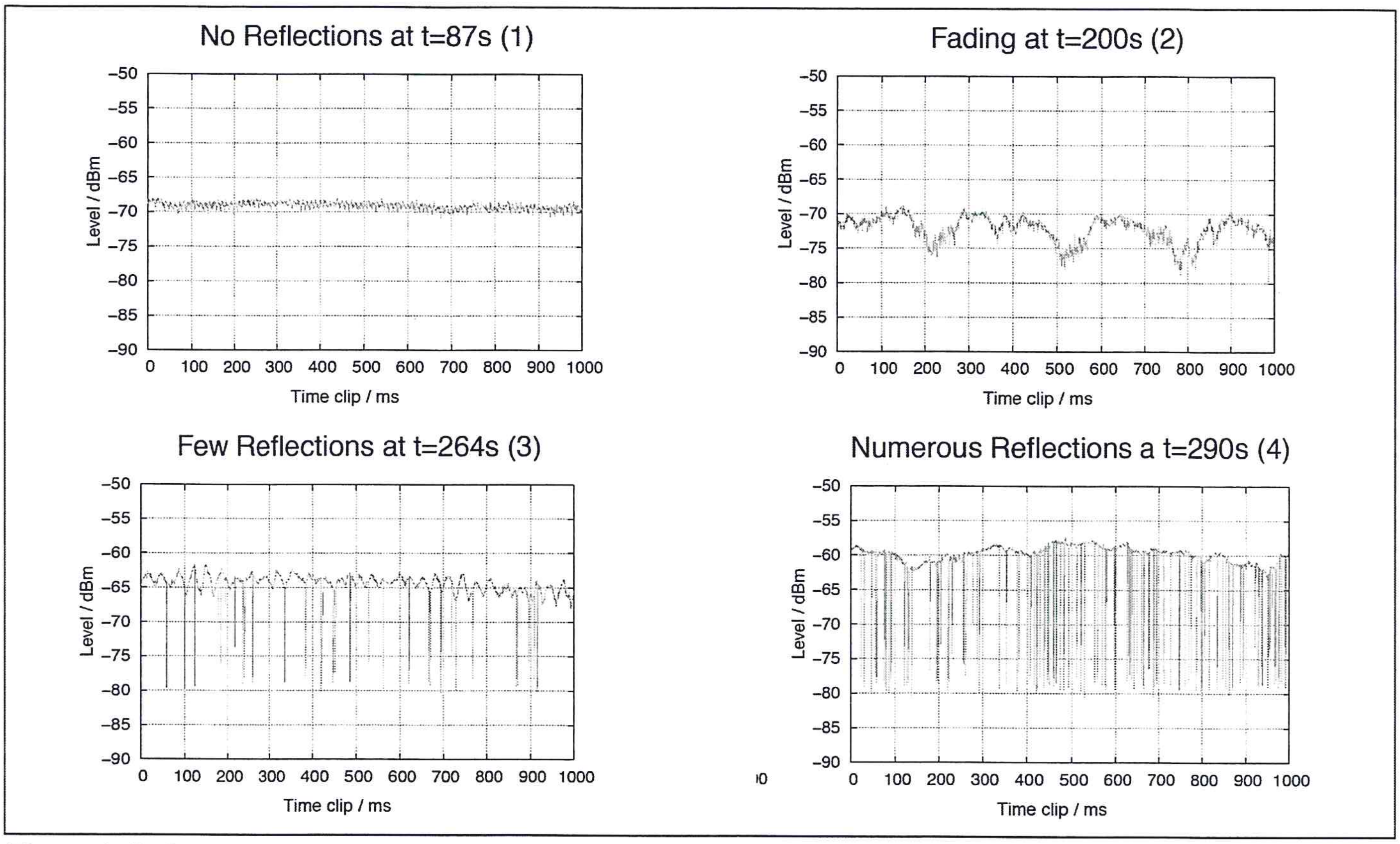

Figure 8: Pulse levels within periods of different sections

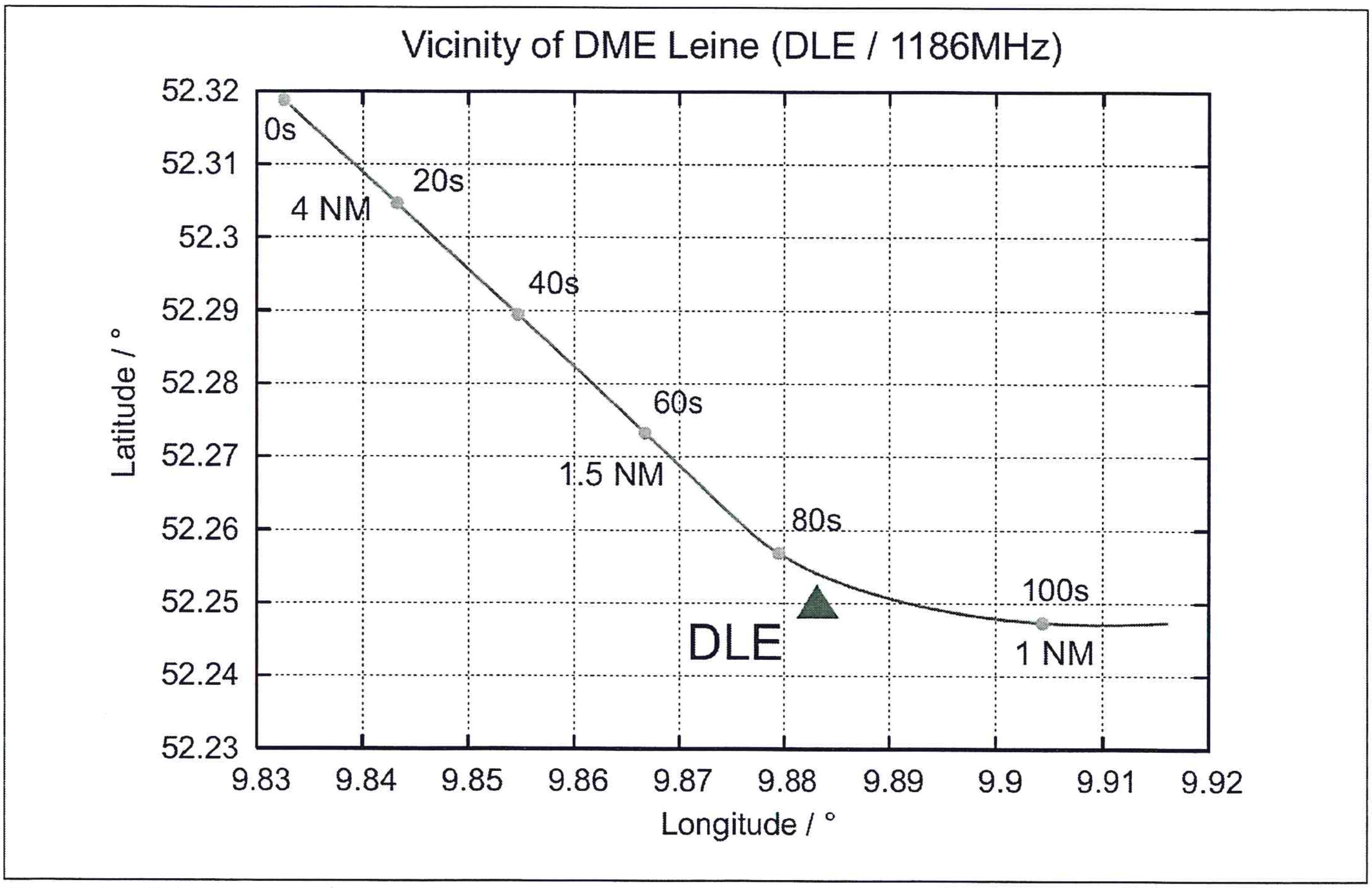

Figure 9: Flight path near by DLE

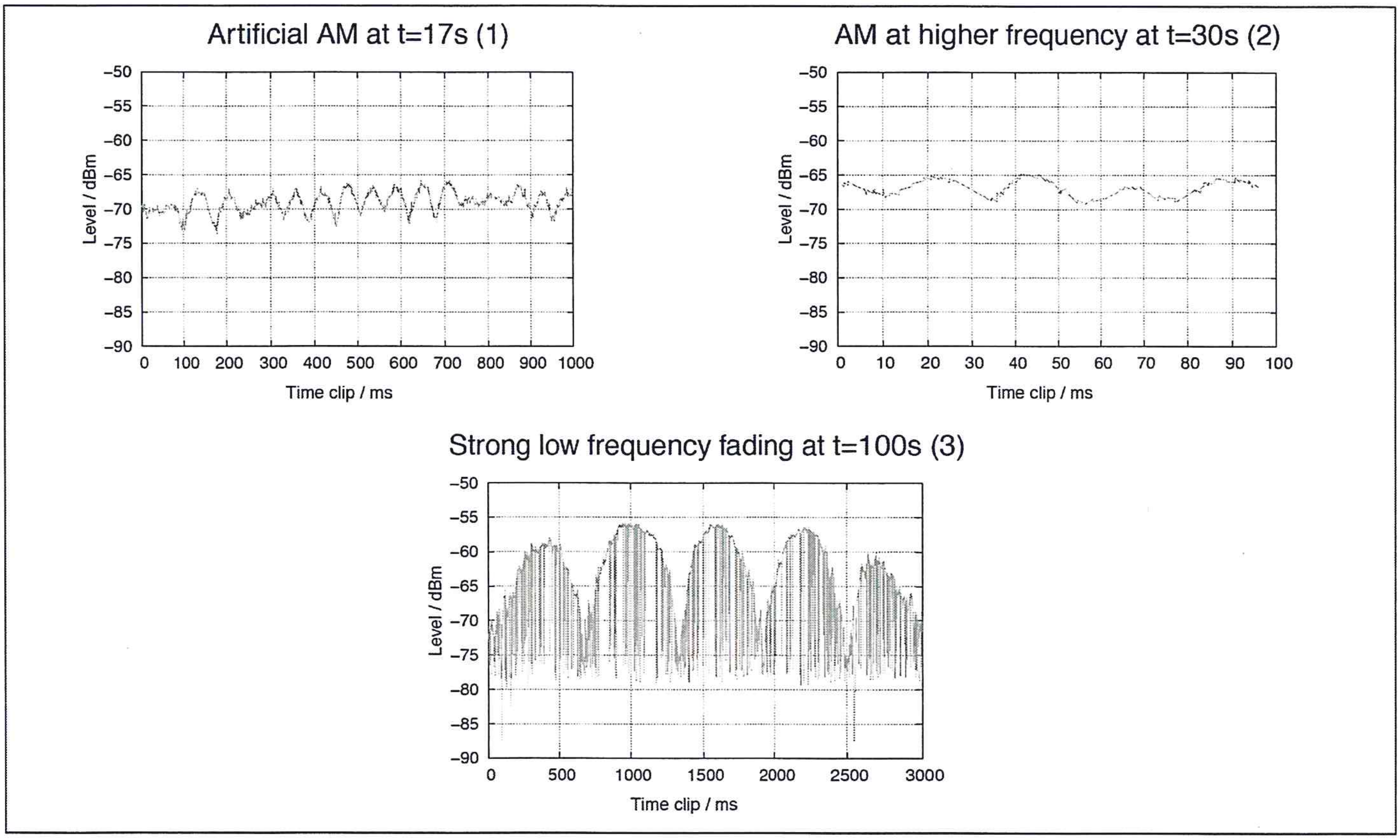

Figure 10: AM effects in the vicinity of DLE

Evaluation of pulses and reflections

By zooming into the baseband video of single pulse pairs we get some pictures similar to those in figure11. These are all taken at radial distances of 6NM or less to the beacon and represent the typical impact of multipath propagation effects encountered by the airborne receiver: Multipath propagations reaching the antenna over short and long detours interfere with the direct signal. The subfigures are sorted by increasing level of reflection and show that the reflected pulse amplitudes may be higher than the direct pulses. In contrast to diagrams (2) and (4), where the pulses from the line-of-sight remain intact, they look quite distorted in diagrams (1) and (3). Their rising edges and peaks cannot be precisely determined by a DME device causing an additional range error: The pulse maximum in (3) is shifted to the right about 1µs which reaches the required accuracy (150m) as stated in ICAO Annex 10 [2, *section 3.5.4.5*].

In order to record as many DME beacon pulses as possible, the aircraft DME device was switched off during that test flight. However, SISMOS and DME can work in parallel but SISMOS reception is blanked out during aircraft L-band emissions as of SSR transponder and DME interrogator.

Usually, the vertical radiation pattern of a standard DME antenna has significant attenuation at high elevation angles. In other words, approaching and overflying a DME ground transponder does not increase the received field strength as much as in the case of an isotropic radiation pattern. Consequently, the reflected portion of a DME pulse pair can be received stronger than the direct line-of-sight signal (4).

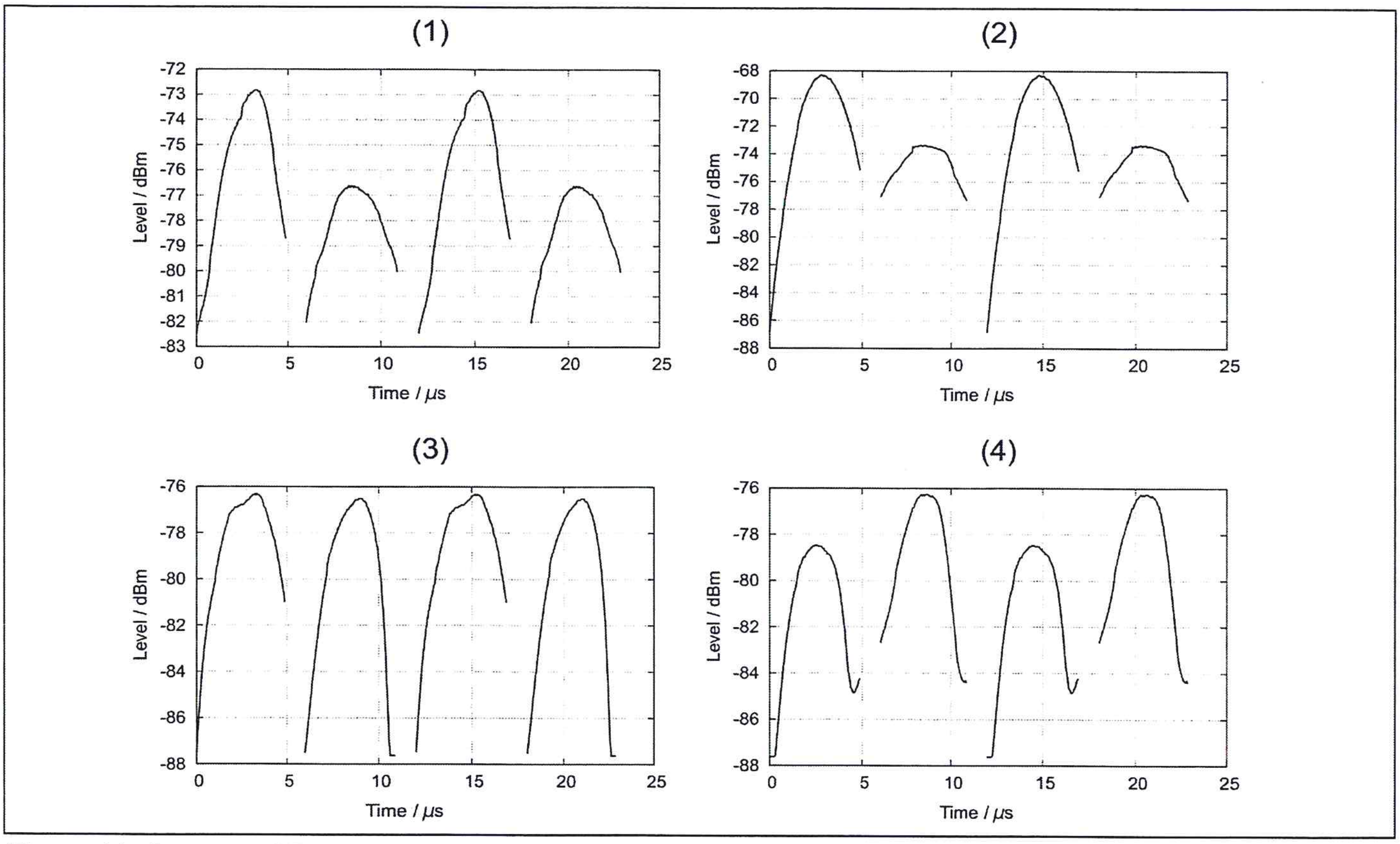

Figure 11: Corrupted DME pulse pairs

THE IMPACT OF DME ON GPS L5 AND GALILEO E5

Various studies have highlighted the potential interference problem from DME on new GNSS signals now allocated to that band. While the existing DME navigation service has spectral priority over new GNSS signals, the significant benefits of these new signals (two frequency bands with aviation safety of life status, making GNSS signals significantly more robust) warrant a closer look at what can be done to make these two services compatible. This has been recognized by ICAO in the report of the 11th Air Navigation Conference last fall, recommending to states to minimize potential interference to GNSS in the deployment of new DME's (Working Paper 121, ICAO ANC/11 [4]).

Initial studies (The draft paper by Benoit Roturier [6]) have identified two problem "hot spots" over the U.S. and Europe, where the combined load of received DME pulses above 40'000 feet (FL400) reaches levels that could be critical to a Galileo E5 and GPS L5 receiver. This analysis is carried out by EUROCAE Working Group 62 on Galileo and RTCA Special Committee 159 WG6, GPS-Interference. Recent meetings carefully suggest that – depending on nuances of the analysis, GNSS receiver technology and the treatment of the aviation safety margin – interference free dual frequency GNSS operation is possible even at high altitudes. However, all of these results are based on significant modeling and theoretical analysis. While the spectral load of DME propagations is just one variable in that significant work, the DME function of SISMOS could be used to validate those assumptions. This could be prudent because while the analysis uses a worst case scenario in many other aspects, it neglects the possibility of significant levels of pulse reflections demonstrated above.

CONCLUSIONS AND FURTHER WORK

A system capable of receiving and detecting DME pulses was introduced in this paper. It can be installed either on ground or airborne platforms in order to analyze the effective DME channel performance, including reflections and distortions on the basis of the time domain pulse shapes. Ground and in-flight verification testing has demonstrated that significant distortions and reflections do typically occur, including some with a desired to undesired ratio less than one.

Currently, the experimental SISMOS/DME is mounted in a 19-inch, 2U form factor light weight chassis which can be installed airborne.

It is envisioned that SISMOS will be able to serve all NAVAID and GNSS applications. The basic goal is to have an advanced time and frequency domain analysis capability that is as close as possible to the SIS. The implementation of the DME functionalities demonstrates that this is achievable. However, one key element that stands between SISMOS and the real SIS is the antenna, which is necessary by the very nature of the problem. In order to obtain accurate SIS measurements with SISMOS, the antenna which it is connected to needs to be precisely understood. In particular in the area of field strength assessment, it is desirable to know exactly how much loss is introduced by the antenna. Modeling conducted by [7] on VHF antennas suggests that significant nulls can occur in many azimuths at shallow elevation angles up or down from the horizontal plane of the aircraft. Antenna gain patterns of flight inspection aircraft are typically calibrated only in the horizontal plane, while actual measurements usually involve a slant range. Since NAVAID link budgets typically include generous allocations to aircraft implementation losses including installed antenna performance, it is feasible to ease the ANSP burden of minimum field strength provision by removing the conservative measurement inaccuracies resulting from an insufficient knowledge of the 3D gain pattern of an installed antenna. However, this should only be considered if all channel effects including fading are well understood.

Consequently, the DME and other antennas will be measured in a TEM-cell in order to obtain their uninstalled gain performance. To complete those investigations the antenna installed performance mounted on the aircraft will be numerically computed with appropriate methods. This is a prerequisite for implementing real field strength and coverage measurements as stated in ICAO DOC 8071 [3] to higher accuracies than currently achievable. In the ground application, with SISMOS/DME connected to the antenna path of a DME beacon, it could serve to find alternative DME sites with less reflectivity or possibly identify and remove significant sources of reflection and distortion in the proximity of the installation.

The airborne application of SISMOS/DME includes an advanced capability to assess the DME service quality, while other measurements serving the purposes of spectrum planning and optimization are also possible. The most notable example of the latter is the possibility to measure the radio field load to assess compatibility with the planned new GNSS services.

Further work will expand SISMOS functions to other NAVAIDS, where despite the fact that the frequency domain is more relevant, the basic challenges associated with frequency channel performance assessment are similar. One expansion which could also be implemented for the DME airborne function is the combination of the SISMOS data with 3D high-resolution terrain data. Given that the flight inspection aircraft provides a precise trajectory, larger sources or areas of multipath propagation could be identified.

Given the increased complexities of navigation services in the developing environment of today, advanced analysis capabilities such as SISMOS will be needed to complement today's flight inspection systems in order to continue to guarantee safe and efficient navigation for aviation.

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