Importance of Time Synchronization and Signal Filtering in Automated Flight Inspection Systems

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ABSTRACT

By the introduction of automated flight inspection systems and computerized data management systems, the efficiency of flight inspection missions has increased in terms of the number of calculating operations which can be performed in parallel. The automated flight inspection systems have contributed to more cost-efficient operations for the operator organizations, as well as a better working environment for the flight inspectors.

Over years, lots of efforts have been invested by FAA, ICAO and national authorities in defining unified procedures and tolerances on how to perform flight inspection. However, when it comes to how flight inspection systems shall be designed to process inputs and provide trustworthy outputs, there are no specific rules or regulations on a corresponding level. This leaves the manufacturer of the flight inspection systems with the sole responsibility to ensure that the data coming out from their systems is correct.

With a flight inspection system incapable of handling time-synchronization of streaming data, including delays and distortions that will always affect a signal stream during the processing, results cannot be guaranteed to be correct. It is therefore a critical aspect of any automated flight inspection system that for all signals being processed by the system, these factors must be known, controlled and corrected for.
Also, to consider is the individual characteristics of avionic sensors and subsystems being used to provide input data to the automated flight inspection system. These are ranging from traditional analogue to new generation digital electronic units with a great variation of physical interfaces and internal processors, in turn resulting in varying characteristics of signals entering the flight inspection system. This means that a fully automated flight inspection system must be able not only to read signals straight from standard avionic sensors, but it must also have the capability to apply algorithms as required to extract correct signal properties.

INTRODUCTION

A general and basic property of a measurement system is to know WHAT it is supposed to measure, and design the system in accordance to that. In a traditional laboratory there is a lot of opportunities to create the environment as needed, and make sure that all the surroundings are set to optimize the task of measuring whatever there is to be measured. In most cases, it is the budget defining how fancy and how accurate the facility can be.

The second step on the complexity ladder is that a measurement system should not measure only one signal, but perhaps two, and maybe even more signals at the same time. Besides the need of more devices to capture data, it is also required to ensure that if utilizing multisource data set with the aim of finding relations between measurements, each measurement in a comparison would need to be made at the same time. This introduces the need for time synchronization between the devices, it is required to know WHEN each signal was captured relative to other signals, otherwise it doesn't make sense to compare them. Just to synchronize several devices can be a complex task in itself - but what if the laboratory with all the measuring equipment moves around in space relative to the signal sources? In this scenario, in addition to knowing WHAT is to be measured, this introduces the need for knowing WHERE the laboratory was at the time WHEN the measurements from numerous measuring devices were done.

The requirements a flight inspection system is operating under when performing flight inspection on an ILS category III runway is to measure approximately 70 signals simultaneously, being accurately positioned in space within a certainty of 0.009 degrees, while traveling at a speed of 140 knots.

MOVING AT 140 KNOTS

The theory of the ideal signal propagation in space is easy to understand and to apply, but reality is never as easy as the theory assumes. For that reason, flight inspection must be executed at the exact point where the signal is – or is supposed to be – hence the laboratory must be airborne.

Even if flight inspection by helicopters exists and are being used to some extent, still the most common vessels for flight inspection are fixed wing aircrafts. This makes the system very mobile, able to cover large areas, but the obvious disadvantage from a measurement point of view is that to stay airborne, a fixed wing must move at a certain minimum speed. This is the cause of one of the most complicated features of a flight inspection system: Being on the move, and at the same time having strict requirements of positioning accuracy. This introduces a factor that must be known and considered during the design of the AFIS.

For future reference, Table 1 shows a few calculations of how the distances pass while moving at certain speeds.

TABLE 1: Distance travelled at different ground speeds

Groundspeed [knots]	Distance travelled per second [m]
130	66.9
140	72.0
150	77.2
160	82.3
170	87.5

POSITION ACCURACY REQUIREMENTS

The requirements for position accuracies are well defined for all NAVAIDs in both in ICAO and FAA publications. Table 2 gives a reference for ICAO requirements for the most common NAVAIDs [1].

TABLE 2: Required position accuracies sorted by NAVAIDS in degrees [1], and the corresponding accuracies recalculated into required distance.

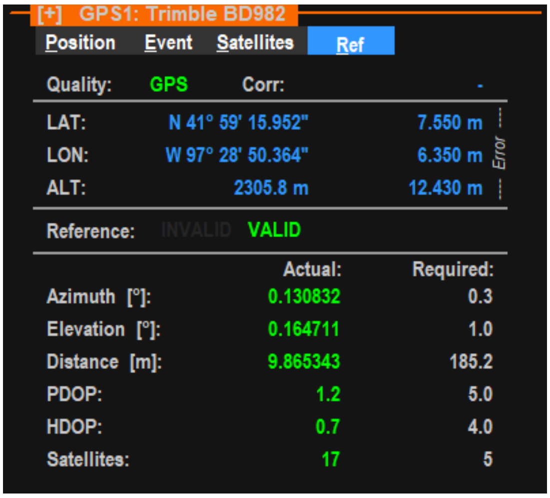
	Required accuracies [degrees]		Required accuracies [m]		
	Horizontal	Vertical	Horizontal	Vertical	Constraint point
ILS CAT I	0.020	0.018	1.0	0.20	Point C
ILS CAT II	0.007	0.009	0.3	0.06	Point T
ILS CAT III	0.006	0.009	0.2	0.06	Point D
VOR, DME, TCN	0.3	n/a	3.0	n/a	0.3 NM from NAVAID
VASI, PAPI	n/a	0.05	n/a	5.0	3 NM from point T
NDB, Radar	0.5	n/a	50	n/a	3 NM from NAVAID

Although other reference positioning systems are available in market and in use in the field, the most common and convenient positioning system to use is based on global navigation satellite systems (GNSS). Being developed and operated by different providers, such as GPS (United States), GLONASS (Russia), Galileo (EU) and BeiDou (China), these systems are “always” present all over the world, thus being stable sources for positioning determination. Another important feature of GNSS is the availability of augmentation systems, which basically are different technologies which can be implemented to improve the accuracy of the positioning. Table 3 shows the different augmentations systems and the resulting nominal accuracies for GPS.

TABLE 3: Nominal GPS accuracy of different augmentation systems [2].

	GPS Nominal accuracy [m]	
	Horizontal	Vertical
GPS standalone	7	10
GPS SBAS	3	5
GPS DGPS	1.5	2
GPS Omnistar	0.2	0.3
GPS RTK	0.02	0.03

Based on information in Table 2 and 3 above, it is a straight-forward task to choose which augmentation system that must be available and enabled to execute a proper flight inspection on any given NAVAID when using GPS as the reference positioning system. A useful feature of most automatic flight inspection systems in the market is to monitor the status of the positioning system during execution, providing the operator with a status ensuring that positioning accuracy is within tolerances as required, and that the operation is producing valid results.



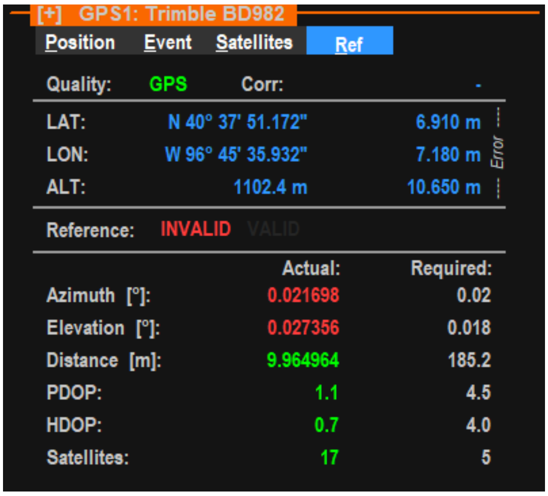
Quality: GPS Corr: -

LAT:	N 41° 59' 15.952"	7.550 m
LON:	W 97° 28' 50.364"	6.350 m
ALT:	2305.8 m	12.430 m

Reference: INVALID VALID

	Actual:	Required:
Azimuth [°]:	0.130832	0.3
Elevation [°]:	0.164711	1.0
Distance [m]:	9.865343	185.2
PDOP:	1.2	5.0
HDOP:	0.7	4.0
Satellites:	17	5

FIGURE: Example of an automatic GPS reference status monitoring where standalone GPS proves to have the accuracy as required by FAA while performing flight inspection on a VOR.



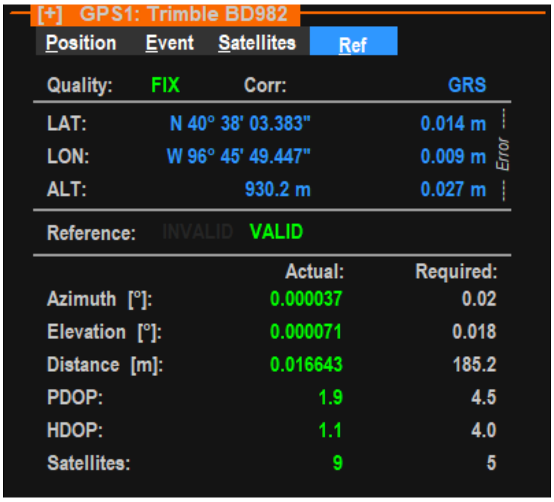
Quality: GPS Corr: -

LAT:	N 40° 37' 51.172"	6.910 m
LON:	W 96° 45' 35.932"	7.180 m
ALT:	1102.4 m	10.650 m

Reference: INVALID VALID

	Actual:	Required:
Azimuth [°]:	0.021698	0.02
Elevation [°]:	0.027356	0.018
Distance [m]:	9.964964	185.2
PDOP:	1.1	4.5
HDOP:	0.7	4.0
Satellites:	17	5

FIGURE: Example of an automatic GPS reference status monitoring where standalone GPS fails to have the accuracy as required by FAA while performing flight inspection on a ILS CAT-I runway.



Quality: FIX Corr: GRS

LAT:	N 40° 38' 03.383"	0.014 m
LON:	W 96° 45' 49.447"	0.009 m
ALT:	930.2 m	0.027 m

Reference: INVALID VALID

	Actual:	Required:
Azimuth [°]:	0.000037	0.02
Elevation [°]:	0.000071	0.018
Distance [m]:	0.016643	185.2
PDOP:	1.9	4.5
HDOP:	1.1	4.0
Satellites:	9	5

FIGURE: Example of an automatic GPS reference status monitoring where GPS with RTK from ground station proves to have the accuracy as required by FAA while performing flight inspection on a ILS CAT-I runway.

FIS POSITION ACCURACY ON THE MOVE

As for any other signal being measured in the AFIS, also the signal providing reference position must be collected and processed in the system. That is applicable independent of which positioning system being used, and independent of which augmentation system that is being used. Recalling that the measuring system is measuring data while moving around 72 meters per second [Table 1], the fundamental question to ask is how can one be sure that the position data measured at a given point is correct knowing that it will take a certain amount of to process the signal internally.

In particular: Having in mind that there are positioning requirements as strict as 0.009 degrees [Table 2], the effect of processing time versus recorded position is not only “nice to know”; it is critically important that is known, that is understood, and that it is handled. Otherwise, the actual position might be completely different than anticipated, and the validity of the results may be voided.

This concept is most easily understood by the example of the positioning system, and that a position is something else than it was a certain amount of time ago, after flying away at a certain velocity. The fact is that this issue is no different for any signals in the AFIS, it is a general feature that applies to all signals flowing through.

FIS MEASUREMENT SYSTEM AND SIGNAL FLOW

A general measurement system for a RF-signal must as a minimum contain an antenna and a sensor unit. The sensor will always contain at least some functionality to process the RF-signal into a desired output signal, but further to that, the unit may have different levels of build-in functionality. Some sensors will be an incorporated part of a complete instrument system providing both calculations and presenting readily processed data to a display, while other sensors are doing nothing more than passing on interpreted signals on a dedicated data format for other units to process further.

In the flight inspection world, sensor units will as often as possible be standardized *avionic receivers/transceivers* as used in any aircraft worldwide today, certified and designed to interpret signals from NAVAIDs. However, avionic receivers are optimized for being receivers for pilot navigation equipment in cockpit, and not lab-equipment. This means that they need to be used differently in an AFIS than they are originally designed for, and they also sometimes need to be modified because flight inspection demands are higher and need more features than a standard avionics receiver can provide. Even though a receiver is standardized and providing outputs on standardized formats, the output formats may be of more than one type, even for one single sensor. In addition to outputs from sensors, it is also required with controller lines, since an AFIS should also be capable of automatic tuning and system configuration in accordance to which procedure that shall be executed. Finally, even though standardized sensors will be used as much as possible, modern multi-purpose AFIS will also contain signal receivers other than just avionics receivers to provide additional supporting functionality which is not a part of standardized avionics.

All in all, this complex picture of a wide range of signals in and signals out makes it convenient to have a centralized collection and interface point for data stream, a *data acquisition system*, which makes a single interface to the physical signal handling.

Once all the signals are collected into a system, the job is still only half way done. While some signals are properties of their own, directly required as a part of a flight inspection mission, there are certain other signals which are only components in algorithms to provide flight inspection results. To do this, the AFIS must apply *algorithms* on the signals, and only after all necessary calculations have been performed, the system is ready to present results to the operator.

A simplified block diagram of one single signal being processed in an AFIS is shown in the figure below.

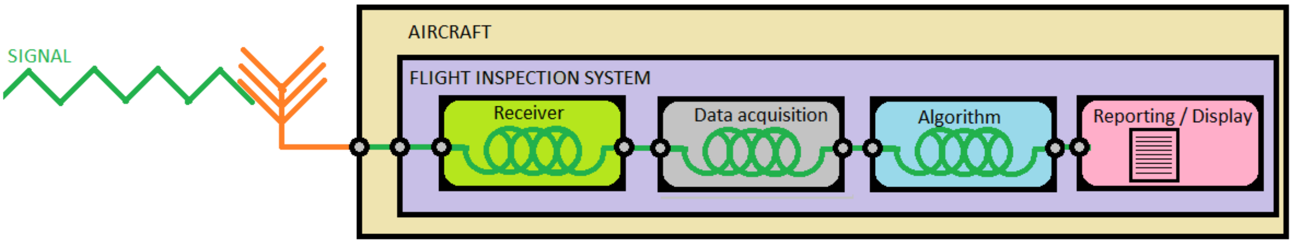


FIGURE: Block diagram of all steps one single signal must go through in a standard flight inspection system after being picked up by the antenna until it is prepared as a result for the operator.

TIME DELAYS

Each processing step one signal goes through, even just the transportation leg through a high-quality impedance optimized RF-cable, takes a certain amount of time. Even though radio frequency waves travels through air by the speed of light, and modern data processors can perform millions of operations per second, the time it takes from a signal being picked up by an antenna until it is being displayed on an operator's panel or a printed report is not zero.

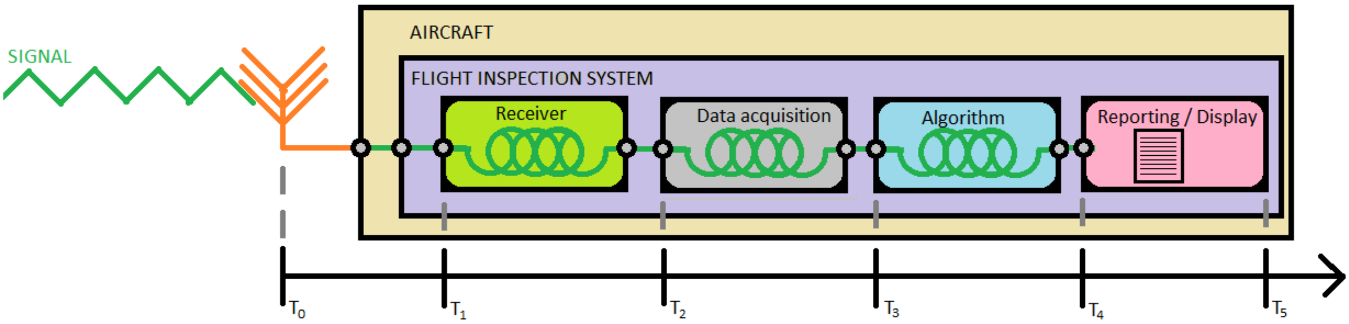


FIGURE: Block diagram of all steps one single signal must go through after being picked up by the antenna until it is prepared as a result. Note the time line at the bottom indicating that each process will introduce a time delay in the signal flow which must be considered in the design.

This is something that must be taken into consideration when designing flight inspection systems. In connection to this, one must also always consider that the measurement system is travelling at speeds of 140 knots or more. This is not introducing a time delay by itself, but it increases the necessity of knowing when the signal was captured. Knowing that the position requirements may be as strict as 0.20m horizontally (for an ILS CAT III) [Table 2], using GPS-RTK as reference position with a nominal horizontal accuracy of 0.02m [Table 3], it is critical to realize that just the time delay of the signals through the system may void the accuracy required to produce a valid flight inspection result.

In other words: If the signals move too slowly through the system, and the time delays introduced in all the processing steps is not accounted for, the system doesn't know when and where the actual measurement was made – and the validity of the results is voided.

TIME STAMPING

Time stamping means to index a measurement set with a counter or timing device. After time stamping, the system has a reference point of when a measurement was made. This makes it possible to track what happens to the signal down the line during processing, and by that the means of keeping account of the time delays accrued after time stamp has been set.

It is obvious that as a general principle, the time stamping should be performed as early as possible in the signal flow, to eliminate as much of the uncertain time delay as possible. In the part of the flow before a time stamp is set, the system has no information about how long time it takes for the signal to pass through. In an ideal world, it would be possible to know the exact timing exactly when a signal entered the antenna, and then start a counter. But for practical reasons, this is not feasible, so the timestamping must be done on later stage.

The requirements of a time synching device are very strict and it requires a real-time environment. In addition to the timing source itself, it is required with some computing resources to capture both the timestamp signal and the measurement signal and pair them together. This means that the earliest possible point of doing this would be on the receiver level, which by nature does contain computing power to a certain extend. Introducing time stamping here is practically possible, technology exists and some AFIS manufacturers do this. But using time stamping in this stage is highly dependent of the capability of the receivers and sensors used, and also the complexity and number of different sensors in use in the AFIS. As mentioned before, standard avionics transceivers and receivers are not primarily designed for laboratory purposes, so most of this equipment doesn't support time stamping features. There is laboratory equipment available in the market which can replace avionics receivers, containing time synchronization features which can be utilized, and which may be a practical way to implement time synchronization in simpler systems. However, in multipurpose AFIS containing a full range of features, with then a corresponding large number of receivers and sensors of a mixed range and type, outputting a wide specter of different signals, it will become a very challenging task to time synchronize the measurement at sensor level.

The next step in the signal flow process is then the data acquisition point. This is the step where all signals and data from the sensors are collected in one single point, and it is a natural and practical place to perform timestamping, since the time stamping source can be an incorporated part of the data acquisition system.

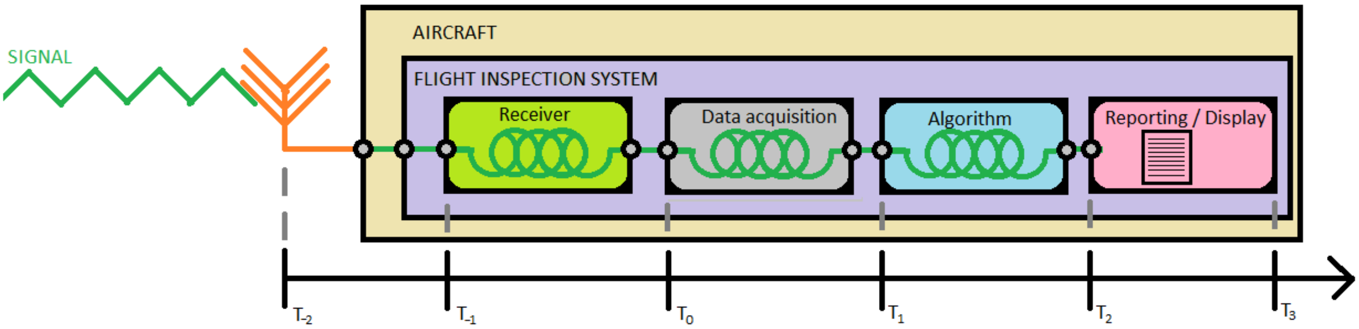


FIGURE: Block diagram of all steps one single signal must go through after being picked up by the antenna until it is prepared as a result, with the time line indicating point of time stamping as T_0.

Table 4 summarizes the steps in relation to the figure above, and emphasizes the time delays and consequences.

TABLE 4: List of steps that a signal must run through with time delay and consequence for each step

Time step	Process description	Time delay	Consequence
$T_{-2} – T_{-1}$	Signal travels to from antenna to receiver	Low and neglectable	Non-critical
$T_{-1} – T_0$	Signal processed by the receiver	Varying and unknown - dependent on receiver	Can be anything from non-critical to critical
$T_0 – T_1$	Signal collected by the real-time computer, and time-stamped	Known and neglectable	Non-critical; all signals are now in a controlled time frame
$T_1 – T_2$	Signal being subject to calculations and preparation	Varying, but known - dependent on complexity	Critical unless handled correctly
$T_2 – T_3$	Results preparation	Varying, but known - dependent on complexity	Critical unless handled correctly

With reference to Table 4 above, the time stamping performed in step T_0-T_1 is the key point. From this point and onwards, time delays introduced by the system can be large, medium or small – but the point is that they are within the system time frame. It must be noted that the delays are not eliminated. Processes must be implemented to handle the delays as they accrue also after T_0, otherwise they have the same potential of causing issues. But the framework is in place making it possible to have control of all time delays after T_0, and a well-designed system will use this opportunity.

The number of processing steps taking place before the time stamping happens is now limited, but as Table 4 describes; there is still one processing step which is significant, in which the uncertainty is high, and where the variation in time delay from one signal to the other may be very large. That is the step where the signal is being processed in the receiver.

TIME SYNCHRONIZATION

As long as there is only one signal in play, it does not make any sense to talk about synchronization. However, in a real-life measurement system with several signals being measured simultaneously, the aspect of time synchronization becomes important when it is desired to compare and evaluate signals from different sources.

The figure below illustrates the concept of the collecting output from three different receivers, and how a centralized data acquisition computer handles the time stamping and the time synchronization of the outputs of the system.

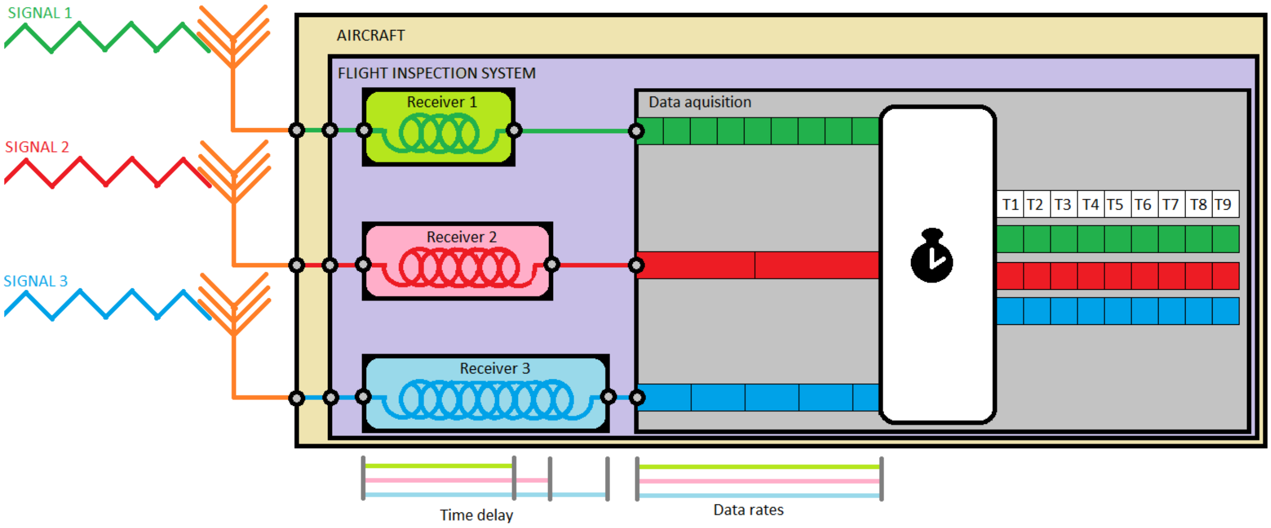


FIGURE: Block diagram of principle of time synchronization of multi-source systems. Note how the different receivers cause different time delays on the different signals, and also how the output data rate is different between the three receivers.

The point when dealing with several sensors and signals is that in real life, each receiver will have different characteristics. By that they will have different processing time, meaning that there will be as many time delays in the system as there are receivers in the system. This is important since it means that the largest source of uncertain time delay is introduced before the system can time stamp the signals, and it means that each signal will have a varying time delay introduced compared to other signals before getting time stamped in the data acquisition computer. It shall be noted that for a wide range of signals, the significance of the different time delays introduced from one signal to the other may be neglectable, and the variation is usually in the range of millisecond. However, as will be discussed later, there are cases where the time delays are playing an important role and has a direct consequence of the integrity of the results.

Another aspect that should be noted from the figure above, is the output rate from the receivers before the data acquisition. Depending on the receiver design, the digitally transformed signal will be output in known standardized formats, such as Arinc-429, serial port data (RS232, RS422/CSDB, RS485), TCP/IP over various protocols, and digital discrete signals. From a general data acquisition point of view, this is a challenge in designing a data collection system; it needs to be able to handle a wide range of signal types, and this is another factor making it convenient to have a centralized data acquisition computer. Other than the formats, the challenge with respect to time synchronization that must be dealt with, is the number of measurement points per time unit from each receiver. Because even though an output may be known by the format, the rate of the data output must also be considered. This is illustrated in the figure above, where receiver 1 produces nine data points per time unit, receiver 2 produces only two data points per time unit, while receiver 3 produces five data points per time unit. The data acquisition system needs to have ways to handle this variation in data rate.

What the data acquisition system does, is to create fixed time slots each of 0.1 second duration, determined by a high-accuracy timing device of a real-time environment. Each time slot can be considered as a container which is filled up with one measurement point from each sensor in the system. Inside each time container, all signals are inserted as they are collected at the data acquisition computer, at the time they arrived the data acquisition computer and got time stamped. After this point, all the signals are arranged in a time vector, and all signals are now possible to compare to other signals as long as they are within the same time slot.

ALGORITHM PROCESS

After each signal has been timestamped and synchronized with all other signals available in the system in a fixed timeframe, the signals are ready to be passed on. Depending on which type of signal it is, some of them may be used directly as they are with no further processing, while other signals may be components going into calculations in a variety of more or less complex algorithms.

The following figure shows the effects of the how different calculation steps will have effects on the overall signal flow.

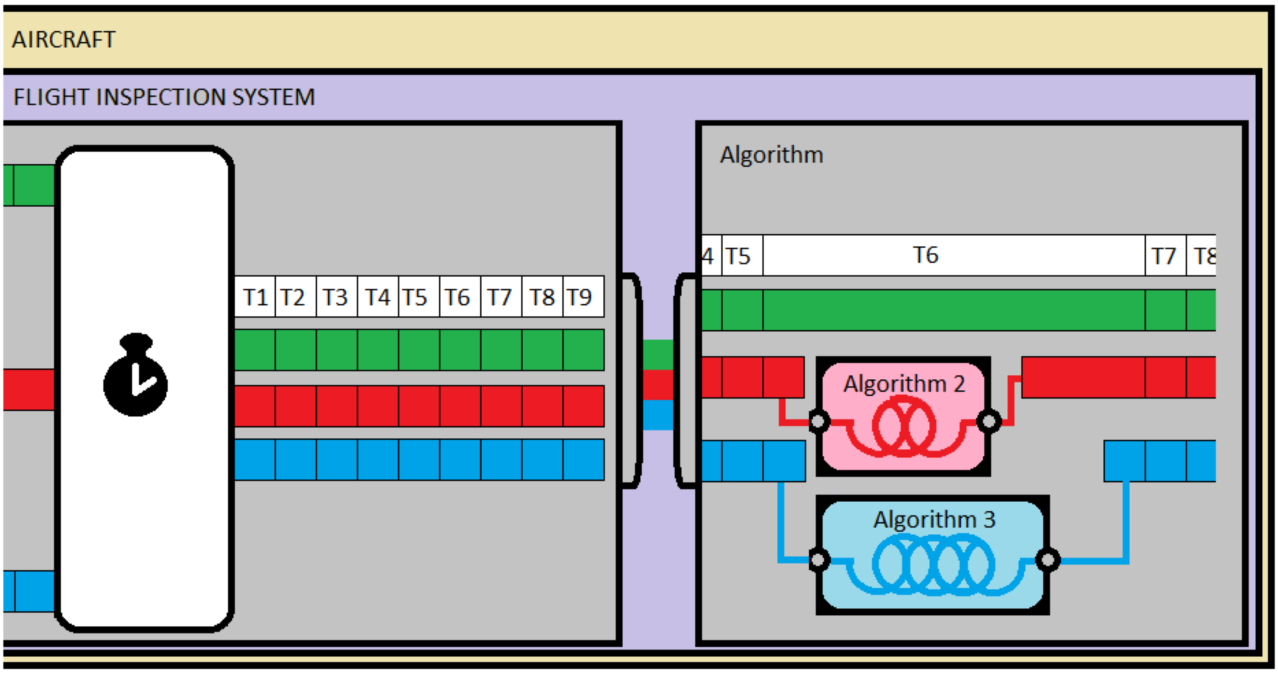


FIGURE: Block diagram of principle of calculation applied on some signals. Note how the different calculation algorithms may cause different time delays on the different signals, and how this affect the signal flow in total.

What is the major difference from the receiver processing delays, is now that the calculations are applied on signals that are timestamped and within the timeframe. This means that when handled properly, one can ensure that data captured at certain point of time is still compared to other data captured at the same point of time even after being processed through a time-consuming algorithm.

The effect is shown in the figure above for a data set in a given time slot; time slot number 6. While the green signal is not going through any calculations, both the red and the blue signal is a part of separate calculation steps. The blue signal is a part of a complex calculation, introducing a big time-delay, and the red signal is a part of faster calculation, causing it to be delayed to some degree. Both the green and the red signal in slot 6 must wait until the blue signal in slot 6 has been processed, and at the time when all signals within the same time interval are done, the signal train can move on. This ensures that all measurements in slot 6 are still compared to other measurements in slot 6, even after being processed. The consequence is that the signal flow through the system is defined by the slowest calculation step, and that a complex and time-consuming calculation step may cause a considerable lag in the overall signal flow. But this is of less importance, the important that takes precedence over everything is that signals are being compared to other signals captured at the same time.

METHODOLGY FOR HANDLING DELAYS PRIOR TO TIMESTAMPING

As already discussed: The challenge of time stamping and time synchronization is that a real-time computer time stamps data at the point of time when data is arriving the time stamping computer, not knowing anything of what happened before that takes place. Whether it is a very quick processing receiver, if the signal from the NAVAID is changing at a very slow rate or the tolerance is very generous, in many cases the variation in time delays prior to time stamping can be neglected. On the contrary, examples exist where this is not the case at all, and that the unknown time delay taking place before time stamping is having a large effect on the integrity of the data. The evaluation must be done if delays are compromising the required accuracy, and it must be done in case by case.

Below is an example of a plotted result from a deviation measurement of a localizer, collected by a crossover procedure flown in a counter-clockwise direction:

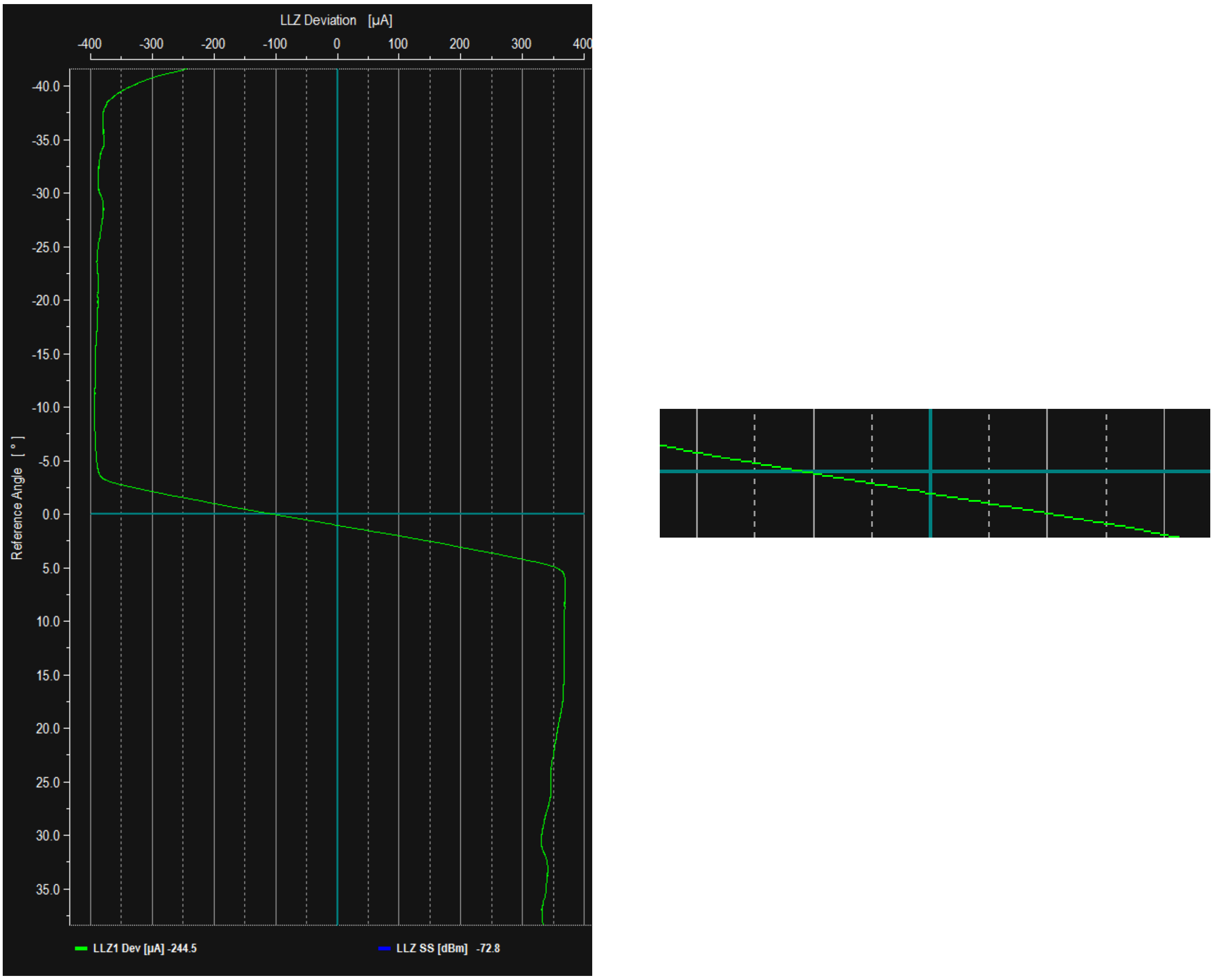


FIGURE: Plotted result from a deviation measurement of a localizer, collected by a crossover procedure flown in a counter-clockwise direction. Note how the deviation is different from the expected 0 µA at the centerline, and that the difference is to towards the left (-) side, meaning that it is in the direction of flying.

The expected ideal result is that when the aircraft is on the centerline of the runway the deviation should be 0 µA. What can be observed in the figure above, is that there is a considerable offset when passing the centerline, indicating that the deviation is not 0 µA at the centerline. But does that mean that the NAVAID is off?

To conclude, the result should be compared to a similar run, just flown in the opposite direction, i.e. clockwise direction:

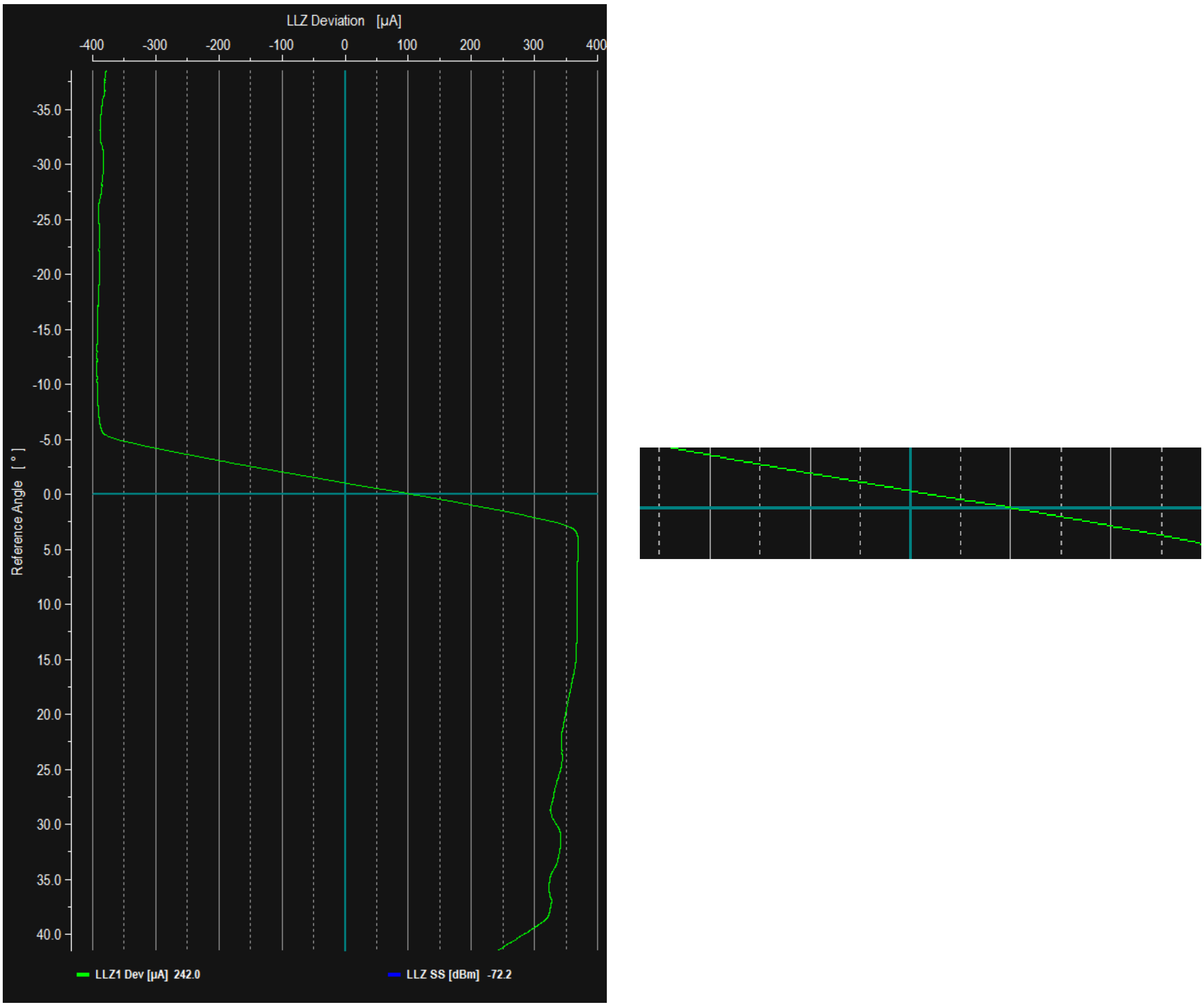


FIGURE: Plotted result from a deviation measurement of a localizer, collected by a crossover procedure flown in a clockwise direction. Note how the deviation is different from the expected 0 µA at the centerline, and that the difference is to towards the right (+) side, meaning that it is in the direction of flying.

The obvious thing to notice in the two results plots above is that both figures show that there is an offset, and that the offsets seem to be of same magnitude. However, the crucial important thing to notice is that the offset values are on the *opposite* side of each other, and that they are following the direction of flying. If the case was that the actual deviation signal from the localizer antenna on the ground had an offset, the symmetry on the offset of the plotted result would be shifted. Since the delays are symmetric, this a strong indication of the presence of a time delay in system which is too big to be neglected.

Using the results from above, the system designers have an opportunity to understand which time delays that is introduced before the time stamping is taking place, and it is therefore possible to calculate the actual delay of a signal prior to time stamping. This can then be applied in a way that the signal gets a shift of the time slot which it originally was been assigned to by the real-time computer, and the signal is moved backwards in the time frame. The concept is illustrated in the figure below.

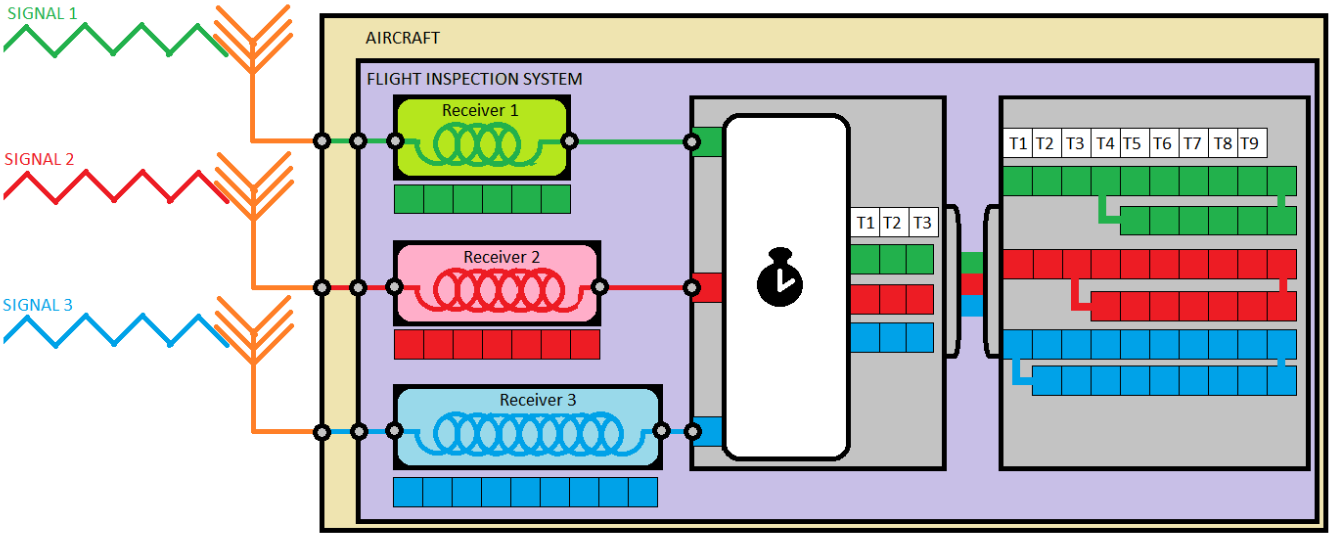


FIGURE: Block diagram of principle of applying an empirically determined delay on a signal after timestamping

Applying the results of the analysis on the unknown time delays on the results above, and performing a recalculation where these delays are taking into consideration, gives the following improved plotted results:

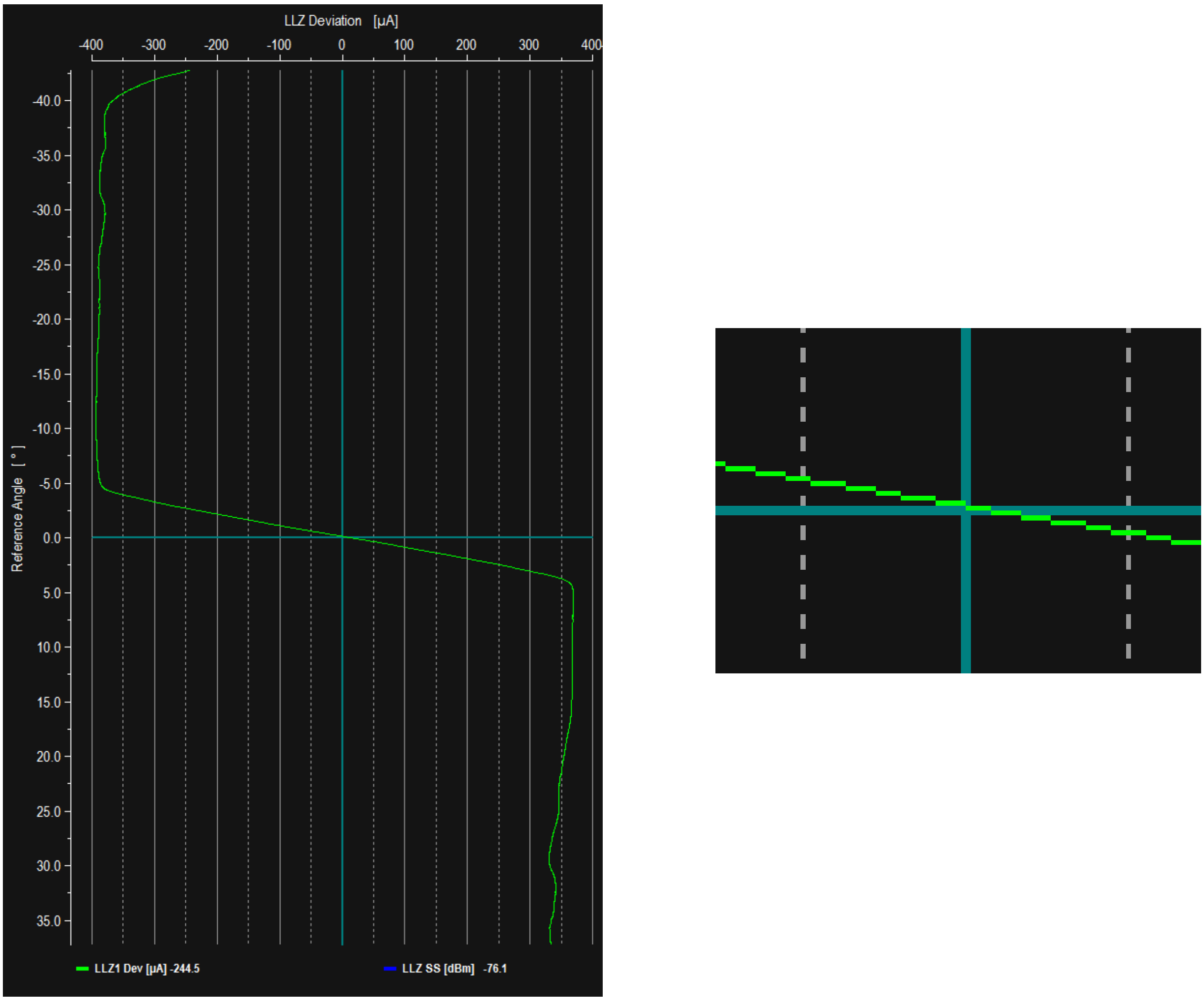


FIGURE: Plotted result from a deviation measurement of a localizer, collected by a crossover procedure flown in a counter-clockwise direction, with receiver time delay applied.

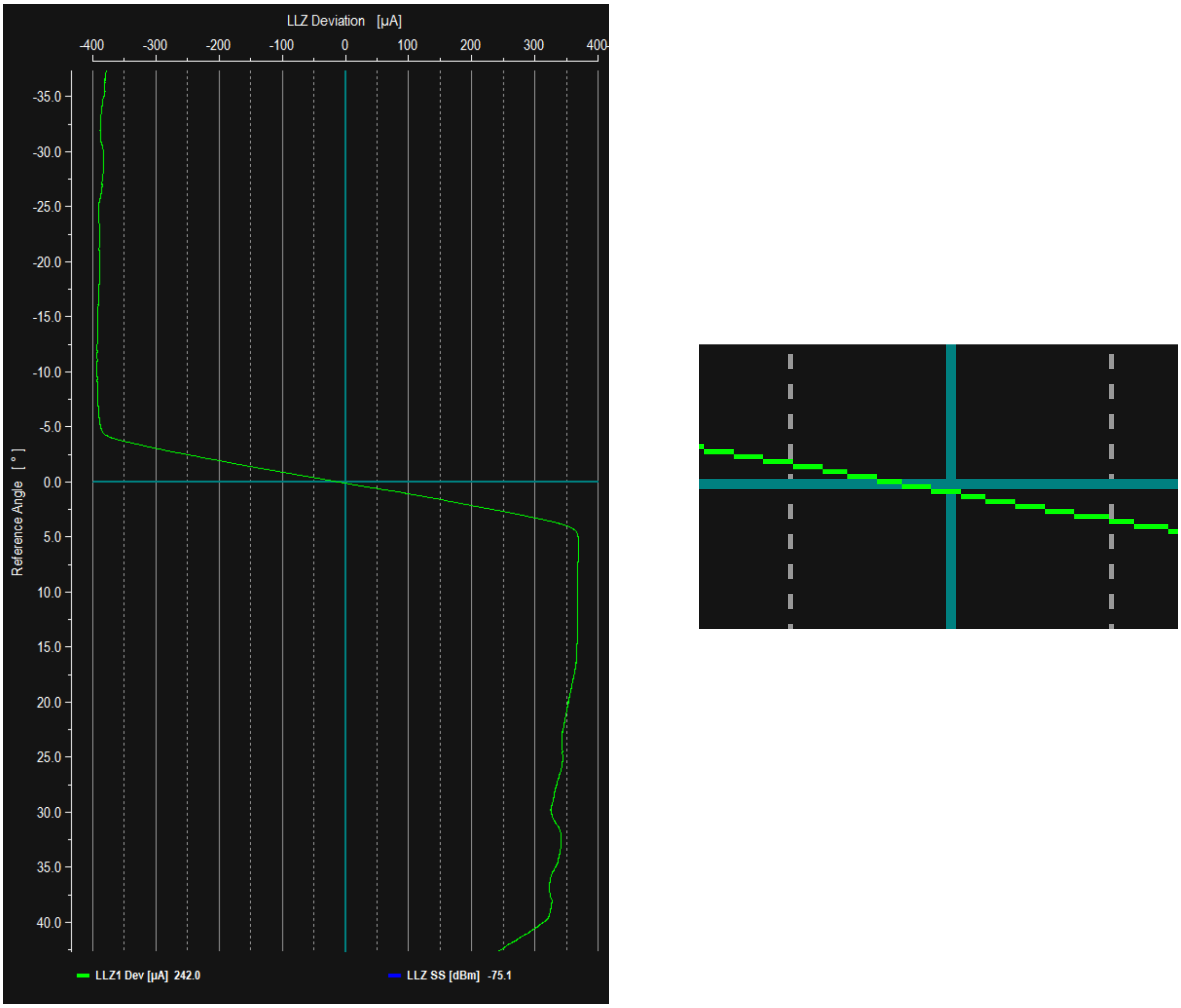


FIGURE: Plotted result from a deviation measurement of a localizer, collected by a crossover procedure flown in a clockwise direction, with receiver time delay applied.

The prerequisite of the methodology is that the receivers in use are performing steadily, which is usually a very basic requirement for most avionic sensors. It must be performed reference measurements on signals which are not fluctuating too much, so it should only be performed on NAVAID's with known performance. It is required only one set of reference measurement, and the actual delay will be applied to all other signals coming from the same sensor, thus improving the sensor overall.

But care must be taken. In this example, with deviation measurement from a localizer receiver, the delay will be identified for all signals related to the localizer, meaning that it will correct the time delays in the signal flow for all measurements related to localizer feature in the receiver. What must be handled carefully is that receivers may have different processing components inside, and on top of that also internal computing steps of varying complexity. In the example of the NAV receiver, such receivers will typically also have VOR and GP capability within the same receiver – but the processing of these signals will be carried out by different components than for the LLZ, and there will also be other internal calculations performed. The result is that the delay introduced in one receiver may not be applicable for all signals from this receiver, and reference measurements must be carried out separately.

REFERENCES

[1] ICAO, 2007, Doc 8071, Manual on Testing Radio Navigation Aids, Volume II – Testing of Satellite Based Radio Navigation systems

[2] Official U.S. government information about the Global Positioning System (GPS) and relating topics - https://www.gps.gov/