

Digital Flight Inspection Navigation Equipment

Maik Ritter

System Engineer
Aerodata AG
Braunschweig, Germany
Phone: +49 531 2359-246
E-mail: maik.ritter@aerodata.de



Dr. Mirko Stanisak

System Engineer
Aerodata AG
Braunschweig, Germany
Phone: +49 531 2359-304
E-mail: mirko.stanisak@aerodata.de



ABSTRACT

In flight inspections of radio navigation aids, a plethora of different measurements must be taken very precisely to meet the internationally harmonized accuracy requirements. ICAO DOC 8071 requires to ensure that the used equipment performs the same as conventional, high-quality aircraft equipment (i.e. with a TSO approval). This is why specialized flight inspection navigation receivers (modified for the assessment of the typical outputs and based on TSO equipment) were often used jointly with laboratory-grade equipment (for further measurements) in the past.

Over the last decades, digital signal processing was adapted to navigation equipment, while still maintaining a high-quality RF frontend. Modern TSO receivers already use digitalized measurements, which can be analyzed by flight inspection systems directly. By incorporating digital software defined radio (SDR) technologies, the authors developed digital flight inspection airborne equipment for ADF, VOR/ILS, MKR and DME, which do not only ensure accurate and reliable flight inspection measurements, but also allow for in-depth analyses of the received RF signals.

This paper will detail the developments, the operational concept and the additional capabilities of the new flight inspection measurement equipment. Initial flight test results will be shown, indicating a very good agreement with legacy systems.

INTRODUCTION

The primary objective of flight inspection is to ensure the integrity and accuracy of the signal-in-space (SIS) provided by ground-based navigation aids. To maintain global aviation safety, international organizations, most notably the International Civil Aviation Organization (ICAO) with its Doc 8071 [1], define stringent requirements for the performance and calibration of flight inspection systems.

A fundamental challenge in the design of such equipment is the inherent conflict between two primary goals.

On the one hand, flight inspection shall primarily ensure the safety of flight for all airplanes using a ground navigation aid. Subsequently, the flight inspection equipment should react to the received signal-in-space exactly like conventional navigation equipment. ICAO Doc 8071 [1] specifies that flight inspection receivers should output guidance signals representative for equipment typically used with the respective ground navigation aid. This is best achieved by using equipment that is approved via a technical standard order (TSO). This way it is ensured that the equipment is tested to operate within all limits.

On the other hand, flight inspection systems must be able to analyze the received signal-in-space in great depth, which far exceeds the capabilities of standard avionics.

Historically, these challenges typically could not be addressed jointly, but were addressed by integrating two units of different grades into a flight inspection system for inspecting the same navigation system.

On the one hand, laboratory-grade measurement devices (often based on RF spectrum analyzers) are optimized for best RF analysis performance to provide high-accuracy analysis functions. Subsequently, laboratory-grade equipment often utilizes extremely sharp digital filters to isolate signals for maximum measurement accuracy. Such equipment (e.g. Rohde & Schwarz's EVSG1000 as shown in Figure 1) is also available for the use in flight inspection aircraft but lacks a direct link to primary navigation equipment of typical avionics.



Figure 1: Laboratory-Type Navigation Analyzer: Rohde & Schwarz EVSG1000 (image courtesy of Rohde & Schwarz)

Avionics equipment, on the other hand, is optimized for reliable and safe flight operations over a wide range of operational conditions. Such TSO-approved often use intermediate frequency (IF) filters specifically tuned to match the interference rejection and group delay characteristics required for safe flight operations.

The discrepancies between both types of equipment can lead to significant differences and uncertainties. A laboratory unit might "clean" an unstable signal that would actually cause guidance errors or interference in standard navigation equipment. Similarly, the Automatic Gain Control (AGC) in laboratory units is typically designed for high speed and linearity to ensure precise signal strength readings. Aircraft receivers, however, employ specific AGC timing and non-linear response curves optimized to maintain guidance stability in complex multipath environments. Furthermore, the logic for triggering warning flags in TSO equipment is strictly governed by the respective standards, whereas laboratory devices often prioritize data collection. Relying exclusively on non-TSO equipment can therefore result in measurement data that does not fully reflect the operational reality experienced in the cockpit.

Past practical experiences have shown that certain ground station malfunctions, such as antenna feed errors or phase-related issues in DVOR systems, can remain hidden because the equipment's internal processing masks signal instabilities like unstable FM deviation ratios (FMDR). Furthermore, such faults often cannot be detected by ground-based laboratory equipment, as ground checks typically rely on transmitter test ports or near-field measurements, which fail to capture anomalies that only manifest in the far-field.

Such effects can only be resolved in flight with deep access to internal parameters and corresponding analysis functions.

For this, flight inspection usually involves specialized equipment, which is based on TSO-approved navigation equipment, but was modified extensively for providing the necessary analysis capabilities. An example for this kind of specialized flight inspection equipment is Aerodata's AD-RNZ850 shown in Figure 2. While such equipment ensures high operational fidelity as recommended by ICAO Doc 8071, they are often limited by their internal analog or baseband-only signal processing. This necessitated the use of additional external laboratory equipment (such as oscilloscopes or spectrum analyzers) for the analysis of composite signals (e.g., the 90/150 Hz modulation in ILS or the VOR composite signal) or specialized spectrum analyzers (to capture signal-in-space parameters that the flight inspection equipment could not provide itself). Integrating and calibrating these combined setups, consisting of a modified receiver and various external measurement tools, over a wide range of environmental conditions added significant complexity, weight, and potential for cumulative measurement errors to the flight inspection system.



Figure 2: Legacy Flight Inspection Receiver: AD-RNZ850 (based on Honeywell RNZ850)

Such mostly analog systems can nowadays be replaced with modern digital TSO-certified navigation equipment. By incorporating software defined radio (SDR) technologies based on direct intermediate-frequency (IF) sampling into modern TSO-approved equipment, laboratory-grade analysis functions can be integrated directly. This allows to eliminate the need for external oscilloscopes and spectrum analyzers, while maintaining the "native" reception characteristics of a certified navigation unit. This approach ensures a smooth transition from legacy hardware to modern, fully digital flight inspection equipment that meets the highest quality and fidelity standards.

This paper will describe the development process of new digital flight inspection navigation equipment. Based on a set of requirements, the developed hardware and the resulting overall flight inspection performance will be detailed in this paper.

REQUIREMENTS

The design of a modern flight inspection receiver must bridge the gap between established certification standards, such as ICAO Doc 8071, and the expanded analytical capabilities provided by Software Defined Radio (SDR) technology. The primary objectives are to achieve the required measurement level of performances and to introduce high-resolution diagnostic features for flight inspecting non-directional beacons (NDB), VHF omnidirectional radio ranges (VOR), instrument landing systems (ILS), marker beacons (MKR) and distance measurement equipment (DME) ground installations.

Instead of one flight inspection unit covering basically all functionalities, more modular navigation equipment was chosen as the base, resulting in distinct flight inspection equipment for the different technologies.

Core Equipment

All new flight inspection equipment is based on commercial TSO-approved primary navigation equipment, which is complemented with additional components. It must be ensured that the core functionalities still maintain a good level of agreement with typical navigation equipment, even with the additional components providing flight inspection outputs in parallel. Subsequently, the additional components may not alter the overall characteristics of the core unit.

Mechanically, the modifications may not result in significant changes to the external dimensions, so that the existing installation trays of the core units can also be used by the modified equipment. Subsequently, all necessary additional components must be integrated into the core units.

External Interfaces

To facilitate a seamless integration of core and additional functionalities, the flight inspection equipment needs multiple electrical interfaces. All interfacing is done using the tray connector of the core unit, even though the pinout is modified.

For maximum compatibility with previous flight inspection equipment, the new equipment provides ARINC 429 (A429) interfaces for tuning and data output. The data output uses a high-speed (HS) bus which incorporates the core unit's outputs with the additional flight inspection outputs.

For future interfacing, the new flight inspection equipment also provides an Ethernet interface via the tray connector. This way, even more data can be transported, allowing for various deep analysis in operation. Serial RS-232 ports are used for calibration and maintenance tasks.

In addition, a dedicated pulse-per-second (PPS) input was required. This PPS input is intended to support the precise timestamping of the flight inspection measurements and is

also used to discipline oscillators for best overall measurement performance and stability.

Internal Interfaces

The core units are modern digital navigation equipment with various digital interfaces, which are also used by the flight inspection components. This way, as no additional analog-to-digital conversion (ADC) is required, the long-term accuracy, stability and performance is improved when compared with legacy flight inspection equipment.

Received Signal Strength Determination

A fundamental requirement for all receiver types is the precise determination of the received signal strengths, which is used in conjunction with the known antenna directivity models to estimate the SIS field strength.

An automatic gain control (AGC) is used by the core equipment to ensure a wide dynamic of the RF signals. The digital AGC command for the core units is used to calculate received signal strength indications (RSSI) for every RF input.

To meet the accuracy requirements over a wide range of environmental conditions, each flight inspection unit is calibrated in an environmental test chamber. Multi-dimensional interpolations and look-up tables (LUT) ensure a very high level of accuracy in the signal strength determination throughout all possible operational environments.

The use of digital interfaces minimizes unit-to-unit variance and significantly reduces the long-term drift typically found in analog circuits.

I/Q Sampling for SDR Analysis

The transition to intermediate frequency (IF) I/Q sampling represents a significant advancement over traditional baseband-only architectures, allowing for deeper insights into the signal-in-space.

By sampling at the IF stage, the system preserves the original carrier information next to the modulated side bands. In contrast, legacy baseband I/Q sampling removes the carrier reference prior to sampling. IF sampling subsequently enables direct analysis of the energies of the carrier and its modulated side bands in the digital domain, which results in a superior determination of modulation depths.

Utilizing complex I/Q sampling (instead of real-only sampling) provides instantaneous phase and magnitude information without the need for complex Hilbert transforms, enabling more robust demodulation and better rejection of image frequencies within the digital domain.

High-Resolution VOR Phase Integrity

Certified aircraft navigation receivers are usually optimized to provide smooth deviations to the pilots and apply significant low-pass filtering to their raw deviation measurements. However, low-pass filtering introduces certain time delays to the deviations, which is not desired in flight inspections, especially for orbits around VOR stations (where the deviations change constantly).

For high-precision VOR measurements without delays, dedicated additional custom signal processing can be implemented, using the digitalized I/Q data without the low-pass filtering. This is particularly important for orbit flights around a VOR ground station, because any time lag results in differences between clockwise and counterclockwise flights.

In addition, by using the raw I/Q IF samples, many effects of the signal-in-space can be analyzed and visualized easily, as shown in Figure 3. Here, the complete spectrum of a VOR signal is shown, including the station's ident.

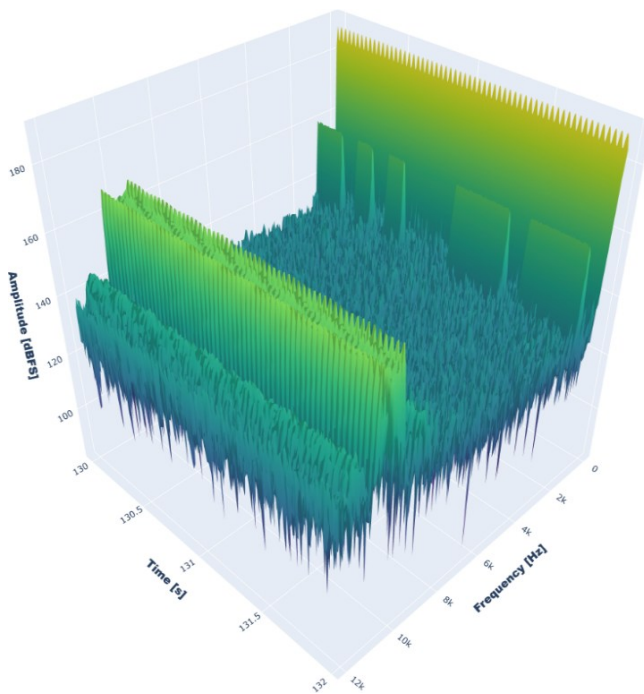


Figure 3: Example of Advanced Flight Inspection Analysis (3D-Waterfall Plot of VOR Station with Ident)

Modulation Analysis of Marker Beacons

Flight inspections of marker beacons usually involve direct overflights to analyze the modulation depth of the incoming signal. Due to the narrow beamwidth and relatively high approach velocities, such overflights only cover short periods with strongly changing RF field strengths. The precise determination of modulation depths requires direct comparisons with the 75 MHz carrier, which is often not directly available in legacy flight inspection equipment, but

can be analyzed directly using the raw I/Q samples of the RF signal.

DME Pulse Shape Analysis

For inspecting the pulsed transmissions of distance measuring equipment (DME) ground stations, not only the timing of the received pulses must be registered, but also their shape. This pulse shape monitoring assesses critical parameters (such as the rise time, duration, and fall time as shown in Figure 4) continuously in real time.

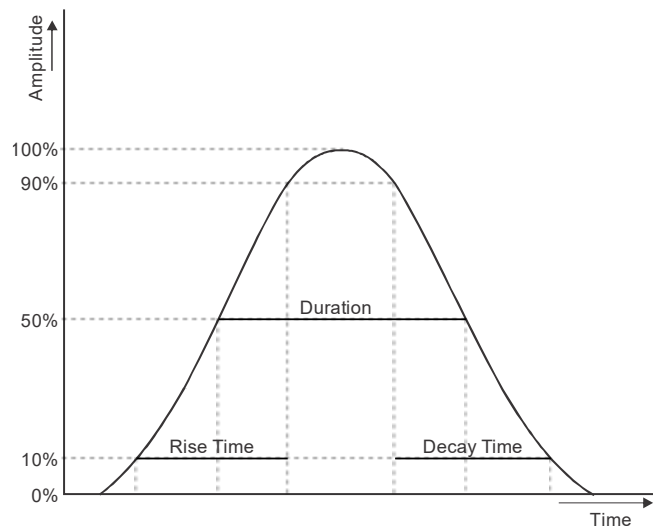


Figure 4: DME Pulse Shape Parameters (based on [2])

The analysis of the received pulse shapes allows for the automated detection of multipath effects, which previously required manual observation with additional external equipment.

Two-Frequency ILS Signal Separation

Two-frequency ILS installations provide an additional safeguard to ILS operations, suppressing undesired sidelobes. The course signal dominates only in the approach sector. Outside of the approach sector, the clearance component prevents false localizer and glideslope indications. Both components need to be checked during flight inspections to ensure the correctness of an ILS ground installation.

Aircraft ILS receivers generally evaluate only the more dominant component. While this is sufficient in regular operation, flight inspection requires both components to be evaluated separately. Unlike legacy ILS receivers, the digital I/Q IF data enables the use of multiple digital filters in parallel. This way, the digital flight inspection receiver can incorporate different filter settings for analyzing both signals together and separately. This eliminates the need for integrating additional equipment for course/clearance analysis and enables various possible processing modes.

HARDWARE DEVELOPMENTS

The above defined requirements can only be met by digital navigation equipment with heavy modifications. Instead of developing one navigation unit capable of handling all types of ground navigation aids, three distinct units have been developed. As all three core units belong to the same family of TSO-approved navigation equipment, the three flight inspection units also share a common FPGA-based architecture.

The functionality for flight inspections of non-directional beacons (NDB) is implemented in the new AD-FISADF-0100 device. This flight inspection automatic direction finder (ADF) not only allows to precisely analyze NDB signals but also incorporates a power supply to support an extra ADF antenna if necessary (for use with a spectrum analyzer for instance).

For inspections of DME ground stations, the new AD-FISDME-0100 was developed. This unit can inspect and analyze three ground stations in parallel. As DME requires the transmission of pulses with high power levels, the additional modules integrated into this transceiver are specifically protected and shielded to not be affected by the transmitted pulses.

For flight inspections of VOR, ILS and MKR, the new AD-FISNAV-0100 was developed, covering the three required RF frequency bands in parallel. This way, the FISNAV is capable of analyzing the signals in all three bands simultaneously during flight inspections.

The name plates of the three devices are shown in Figure 5.



Figure 5: Name Plates of Developed Flight Inspection Equipment

Compared to the previously used legacy combined flight inspection equipment, having multiple smaller units gives more flexibility for adapting the flight inspection system depending on the customer's requirements.

By using an established aviation radio platform as a baseline, the new flight inspection equipment combines the proven RF frontends of the core equipment with digital signal processing architecture. This enables the new flight inspection equipment to use software-defined radio (SDR) algorithms flexibly.

Physical Interface

To facilitate the seamless integration of this modified equipment into modern flight inspection aircraft, the external electrical interfaces were redesigned while maintaining general compatibility with existing mounting tray assemblies. Due to different mechanical coding keys, it is ensured that the original navigation equipment cannot be installed instead of the flight inspections ones, and vice versa. No other connections than the tray connections are required, ensuring that also the modified units can be replaced easily if necessary.

Various input and output pins of the tray connector were modified to enable multi-protocol communication and additional functions. All flight inspection equipment types support tuning via a low-speed A429 bus and transmit their data (both the core data from the original equipment and the additional flight inspection data from the additional analysis functions) via a high-speed A429 bus. This allows easy integration in standard automatic flight inspection systems.

Next to A429, integrated Ethernet ports allow for high-rate data transfer of raw measurements and other data, enabling potential Ethernet-only integration into flight inspection systems in the future. In addition, the Ethernet port is used for the automatic calibration of flight inspection measurements. Two RS232 ports for diagnostic and service tasks are available, too.

Digitalization and IF Undersampling

A key innovation in the hardware design of the new digital flight inspection equipment is the direct digitalization of the intermediate frequency (IF) signals. All newly developed equipment utilizes an undersampling architecture (as described for example in [2]) to minimize the computational effort as far as possible. Here, the signal is sampled at a rate lower than the IF frequency would conventionally require, yet high enough to satisfy the Nyquist criteria for the actual signal bandwidth. Through precise band-pass filtering followed by digital down-conversion and decimation, the signal information is shifted to a frequency range that enables resource-efficient digital signal processing (DSP) without any loss of signal integrity or precision.

The resulting Software-Defined Radio (SDR) architecture provides the flexibility to incorporate complex processing functions that were previously impossible to implement in analog hardware.

Digital Data Processing

The flight inspection equipment integrates additional processing capabilities as part of the modification of the core units. These are designed to integrate directly into the internal digital data buses of the core units. This deep integration allows the supplemental logic to monitor internal

telemetry without interfering with the core equipment's flight-critical functions.

The additional components include high-speed field programmable gate arrays (FRGA) and digital signal processors (DSP). While the FPGAs are dedicated to deterministic, high-rate tasks (such as real-time pulse analysis and high-bandwidth data serialization), the DSPs focus on complex processing algorithms and digital filtering.

Due to the flexible SDR architecture, the new flight inspection equipment can benefit from existing processing functions already implemented for legacy equipment. This ensures components, which have been in regular use for decades in other equipment types, can be re-used here, too.

Stability & Qualification

For reliable and stable operation over the wide environmental conditions (especially ambient air pressure, temperature and vibration) found in flight inspection aircraft, the equipment must be qualified accordingly. Even though the base units are (as required for TSO approval) qualified over an even larger environmental envelope, intensive testing of all core functions is required after modification to ensure that the newly added components work as intended and do not degrade the core functionalities in any way. Subsequently, the qualification tests do not only cover the correctness of the newly added functionalities, but also of the base units.

Calibration

A highly accurate calibration is the foundation for high-precision flight inspection measurements. To achieve the required measurement performance, various parameters must be corrected via multi-dimensional interpolations over a wide range of operating frequencies, ambient temperatures, and signal levels. The calibration data is stored in non-volatile memory within the flight inspection navigation units, allowing for instantaneous correction of all measurement outputs.

The calibration itself happens fully automated in an environmental test chamber, using calibrated signal generators, test fixtures and interconnection cables. Due to the high level of automation, the achieved performance is traceable across the operational service life.

Development Status

Even though all three flight inspection units share common basics, the development progress varies between them.

After having completed all qualifications and flight tests, the AD-FISADF-0100 ADF receiver has left the development phase and has entered the operational phase.

For the AD-FISDME-0100 DME transceiver, the technical development and qualification tests are completed, with only the final verification and flight-testing ongoing.

The AD-FISNAV-0100 VOR/ILS/MKR receiver still is under development. The hardware development has finished; the development focuses on specialized SDR algorithms and the calibration currently.

FLIGHT TEST RESULTS

The real-world performance of equipment cannot be determined by laboratory tests only but needs to be flight tested under real-world conditions. For this, the new digital flight inspection equipment needs to be compared and validated against proven legacy flight inspection equipment.

Flight tests were conducted in collaboration with the Royal Netherlands Aerospace Centre (NLR) to verify the flight inspection operation of the new AD-FISADF-0100. Two flights with identical profiles were conducted at subsequent days, one with the legacy Collins ADF462 ADF receiver and one with the new AD-FISADF-0100 installed in the automatic flight inspection system to ensure a direct and fair comparison between the two systems:

The data collection focused on the accuracy of the two critical parameters for flight inspections of non-directional beacons, the relative bearing output and the calibrated received signal strength indication (RSSI). All outputs of both receivers were recorded in the automatic flight inspection system and were used for an in-depth performance analysis.

The results showed very good agreement between the receivers and confirmed that both can be operated flawlessly in a flight inspection environment. Throughout the entire flight tests, no data loss or system resets occurred, even during maneuvers with high signal dynamics or at the edges of the station's coverage volume.

Despite some minor differences due to differently set internal low-pass filters between both receivers, the relative bearing outputs of the new receiver and the legacy ones consistently matched. The core ADF receiver of the AD-FISADF-0100 uses significantly shorter time constants, resulting in less low-pass filtering and subsequently for better performance for flight inspection purposes.

The calibrated field strength measurements (as derived from the internal digital data) showed excellent correlation with the output of the calibrated legacy ADF receiver. All measurements remained well within the acceptable tolerances defined by international flight inspection standards.

To conclude, the flight test campaign successfully proved that the digitalization of the IF signal and the use of

supplemental SDR-based analysis do not compromise the TSO-certified core functions. Instead, the high repeatability and improved data resolution confirm that the digital receiver platform is fully capable of replacing and surpassing legacy flight inspection equipment in terms of analytical depth and long-term stability.

CONCLUSIONS

The transition from legacy analog equipment to a modern, software-defined architecture marks a significant milestone in the evolution of flight inspection technology. The development of the new equipment suite successfully demonstrates that high-precision navigational analysis can be achieved by augmenting proven avionics platforms with advanced digital signal processing.

The implementation of a fully digital processing chain, based on I/Q sampling of the IF signals and band-pass undersampling, provides a level of flexibility previously not achievable in legacy flight inspection equipment. The hybrid FPGA and DSP architecture allows for the continuous, real-time analysis of complex signal parameters, such as DME pulse envelopes and VOR phase transients, without the limitations of analog filtering or component-induced drifts. This versatility ensures that the system can adapt to evolving signal environments and more stringent measurement requirements through software updates rather than hardware redesigns.

A focal achievement of these developments is the integration of analytical functions (which were only available on laboratory-grade types of equipment) in modern TSO-approved equipment. By utilizing a certified baseline receiver for primary navigation and accessing its digital internal communication buses for additional analysis

functions, it is ensured that the flight inspection system can use measurements from both worlds.

The successful flight test campaign of the AD-FISADF-0100, conducted with the NLR, validates this approach, proving that the new fully-digital processing provides measurement accuracy and operational stability that meet or exceed flight inspection requirements.

The high repeatability, the improved long-term stability, and the extensive diagnostic capabilities of the digital flight inspection equipment suite establish it as a new benchmark for flight inspection equipment. As the industry faces the obsolescence challenge of legacy systems, this modular and software-defined platform provides a future-proof solution. By enabling more efficient, automated, and accurate measurements, this equipment is positioned to become the standard for future flight inspection systems, ensuring the continued safety and integrity of global air-navigation services.

REFERENCES

- [1] International Civil Aviation Organization (ICAO), “*DOC 8071, Manual on Testing of Radio Navigation Aids, Volume I - Testing of Ground-based Radio Navigation Systems*”, Fifth Edition, 2018
- [2] International Civil Aviation Organization (ICAO), “*Annex 10, Radio Navigation Aids, Volume 1*”, Seventh Edition, 2018
- [3] Lyons, Richard G., “*Understanding Digital Signal Processing*”, Third Edition, 2010