High-precision Reference Positioning in Case of GNSS Jamming

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ABSTRACT

Flight inspection has been using high-accuracy phase-differential GNSS reference positioning for decades. Under normal conditions GNSS-based reference positioning achieves levels of positioning accuracy meeting the requirements for calibrating CAT-II/III installations.

However, GNSS jamming (due to RFI in the used frequency bands) prevents from using GNSS as continuous positioning reference during flight inspection. It is evident that a solution is needed for flight inspection in a GNSS-denied environment. Two different approaches are possible in this situation.

Firstly, technologies like controlled radiation pattern antennas (CRPA) allow to continue receiving the satellite signals by nulling out the antennas receiving pattern in the direction of an interferer. However, not all GNSS reference positioning techniques can be realized with CRPA antennas.

Secondly, GNSS-independent sensors (like theodolites, laser trackers, inertial reference systems, line scan cameras, or video cameras) can provide a plethora of different measurements. Combining multiple sensors in a carefully set-up hybridization filter allows to estimate a continuous high-accuracy reference position, along with its uncertainty.

This paper presents various approaches with their corresponding advantages and disadvantages, and compares

the achievable performance with the requirements for different inspections.

INTRODUCTION

Due to the limited available power of the GNSS satellites and due to the free space attenuation, GNSS signals are received at very low power levels, often below the ambient noise. GNSS receivers need to de-spread the received signal in order to operate correctly.

This results in a high susceptibility of GNSS receivers on radio frequency interference (RFI). Even low power interferers can deny any GNSS positioning over a large area.

In flight inspection and procedure validation, GNSS plays a vital role on multiple levels. Next to its use for GNSS-based instrument flight procedures, it has become the major source for a high-precision positioning reference.

An example for the required performance of a positioning reference system is detailed in the ICAO DOC 8071 [1]. The most challenging requirements are for flight inspecting instrument landing systems (ILS). Depending on the ILS category and the kind of measurements, different minimum positioning accuracies are required.

Both ILS transmitters (localizer and glideslope) provide angular outputs. For angular reference measurements with the same origins, the limits are given in Table 1. These limits are e.g. for elevation/azimuth angles provided by a theodolite located in close vicinity to the respective transmitting antenna. The constraint points depict the ILS points at which it is most critical to meet the requirements.

Table 1: Minimum Positioning Accuracies for Angular Measurements [1]

	Category I		Category II		Category III	
Angular Values	Constraint Point	Accuracy	Constraint Point	Accuracy	Constraint Point	Accuracy
Localizer	C	0.02° - 0.06°	T	0.0058° - 0.0173°	D	0.0058° - 0.0173°
Glide Path	C	0.0091 Θ	T	0.0055 Θ	T	0.0055 Θ

With the availability of absolute positioning references (e.g. using GNSS), these required angular accuracies were transformed [4] into the absolute positioning accuracies shown in Table 2. For this, the angular accuracies at the most critical point (constraint point) were transformed in order to achieve a comparable level of overall performance. Due to the different constraint points, the absolute accuracies for a localizer measurement differ between CAT-II and CAT-III installations, even though the angular accuracies are identical.

ICAO DOC 8071 however does not restrict the use of any reference positioning principle, as long as it meets the given accuracy requirements. All uncertainties (and accuracy requirements) in DOC 8071 are given as 2-sigma values. If a normal distribution can be assumed, this results in a probability of approximately 95% that a measurement value is within the given interval.

Table 2: Minimum Positioning Accuracies for Absolute Measurements [1]

	Category I		Category II		Category III	
Absolute Values	Constraint Point	Accuracy	Constraint Point	Accuracy	Constraint Point	Accuracy
Cross Track	C	2.17 m	T	0.61 m	D	0.33 m
Vertical	C	0.27 m	T	0.083 m	T	0.083 m

Some national regulators however require all reference positioning algorithms and principles to be certified and approved, which adds significant challenges and efforts to any changes in reference positioning.

In the last decades, virtually all flight inspection operations were based on phase-differential GNSS principles with ambiguity resolution. With fixed ambiguities, the resulting accuracy is sufficient for all operations. However, with more and more areas being heavily affected by radio frequency interference in the GNSS bands, this approach is no longer feasible in these regions.

This has severe consequences for flight inspection operations in these areas. If GNSS jamming for instance regularly affects the primary GNSS receivers of approaching aircraft, well operating conventional navigation aids (like VOR, DME, or ILS installations) are required to provide precision guidance, especially for approach and landing operations. However, if a flight inspection for a specific installation cannot be carried out due to the effect of GNSS interference on the flight inspection reference positioning, the ground navigation aids fall out of their flight inspection intervals, invalidating their usability for normal operation.

This is why it is crucial to have contingency plans for flight inspections in GNSS-denied scenarios. Two different mitigation strategies are detailed in this paper. The first option is to continue with operating with GNSS even in case of GNSS jamming. This is possible with so called anti-jam GNSS systems. The second option is to use alternative GNSS-independent sensors to ensure a sufficient level of performance without relying on GNSS.

One important aspect of GNSS jamming is that this does not only affect the navigation of an aircraft, but also a plethora of other advisory and warning systems (like TAWS, wind shear advisories, etc.) as well as surveillance systems (like ADS-B). Even if a conventional approach can be flown without GNSS, these systems (to which the pilots are used to) are not available, resulting in a higher workload and possibly a loss of safety margins.

USE OF GNSS ANTI-JAM TECHNOLOGY

GNSS anti-jam technology targets on mitigating the effects of radio frequency interference (RFI) on GNSS receiver, so that GNSS-based positioning remains possible even in case of strong interferers. Used in flight inspection aircraft, these systems can ensure that some GNSS-based reference positioning solutions remain available even in case of strong radio frequency interference (RFI).

Principle

The usable GNSS signals are transmitted from the respective satellites and are usually received from elevation angles above the horizon. In contrast, most GNSS interference is transmitted from the ground, so that it is received from elevation angles below the horizon.

Anti-jam systems benefit from these spatial differences by using controlled radiation pattern antennas (CRPA). These allow to attenuate signals coming from certain directions (the interferers), while maintaining a high level of sensitivity for other directions (the GNSS satellites).

The general block diagram of an anti-jam system is shown in Figure 1. The elements of the antenna array (four in this example) are connected to a control unit via phase-synchronized RF cables. In the control unit, the individual RF signals are precisely delayed using phase shifters. The phase shifters can be seen as elements of variable electrical lengths, which can be set variably. The phase shifted RF signals are then combined via a power combiner. The resulting combined RF signal can then be connected to any GNSS receiver, for which the anti-jam system does not differ from any active GNSS antenna.

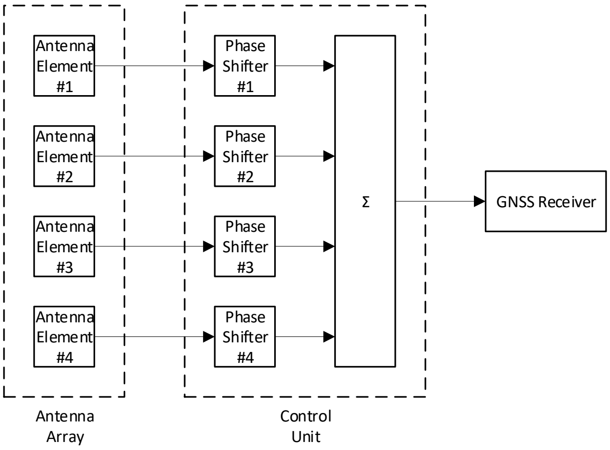

Figure 1: General Overview of a GNSS Anti-Jam System

The resulting sensitivity of the antenna (which is shown in an antenna diagram) is highly dependent on the orientation and characteristics of the individual antenna elements, as well as the applied phase shifts. Depending on the elevation/azimuth, the different signals overlay either constructively or destructively, so that the sensitivity for a specific direction is either increased or decreased significantly.

This general principle has been used in various applications for years (e.g. beam forming or electronically steered radars). In contrast to these modes of operation (which are targeting at providing best sensitivity in a certain direction), modern GNSS anti-jam systems use a complement strategy called “nulling”. Nulling ensures that the overall reception sensitivity remains constant, but that specific areas of the reception pattern ensure a high level of attenuation. In principle, using an antenna array consisting of N elements, GNSS anti-jam systems can generate $N-1$ nulls at specific directions.

Given a certain antenna array, the crucial factor for a high-performance anti-jam system is the proper selection of the individual phase shifts. The phase shifts of the individual elements (also called weights) are not constant, but are updated continuously and precisely by the controller, depending on the current RFI situation. The algorithms for selecting the optimal phase shifts usually are proprietary and not publically known.

Installation on flight inspection aircraft

Aerodata AG has successfully integrated GNSS anti-jam systems for customer aircraft, which are intended to operate in heavily affected areas. The installed commercial anti-jam system consists of an eight-element antenna array and a corresponding control unit, which allows the system to suppress up to seven individual interfering signals with an attenuation of approximately 50 dB. In contrast to the block diagram shown before, the anti-jam system uses digital signal processing on a field programmable gate array (FPGA) instead of analog signal processing.

The anti-jam system is currently connected via an RF switch to the FIS GNSS receiver. This software-controlled switch allows to either use the controlled reception pattern antenna (CRPA) or the conventional fixed reception pattern antenna (FRPA) for reference positioning. While the reference positioning is based on the FRPA in nominal conditions, the CRPA can be used in case of GNSS RFI.

This installation (without its use for primary navigation guidance) was approved via a supplemental type certificate (STC) as part of the modification, without any operational constraints. An example installation on a flight inspection jet aircraft is shown in Figure 2. The anti-jam system is only approved to support the reference positioning for flight inspections currently, even though Aerodata is actively working on allowing its use for the primary aircraft guidance if this is denied due to excessive GNSS RFI.

Figure 2: GNSS Anti-Jam Antenna (Marked) Installed on the Fuselage of a Flight Inspection Aircraft

In addition to the anti-jam system, modern commercial GNSS receivers already include sophisticated algorithms for interference mitigation. These algorithms can further improve the overall behavior in case of GNSS interference. Primary GNSS receivers (i.e. TSO-approved GPS receivers approved for aircraft navigation) on the other hand usually do not include any of these mitigation algorithms due to the additional certification efforts necessary. Instead, TSO-approved receivers are strictly tested according to the respective minimum operational performance specifications (MOPS) in order to ensure reliable and reproducible operation in a typical aircraft environment. This is why the behavior of primary and commercial GNSS receivers can differ significantly even for the exactly same interference.

Limitations

As presented in the previous section, GNSS anti-jam systems can be very beneficial to allow a continuous operation in case of GNSS jamming. Unfortunately, their use also includes some drawbacks and limitations.

First, phase-differential GNSS positioning is not working reliably with CRPA systems. The phase center of controlled radiation pattern antennas depends on the current anti-jam settings and changes continuously during operation. Phase center variations are known to limit the resulting performance of any phase-differential GNSS positioning significantly. This results in challenges validating fixed phase solutions.

Second, it has to be emphasized that the integrated anti-jam system is not certified for primary navigation. Even though qualified for a wide range of environmental conditions and in trouble-free operation on various platforms, the installed anti-jam system was not formally tested against all requirements for a TSO approval. This is why its use is currently limited to the flight inspection system. Its use for supporting primary navigation in case of GNSS RFI is currently under investigation.

Third, anti-jam systems are considered a military technology, which requires end-user statements and export licenses. This adds an additional organizational challenge, especially regarding schedules for a FIS modification.

GNSS-INDEPENDENT POSITIONING METHODS

With the upcoming availability of global navigation satellites systems in the late 1980’s and early 1990’s, most flight inspection operators switched their reference positioning to GNSS-based algorithms. This clearly indicates that the use of GNSS had numerous advantages over the existing legacy systems – and still has.

However, most legacy systems of the generation before the widespread use of GNSS were analog systems. Thus, with radio frequency interference limiting the availability of GNSS-based positioning, the main question is if these systems (in a modernized form) can still be of use for GNSS-independent reference positioning, or if other systems and approaches can help to provide a performant reference positioning without GNSS.

In the following sub-sections, some of the legacy systems as well as potential sources will be presented in more detail. Given that no system can act as a direct replacement for GNSS-based positioning, the combination of various sensors is essential for meeting all reference position requirements. This hybridization is detailed at the end of this section.

Theodolite

Theodolites (as shown in Figure 3) are one of the oldest principles to obtain a reference position for flight inspection purposes. An operator needs to control the theodolite manually to keep the aircraft in boresight. The resulting azimuth and elevation angles are usually transferred to the flight inspection aircraft via a digital datalink. Installed in close vicinity of the inspected systems (i.e. close to the localizer or glideslope antennas), the angular measurements are directly comparable to the angular localizer / glideslope deviations. The automatic flight inspection system (AFIS) on board of the aircraft thus can use the received angular measurements of the theodolite directly with the deviation measurements of the onboard ILS receiver. This allows for easy consistency checks, but implies that the location of the theodolite needs to be changed when switching from localizer to glide slope inspections.

The main challenges in using a theodolite are low visibility conditions and the proficiency of its operator to follow all deviations of the aircraft precisely. Without any way of separating tracking errors from actual deviations, the overall results rely on the skills of the operator. However, with a skilled and proficient operator, theodolites are still in operation today, mainly for contingency reasons.

Figure 3: Modern Digital Radio Telemetry Theodolite (DRTT)

In practice, theodolites are most beneficial in situations without big relative changes of the position of the aircraft – i.e. especially for approaches. Of course, requiring line-of-sight with the aircraft, its operation is limited in low visibility conditions.

Laser Tracker

Laser trackers (as shown in Figure 4) can be a powerful tool for reference positioning. Consisting of a ground based laser and a corresponding reflector on the airplane, these systems do not only output angular elevation and azimuth angles, but also slant range measurements. Capable of tracking a locked target automatically, a laser tracker is capable of following a flight inspection aircraft with a high precision.

For this, laser trackers require a bidirectional telemetry link. The flight inspection aircraft sends its approximate position to the laser tracker for locking on initially. Then, the laser tracker uplinks the elevation, azimuth, and distance measurements to the aircraft. As this allows determining the aircraft's absolute position very precisely, a single laser tracker location can be used for inspecting both glide slope and localizer installations. However, two operational limitations led to a decrease in operational use.

Figure 4: Automatic Laser Tracker

On the one hand, the laser tracker ground stations used rather powerful lasers to ensure a sufficient range. With the increasing regulation on laser devices (due to their hazards to human eyes), the approval process for operating laser trackers became challenging.

On the other hand, airborne laser reflectors (as shown in Figure 5) are rather large. This results in a significant influence on the airplane's performance characteristics and noise. In addition, is not clear which of the mirrors the laser tracker has locked. This can result in rather substantial absolute positioning ambiguities.

Figure 5: Laser Reflector Mounted Underneath Aircraft

Due to these reasons, laser trackers were only in very limited use in the last decade, and are no longer commercially available.

Inertial Reference System

Airborne inertial reference systems (IRS) have been used in positioning and navigation for decades. Modern strapdown IRS (i.e. without a mechanical gimballing frame) use the acceleration and angular rate measurements of an inertial measurement unit (IMU) to continuously estimate the current position, velocity and attitude.

Figure 6: Inertial Reference Systems (Left: Avionics IRS, Right: Commercial IRS)

Due to the integration of the raw measurements, the overall position accuracy of an IRS degrades over time. As the vertical information degrades fastest, virtually all IRS include the static barometric pressure from an air data computer (ADC) in order to stabilize the vertical channel, i.e. the altitude estimation of the IRS. This is usually accomplished by using Bayesian filters (like Kalman filters). These filters use the IMU data to propagate the state vector (along with the corresponding covariance matrix) with a very high rate. Additional measurements (which are usually only available at lower rates) are used to update the state vector and the covariance matrix.

The duration an IRS can continue to deliver a guaranteed level of service without further updates depends on the quality of the integrated IMU [1]. For instance, a high-performance IRS could guarantee a drift in the magnitude of 1 NM / hour, so that an RNP10 requirement could be met for multiple hours. As such high quality IMUs are rather expensive, many airplane integrators chose hybrid navigation systems instead. These can use less expensive IMUs with higher errors, but use other external sensors (GNSS in most cases) to deliver a sufficient level of performance – even if this level cannot be maintained for extended periods without GNSS.

For this IRS+GNSS hybridization, different coupling strategies are in use. In loosely-coupled systems, the IRS and the GNSS are used independently from each other to estimate two distinct positions, which can be compared rather easily. Operating independently, these systems require high-grade IMUs in order to meet the performance requirements. In tightly-coupled systems on the other hand, the raw IMU measurements are coupled with GNSS measurements in a joint positioning algorithm. This nominally allows for best performance, as some errors can be estimated rather precisely. This allows tightly-coupled systems to achieve an acceptable level of performance with lower-grade IMUs.

The main focus of inertial reference systems over the last decades was to coast GNSS outages while minimizing the complexity and costs of the equipment. However, with more and more GNSS spoofing attacks, tightly-coupled IRS (which use GNSS measurements to compensate for various errors) can be ruined quickly. Without the possibility to crosscheck the IRS and GNSS position independently, pilot reports indicate that some GNSS spoofing attacks lead to aircraft leaving their assigned tracks. GNSS spoofing is currently not considered during the development and testing of equipment, resulting in an inconsistent behavior of different systems. In general, loosely coupled systems allow crosschecking the position solutions and are able to inform the pilots in case of error, while deeply coupled systems do not allow this.

GNSS spoofing itself comes in various forms and complexities, ranging from simple replay or use of signal generators, up to complex attacks tailored to a specific aircraft and/or avionics. Without alternative means of navigation or surveillance, GNSS spoofing attacks can lead to misleading and hazardous conditions easily.

This has direct consequences for flight inspection aircraft: depending on the actual requirements, different inertial reference systems need to be integrated, ranging from rather low-grade systems (relying on the availability and correctness of GNSS) up to high-grade systems with very good free-inertial performance specifications. In addition, if a primary IRS is to be used (for instance because it is already integrated into the intended aircraft), its strict certification and limited interfaces cause challenges on the integration. In this regard, commercial systems (which can be configured in high detail) allow to implement a way better overall performance, especially with other external sensors as detailed in the next sections.

Conventional Ground Navigation Aids

The positioning accuracy using conventional navigation aids (e.g. DME/DME or VOR/DME) is rather limited compared to GNSS-based systems and depends on the respective ground installations. The achievable performance per se is not sufficient to meet the positioning requirements of Doc 8071.

However, even low-precision position updates from conventional navigation aids can help to limit the maximum position errors of a free-running inertial reference system (i.e. without further absolute position updates). This prevents the IRS' attitude output from drifting away after enlonged periods without other updates.

Visual Systems

Current flight inspection aircraft integrate different kinds of visual systems, which range from downward-facing line scan cameras to high-definition video cameras on the nose of the aircraft. In general, all visual systems (using optical sensors) rely on good visual conditions for a stable and reliable operation. Special emphasis has to be put on the reliability of visual systems under a wide variety of environmental conditions (like lighting, precipitation, surface contamination, clouds, fog, etc.) during operation. However, the performance of visual systems is generally linked to the visibility conditions.

Downward-facing line scan cameras have been used in flight inspection aircraft for decades. An example for a raw image while overflying a threshold is shown on the left side of Figure 7. Each horizontal line in this image was taken at a specific time.

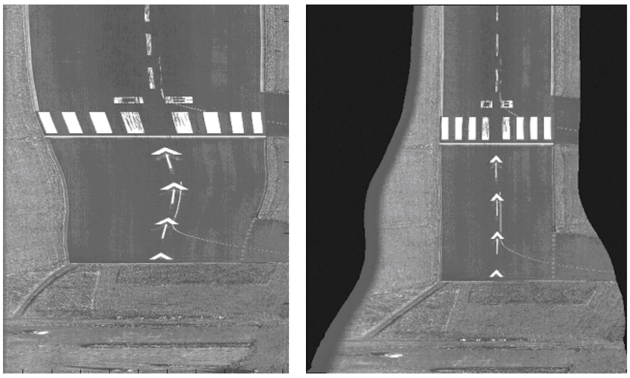

Figure 7: Line Scan Camera Images during Overflight of Runway Threshold. Left: Raw Image, Right: Corrected Image

As this image is heavily affected by changes in the attitude and relative altitude, the first step is to compensate for this. This is done independently for each measurement and results in a rather undistorted image of the runway (as shown in the right side of Figure 7). The correction values originate from an inertial reference system and the laser distance meter.

The position of the threshold is determined fully automatic. Together with laser range measurements to the determined position, a complete 3D offset to the threshold coordinate is calculated. By doing this twice for both thresholds of a runway during an overflight, the two absolute position updates are combined with the data of the inertial reference system in order to estimate its current errors and to obtain a continuous reference trajectory for the complete approach. The resulting accuracy meets the requirements of ICAO Doc 8071 described above.

In the last years, more and more visual camera systems were integrated in flight inspection aircraft. Ranging between one to three high-definition cameras (ref. Figure 8) and primarily intended for procedure validation, documentation, and improved situational awareness, these camera systems could also be used as positioning sensors.

Figure 8: Triple Visual Camera System on Nose of Flight Inspection Aircraft

The video cameras can provide positioning updates via different strategies. One example is to use computer vision algorithms to obtain relative positions to stationary features at known positions (e.g. the edges of a runway). This is not yet implemented by Aerodata, but was demonstrated by the TU Braunschweig within the research project C2Land [3]. By continuously detecting stationary features (like the edges of the runway), determining the relative deviations to this feature (along with corresponding accuracy estimates), and integrating with the IRS data for an approach, a continuous high-accuracy reference trajectory can be calculated for an approach. Even though the individual measurements are not overly precise, a complete forward-backwards optimization of all data allows calculating a high accuracy reference trajectory.

Of course, the achievable performance of this approach depends on the number, installation locations, objective lenses, overall quality, and calibration accuracy of the cameras. An aircraft installation integrating multiple cameras can be used to track the relative position to different features, in order to improve the overall accuracy.

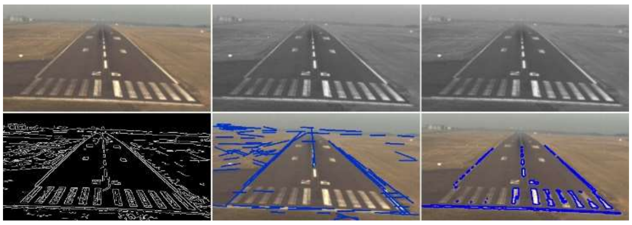

Figure 9: Image Processing and Feature Extraction in Research Project C2Land [3]

Hybridization

As no individual system can meet all performance requirements under all circumstances, the hybridization of multiple systems with different characteristics is required. In general, the main goal here is to combine the advantages of multiple systems in order to mitigate the limitations of any individual systems.

Inertial reference systems always require some kind of aiding for stable positioning. Thus, most inertial reference systems use a two-step Bayesian filter as shown in Figure 10. The primary purpose of this filter is to determine the current state vector (which usually includes the position, along with other parameters) and its uncertainty (the covariance matrix) optimally.

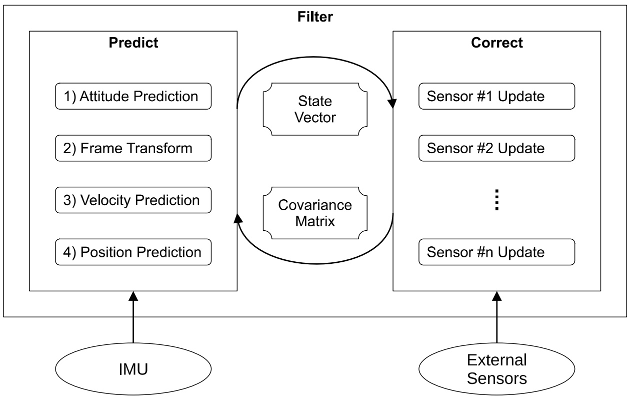

Figure 10: Prediction and Correction in a Hybrid Positioning Filter [2]

The predict step uses the measurements of the IMU in order to advance the estimated state vector to the current time. In order to obtain best performance, this prediction happens at a high rate (up to 1000Hz). However, with all measurement errors being amplified by the processing, the variances of the estimated state vector elements can only increase during this step.

This is why external updates are needed to stabilize the performance and to decrease the variances. Different sensor updates can be implemented in parallel. A specific update is only executed when new measurements of that sensor are available. The updates accuracy is also taken into account in order to weight the update relative to the state vector and its uncertainties.

This "prediction" and "correction" principle has been used for decades, primarily for IRS-GNSS integration. However, the same principle can also be used to integrate other inputs (like the systems described before). By implementing specific update steps for the different external updates, the resulting positioning accuracy can be improved to meet the requirements.

This hybridization of different sensors can be done both in real time or during post processing. If post-processing is an option, it is possible to optimize the hybrid filter's performance over a specific trajectory, both in forward and backward direction. One example is the integration of threshold updates with a line scan camera. The IMU data is hybridized with the two updates (time and relative distance to the thresholds) in order to obtain a precise and continuous reference solution meeting the requirements of DOC 8071 for approaches.

In this context, the availability of the inertial reference system's interfaces is a challenge. While high-performance commercial systems allow obtaining all measurements with high update rates and precisions, primary inertial reference systems usually output this data in lower update rates and with reduced precision. This is why Aerodata recommends integrating a commercial high-performance inertial reference system whenever operation without GNSS is required.

In addition, Aerodata recommends the installation of a commercial IRS instead of an avionics IRS due to two advantages. On the one hand, commercial systems can be configured very flexibly, which allows to implement external state updates in order to obtain more stable performance when operating in GNSS-denied environments. On the other hand, commercial IRS are available in different performance grades, so that a cost-effective solution can be chosen depending on the customer's requirements.

This way, Aerodata can offer a wide toolbox of solutions in order to allow its AeroFIS operators to perform flight inspections over a wide variety of environmental conditions reliably. This allows to use GNSS updates if available, and to use other systems otherwise.

CONCLUSIONS

The primary mission of an automatic flight inspection system is to ensure continuous, accurate, and reliable flight inspections under all conditions, with the reference positioning being one key cornerstone. With the GNSS spectrum more and more under pressure, Aerodata offers a plethora of alternatives for operating the AeroFIS in GNSS-denied areas.

For this, each customer can choose from various sensors and systems. These sensors and systems will then be integrated in a way to ensure best overall performance and reliability, as well as a high degree of automation.

Of course, without GNSS interference (both in air and on ground), phase-differential GNSS can be used. With its high precision and reliability, it remains the most convenient option for a high-precision reference position and is considered the baseline scenario.

The first line of defense against GNSS RFI is the use of an anti-jam CRPA system, which can be used with the FIS GNSS receiver in case of RFI. Even though no phase-differential GNSS positioning is achievable, such a system allows the continuing use of (differential) GNSS, even with strong interferers present. However, as the positioning performance of differential GNSS is sometimes not sufficient to meet the requirements for CAT-II/III installations, other means of positioning must be used in these scenarios.

In order to allow customers to meet all requirements under all conditions, Aerodata recommends the integration of a distinct commercial inertial reference system for the flight inspection system. In contrast to primary IRS installations, a commercial IRS can be configured freely to integrate different external state updates and to output all needed parameters with a high precision and update rate.

For the optimal integration, a coupling algorithm integrates the IRS measurements and the external position updates (from the optical systems) over one measurement approach. By combining the drifting, but high-rate and continuous inertial measurements with fewer absolute external position updates, most errors of the inertial navigation can be corrected. The result is a continuous, high precision and GNSS-independent reference position solution, which meets all requirements towards a flight inspection reference positioning system.

Other systems like theodolites should be considered primarily as backup solutions. Even though meeting all requirements in principle, the low degree of automation requires a proficient operator, a good setup and good visual conditions to actually being able to deliver the required performance.

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