TECHNOLOGICAL TRENDS FOR FUTURE NAVIGATION SYSTEMS

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1 Abstract

The purpose of this paper is to show how technological trends in satellite based radio navigation (GNSS), combined with the increasing capability of MEMS inertial sensors, and advanced hybridization techniques, might impact navigation systems for commercial aircraft or helicopters in the future.

This article describes the performance status of these technologies, and the potential advantages or drawbacks of new solutions on operational use, safety, reliability and physical characteristics such as weight and volume.

2 Context

Commercial aeronautics actors are facing today the challenge to give a satisfactory answer to several technical, political and financial constraints, sometimes contradictory. :

- Increasing traffic,
- Reduction of the environmental impact of operations,
- Hard competition, inducing the need for a strong and continuous cost reduction,
- Demanding passengers and operators, requiring for instance access to the most remote and difficult airports in all meteorological conditions
- Increased independence from ground infrastructure.

The Navigation Systems must contribute to answer these needs. Any new technique must then be analyzed regarding its capability to provide an adequate positioning solution:

- Increased approach accuracy without ground infrastructure;
- Identical landing performance, but obtained with “lighter” ground means (lower maintenance/calibration), and less sensitive to local perturbations.
- Guaranteed integrity, with increased availability.
- Resistance to Interference

These new capabilities must not impede the expected diminution of acquisition cost (linked to manufacturing costs), neither operating cost (maintenance, mass, electrical consumption).

Simultaneously, several technological evolutions are underway:

- Space Based Augmentation Systems to the GPS constellations have been or are being qualified (WAAS, EGNOS, MSAS…),
- Dual frequency GPS (L1/L5) should be available around 2018
- The first Galileo services should be available around 2015,
- MEMS (i.e. Micro Electro Mechanical Systems) inertial sensors, even if they cannot offer the required performance for high grade equipment, might provide in the medium term an intermediate performance with much lower cost, mass and volume,
- GNSS/inertia blending techniques allow getting the best of each sensor (long term precision for GNSS, dynamic and autonomy for inertia).

After an overview of current capabilities, we will examine some of the benefits induced by the emerging technologies, and the tradeoffs which might be considered.

3 Issue

The Navigation sub-system onboard an aircraft fulfills two System Level Functions:

- The *Primary Reference* Function: this function provides the critical piloting parameters necessary to control the flight; the computed parameters are air data, attitudes, angular speed and acceleration. The needs have evolved recently, due to penetration of Electrical Flight Control systems (automatic monitoring, and filtering), and due to new functions such as «Gust Load Alleviation ». This leads to stronger requirement in terms of latency, bandwidth, accuracy and safety.
- The *Aircraft Positioning* Function: this function provides the position, speed and time reference, enabling more accurate and safer guidance of the aircraft. In particular, Aircraft positioning must fulfill the new requirements for En Route (RNP), Approach (RNP AR, …) and Landing operations.

4 Requirements

4.1 Primary Reference

The inertial part of the Primary Reference function is provided by inertial systems. They can be of two types: AHRS (ARINC 705) or IRS (ARINC 704 or 738).

Regional aircraft mostly use AHRS, while Main Line aircraft use IRS.

The accuracies specified by Arinc 704 (IRS) and Arinc 738 (ADIRU), are (2σ values):

- Attitude : 0,1°
- Heading : 0,4°
- Speed : 8 kts

Safety and availability requirements on these parameters are very stringent: Information Loss or Erroneous Undetected Data are classified as catastrophic failures. That is why classical architectures often rely on:

- Two or three primary channels (IRS or AHRS)
- One or two standby channels with a lower performance

Complementary inertial sensors are sometimes used for electrical flight control (mechanical structure modes mastering, redundancy for monitoring, etc…). These sensors also offer a performance significantly lower than IRS or AHRS.

Air Data System is not addressed in this paper, which concentrates on issues linked to inertial, satellite navigation, and hybridizing techniques.

4.2 Positioning

The performances required for the Positioning Function depend on the operational phase. They are mostly defined, including availability and integrity, in RTCA DO236B standard (Required Navigation Performance for Area Navigation). Salient requirements are summarized hereafter:

Flight Phase		Accuracy	Name	Integrity
Oceanic/ Remote	2D	10 Nm	RNAV 10	10^{-5} (/h)
		4 Nm	RNP 4	
En Route/ Continental/ Terminal	2D	5 Nm	RNAV 5	
		2 Nm	RNAV 2	
		1 Nm	RNP 1	
Non Precision Approach	2D	0,3 Nm	RNP APCH	10^{-5} (/h)
	3D	0,1-0,3 Nm	RNP AR	10^{-7} (/h)
		16 m horizontal 4 m vertical	LPV	10^{-7} (/approach)
Landing	3D	3,6 m horizontal 1 m vertical	GLS Cat I & II	
			GLS Cat III	10^{-9} (/approach)
Ground Surveillance/ Guidance	2D	6m		10^{-5} (/h)
		0,5m		

Figure 1

While performance standards for Primary Reference have not changed recently, those for Positioning undergo a significant transformation, driven by two main factors (cf Figure 1):

- New RNP standards for Non Precision Approach
- Increasing use of GPS for approach and/or landing (GLS). GLS is based on differential GNSS information, and consists in visualizing lateral and vertical deviations compared to a fixed trajectory, as for present ILS system.

4.3 NON FUNCTIONAL REQUIREMENTS:

The above functional requirements must be satisfied in a context where competition induces strong constraints, implying reduction in:

- Acquisition cost (i.e. equipment manufacturing cost),
- Operating cost (mass and electrical power consumption ….).

5 PRESENT SOLUTIONS

"Navigation" grade inertia (IRS) provides an autonomous positioning information with a 2Nm/h (95%) drift, and is able to offer the accuracy required for a transoceanic flight, without any ground radio navigation aid (VOR, DME). It also supplies autonomously the attitude (0.1°), heading (0.4°) and speed (8 kts) parameters necessary to fly the aircraft in any operational phase.

The positioning for En Route and Terminal phases, which essentially relied on radionavigation aiding, is now stated as "primary GPS": during the operation, the navigation system chooses the <u>best estimated position</u> from GPS/IRS Hybrid, GPS only, or ground navaids. For the Approach phase, the navigation also relies on the same range of choice but new LPV procedures require an increase in the accuracy of GPS solution, via SBAS constellations such as WAAS, EGNOS…

The Positioning for landing (decision height equal to or less than 200 ft) requires ground infrastructures. These ground installations were up to now radio ILS beacons (sometimes MLS). They will be progressively replaced, in the next decade, by GPS based infrastructures: "GBAS" augmentation. In this case, the required accuracy and integrity enhancements are obtained with a ground receiver, whose position is perfectly known, emitting towards the aircraft corrections on propagation and satellite errors. These corrections are then used onboard to improve the accuracy and integrity of the A/C receiver.

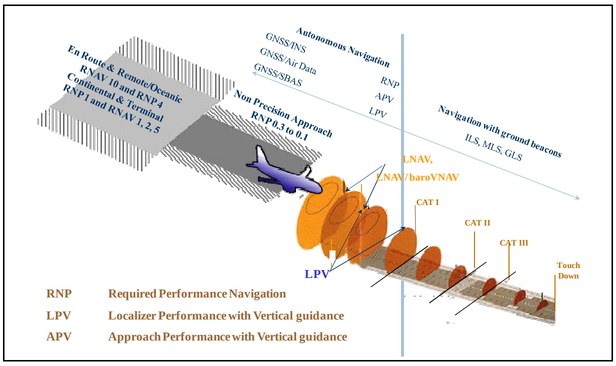

Figure 2

To understand the current architecture solutions, here are some highlights:

- Heading information can only be obtained with
  - o An IRS
  - o A "Super-AHRS" (S-AHRS) inertial system. A Super-AHRS is capable of an autonomous alignment and provides attitude and heading information slightly less accurate than an IRS; it can also provide an autonomous speed and position but those parameters are significantly less precise than IRS.
  - o An AHRS ("Tactical grade" or less), fitted with a magnetic heading sensor.
- The inertial performance required for Electrical Flight Controls Systems, must be provided by an IRS or a S-AHRS, mainly due to monitoring constraints.
- Inertia/GPS hybridizing can improve the heading and position/speed accuracies, without any complementary hardware;
- A GPS receiver with two antennae can supply heading and some attitude information. But this GPS based information raises two problems: availability/continuity of GPS signal (on ground and airborne) and accuracy/integrity. Such solutions contravene the initial principle of autonomous primary reference system.
- For the same reason, using GPS as sole mean for positioning during phases outside landing raises the problem of signal availability. For illustration

purpose, figure 3 below shows a worldwide cartography of present GPS availability, obtained with the DO-229C 24 GPS satellites constellation. There are several areas where the Horizontal Alarm Limit (HAL) of 0.2 Nm (RNP AR performances) is not guaranteed without interruptions ranging from several minutes to over ten minutes. Nevertheless, Thales patented hybridizing techniques with high grade inertia already ensure 100% availability, in any place in the world, even with a single satellite failure.

Today, aircraft not requiring specific performance like RNP AR with 100% availability can be equipped with AHRS/S-AHRS and GPS. This is the case for most of regional aircraft. On the other side, aircraft requiring 100% operational availability, even in the most remote zones, need IRS type inertial systems, coupled with GPS.

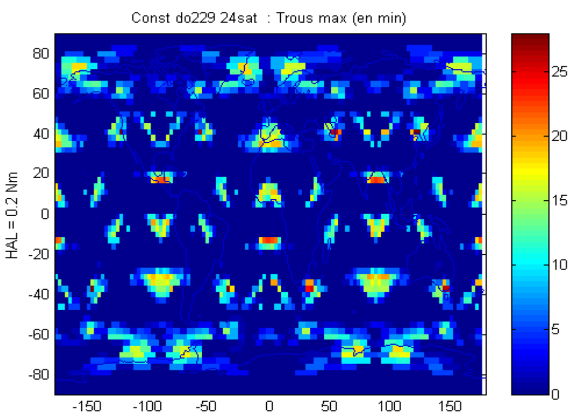

Figure 3

6 Evolution Trends

We will now analyze how the expected evolutions on satellite navigation systems (GPS, Galileo…), inertial sensors and hybridization algorithms may impact the functional architecture of systems, or the physical characteristics of the equipments, while offering new advantages in terms of operation capability, safety or cost.

6.1 Inertial technologies

Inertial performance offered by today's sensors technology is shown hereafter. The trend can be summarized as follows:

- MEMS technology has already demonstrated its capability to satisfy the whole range (a few mg to 80µg) of the accelerometer performances. But this evolution, if considered alone, will bring relatively limited cost and volume improvements.
- MEMS gyros will quickly become available for the AHRS class (5°/hr). It is also expected that next decade will see MEMS gyros with long term repeatability better than 1°/hr. If a hybrid alignment and hybrid attitude are allowed, the requirement on pure inertial heading and position performance will be restricted to a "coasting" period limited in time (the coasting is activated if GPS signals disappear). The impact on a typical inertial equipment will then be very spectacular:
  - Volume and mass for each equipment can be reduced by 40 to 50%
  - Reliability will be multiplied by 2

The issue then becomes: can GNSS and algorithmic evolutions be used not only to improve figures with the same equipments but also to keep the same level of performances while opening the door to the MEMS technology breakthrough?

Equipement Type	Sensor Performances (Repeatability)	Equipment Performance (95%)	Accel Technology	Gyro Technology
IRS (A738)	80µg - 0,01°/h	autonomous alignment attitude 0,1° heading 0,4° 2Nm/h	Accessible to MEMS MEDIUM term	RLG, FOG, HRG
S-AHRS	100µg - 0,05°/h	autonomous alignment attitude xx Heading 0,5° Coasting 4Nm/h ou 0,3Nm/10'	Accessible to MEMS MEDIUM term	RLG, FOG, HRG
S-AHRS lower grade	100µg - 0,5°/h	Limited autonomous alignment Attitude xx Heading 3° Coasting 15Nm:h ou 0,3Nm/5'	Accessible to MEMS MEDIUM term	Accessible to MEMS LONG term
AHRS (A705)	1mg - 2,5°/h	Attitude 0,5° Magnetic heading 2° (5°/h)	MEMS already available	Accessible to MEMS MEDIUM term
Stand-By Instruments or Flight Control Sensors	X mg - Y hundreds °/h	stby attitude from TSO Flight control depending on the A/C	MEMS already available	MEMS already available

Figure 4

6.2 GNSS TRENDS

Figure 5 hereunder shows what the second GPS frequency (L5), and Galileo system can bring towards requirements dealing with RNP, approach, landing, and airport navigation.

Galileo services are expected to be qualified in several steps:

« Satellite only » services:

- OS: Open service (availability #2015) : it will provide a service equivalent to dual frequency GPS. The integrity device will be of the RAIM type, at receiver level (RAIM algorithm uses redundancy offered by the satellites in view to isolate a potentially failed one). As for GPS, Galileo Open Service, combined with IRS type inertia, will enable worldwide 2D RNP, 100% of the time
- SoL : Safety of Life (available around 2020) : this service, with a potentially restricted access, might offer integrity information included within the SoL signal. It will enable a 3D approach worldwide capability 99.9% of the time. Such performance is only available today in the areas covered by GPS satellite based augmentation systems (EGNOS, WAAS…).

Regional and local services:

- These services might also be qualified and certified around 2020. They would rely on EGNOS augmentation, as for GPS. EGNOS would then evolve towards the “MRS” (Multi-Regional System) concept, based on several constellations and frequencies.

Galileo will have a worldwide, real-time, 99.95% of time, ground positioning accuracy of 6m. This accuracy will be obtained without ground beacons.

Dual frequency GPS, on the other hand, will probably not be able to provide this level of accuracy/availability outside the coverage area of SBAS systems.

Flight Phase		Accuracy	Name	Integrity	GNSS Configuration & coverage
Oceanic/ Remote	2D	10 Nm	RNAV 10	10^{-5} (/h)	GPS L1 or Galileo OS
		4 Nm	RNP 4		
En Route/ Continental/ Terminal	2D	5 Nm	RNAV 5		
		2 Nm	RNAV 2		
		1 Nm	RNP 1		
Non Precision Approach	2D	0,3 Nm	RNP APCH	10^{-5} (/h)	
	3D	0,1-0,3 Nm	RNP AR	10^{-7} (/h)	GPS L1 + IRS + advanced Hyb techniques (worldwide 100%) or Galileo OS + IRS without advanced HYB
		16 m horizontal 4 m vertical	LPV	10^{-7} (/approach)	GPS L1 SBAS (regional) or Galileo SoL (worldwide)
Landing	3D	3,6 m horizontal 1 m vertical	GLS Cat I & II		GBAS / GPS L1 or Galileo SoL
			GLS Cat III	10^{-9} (/approach)	GBAS / GPS L1 (TBC) or GBAS/GPS L1/L5 or Galileo SoL
Ground Surveillance/ Guidance	2D	6m		10^{-5} (/h)	GPS L1 SBAS (regional) or Galileo SoL (worldwide)
		0,5m			combination GBAS + others

Figure 5

Preliminary studies show that a typical receiver capable of processing both GPS and Galileo constellations (Multi Constellation Receiver) will have the same surface and power consumption as current single constellation receivers.

6.3 HYBRID SOLUTIONS

The purpose of this paragraph is to assess the impact of the inertial sensor performances on the final hybrid (INS/GNSS) performances.

The simulation, based on a transatlantic flight, takes as an assumption the pure inertial performance and the availability of GNSS.

During the simulated flight, two classes of performances are computed.

- One is the improved Hybrid inertial performance thanks to the blending with GNSS,
- The other one is the coasting capability of these Hybrid inertial parameters after GNSS disruption. The coasting capability corresponds to the time necessary, after GNSS loss, for the Hybrid inertial parameters to exceed the required performance.

Note: The coasting capability is not a regulatory requirement, since any airplane is able to fly on standby instruments, with reduced operational capability though, when the main systems fail.

The quantification of the coasting capability in the figure 6 is therefore given for comparison purposes only in terms of holding the operational capability.

It s possible to extract some trends from the results

- In the presence of GNSS, post 2015 MEMS gyros, blended with dual antenna GNSS, can provide the same Primary Reference and Positioning performances as current IRS systems. After GNSS loss, the simulated coasting time vary between few minutes to few tens of minutes.
- The same MEMS gyros, without Dual antenna GNSS, but with a magnetic heading sensor, will have a coasting time between 10 and 20 minutes, not including the heading which is provided by the magnetic sensor (heading perf around 1 deg)
- In the same conditions, an AHRS shows a coasting capability close to zero.

The Purpose of the Figure 6 below is to show comparative results, not to give exact values.

Equipement class and configuration	Inertial Sensor Repeatability	Accessible to MEMS techno	Speed (kts)			Attitude (°)			Heading (°)			Positioning
			Pure inertial	Blended with GPS	Coasting Time (8kts)	Pure inertial	Blended with GPS	Coasting Time (0,1°)	Autonome (i.e. sans GPS)	Blended with GPS	Coasting Time (0,4°)	Coasting Time (RNP 0,1)
IRS (A738)	80µg / 0,01°/h	Non	<8 kts (=4,1 m/s)	<0,1m/s	no limitation	<0,1°	<0,1°	no limitation	<0,2 °	<0,1°	no limitation	13 '
S-AHRS	100µg / 0,05°/h	Non	10 m/s	0,1m/s	30 '	0,2°	<0,1°	no limit ation	0,8°	<0,1°	no limitation	8 '
Lower Grade S-AHRS with Dual Antenna GPS	100µg / 0,5°/h	Long Term	65 m/s	0,1 m/s	10 '	0,4°	<0,1°	50 '	6°	0,3°	45 '	5 '
Lower Grade S-AHRS with magnetometer				0,1 m/s	9 '	0,4°	<0,1°	18 '	2°	2°	0 '	
AHRS (A705) with Dual Antenna GPS	1mg / 2,5°/h	Medium Term	several 100 m/s	0,1 m/s	3 '	0,5°	0,1°	0 '	NA	0,4°	0 '	2 '
AHRS (A705) with magnetometer				0,1 m/s	3 '	0,5°	0,1°	0 '	2°(5°/h)	2,5°	0 '	

Figure 6

7 Conclusion

Two evolutions trends have clearly been highlighted by this article. The final choice will depend on the emphasis and priorities placed on the parameters

- Improvement on Performance or Safety with the same cost
- Improvement on the Cost of Possession with the same Performance

8 Glossary

ADIRU: Air Data Inertial Reference Unit
AHRS: Attitude & Heading Reference System
APV: Approach Procedures with Vertical Guidance
DME: Distance Measuring Equipment
GBAS: Ground Based Augmentation System
GLS: GNSS Landing System
GNSS: Global Navigation Satellite System
GPS: Global Positioning System
HAL: Horizontal Alert Limit
ILS: Instrument Landing System
IRS: Inertial Reference System
LPV: Localizer Performance with Vertical guidance
MRS: Multi-Regional System
MSAS: Multi-functional Satellite Augmentation System
RAIM: Receiver Autonomous Integrity Monitoring
RNAV: Area Navigation
RNP: Required Navigation Performance
RNP APCH: RNP Approach
RNP AR APCH: RNP Authorization Required Approach
RTCA: Radio Technical Commission for Aeronautics
SBAS: Satellite Based Augmentation System
S-AHRS: Super Attitude & Heading Reference System
VOR: Very high frequency Omni-directional Range
WAAS: Wide Area Augmentation System

9 References

EC-FP6 **ANASTASIA** study: Airborne New & Advanced Satellite Techniques in A System Integrated Approach
ARINC 704: Inertial Reference System (IRS)
ARINC 705: Attitude & Heading Reference System (AHRS)
ARINC 738: Air Data & Inertial Reference System (ADIRS)

RTCA DO229C: Minimum Operational Performance Standards for Global Positioning System / Wide Area Augmentation System Airborne Equipment

RTCA DO-236B: Minimum Aviation System Performance Standard: Required Navigation Performance for Area Navigation

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