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Air Traffic Control Tracking Systems Performance Impacts with New Surveillance Technology Sensors

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1. Introduction

Nowadays, the radar is no longer the only technology able to ensure the surveillance of air traffic. The extensive deployment of satellite systems and air-to-ground data links lead to the emergence of other means and techniques on which a great deal of research and experiments have been carried out over the past ten years.
In such an environment, the sensor data processing, which is a key element of an Air Traffic Control center, has been continuously upgraded so as to follow the sensor technology evolution and, at the same time, ensure a more efficient tracking continuity, integrity and accuracy.
In this book chapter we propose to measure the impacts of the use of these new technology sensors in the tracking systems currently used for Air Traffic Control applications.
The first part of the chapter describes the background of new-technology sensors that are currently used by sensor data processing systems. In addition, a brief definition of internal core tracking algorithms used in sensor data processing components, is given as well as a comparison between their respective advantages and drawbacks.
The second part of the chapter focuses on the Multi Sensor Tracking System performance requirements. Investigation regarding the use of Automatic Dependent Surveillance – Broadcast reports and/or with a multi radars configuration, are conducted.
The third part deals with the impacts of the "virtual radar" or "radar-like" approaches that can be used with ADS-B sensors, on the multi sensor tracking system performance.
The fourth and last part of the chapter discusses the impacts of sensor data processing performance on sub-sequent safety nets functions that are:

- Short term conflict alerts (STCA),
- Minimum Safe Altitude Warnings (MSAW), and
- Area Proximity Warnings (APW).

2. Air traffic control

Air Traffic Control (ATC) is a service provided to regulate the airline traffic. Main functions of the ATC system are used by controllers to (i) avoid collisions between aircrafts, (ii) avoid

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collisions on maneuvering areas between aircrafts and obstructions on the ground and (iii) expediting and maintaining the orderly flow of air traffic.

2.1 Surveillance sensors

Surveillance sensors are at the beginning of the chain: the aim of these systems is to detect the aircrafts and to send all the available information to the tracking systems.

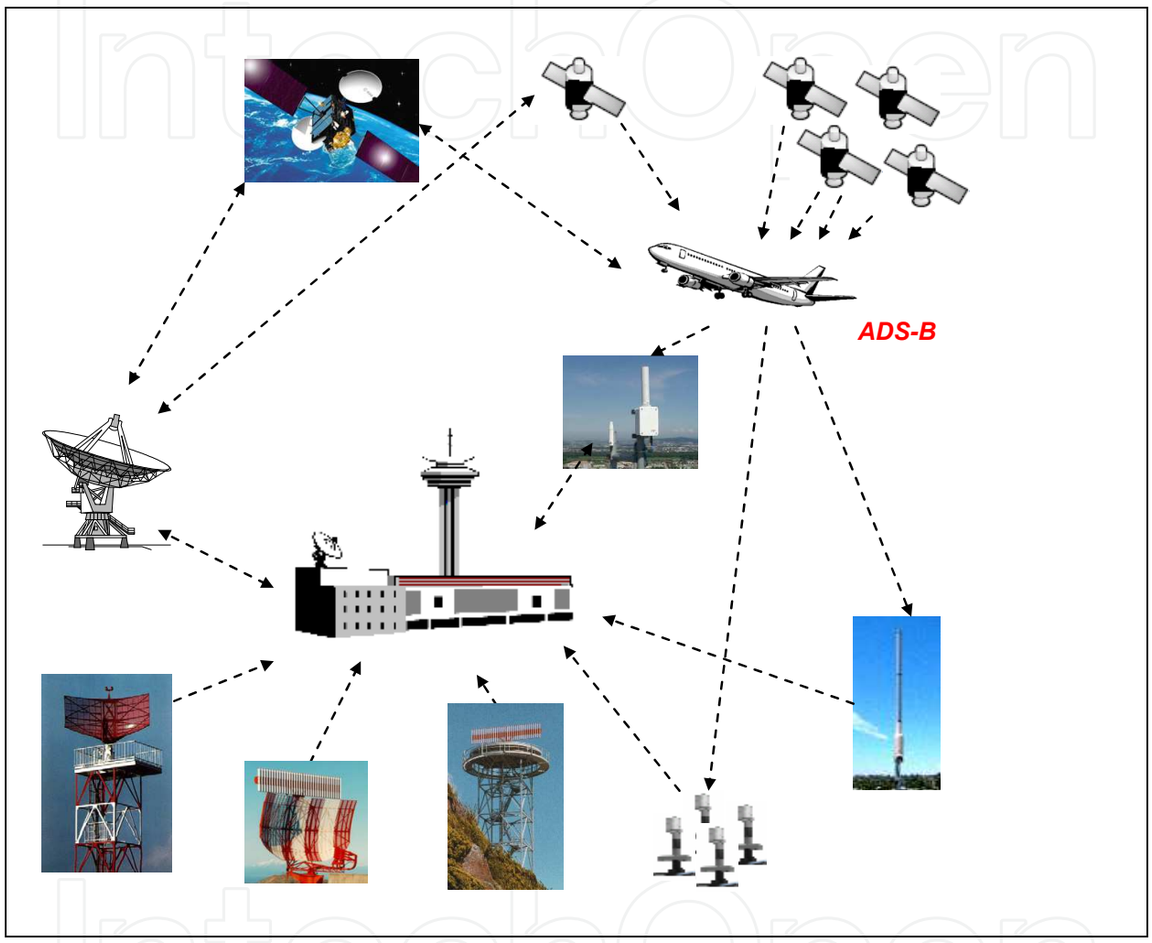

Fig. 1. Surveillance sensor environment

Current surveillance systems use redundant primary and secondary radars. The progressive deployment of the GPS-based ADS systems shall gradually change the role of the ground based radars. The evolution to the next generation of surveillance system shall also take into account the interoperability and compatibility with current systems in use.

The figure 3 above shows a mix of radar, ADS and Multilateration technologies which will be integrated and fused in ATC centers in order to provide with a high integrity and high accuracy surveillance based on multiple sensor inputs.

2.1.1 Primary Surveillance Radar (PSR)

Primary radars use the electromagnetic waves reflection principle. The system measures the time difference between the emission and the reception of the reflected wave on a target in

order to determine its range. The target position is determined by measuring the antenna azimuth at the time of the detection.
Reflections occur on the targets (i.e. aircrafts) but unfortunately also on fixed objects (buildings) or mobile objects (trucks). These kind of detections are considered as parasites and the "radar data processing" function is in charge of their suppression.
The primary surveillance technology applies also to Airport Surface Detection Equipment (ASDE) and Surface Movement Radar (SMR).

2.1.2 Secondary Surveillance Radar (SSR)

Secondary Surveillance Radar includes two elements: an interrogative ground station and a transponder on board of the aircraft. The transponder answers to the ground station interrogations giving its range and its azimuth.
The development of the SSR occurs with the use of Mode A/C and then Mode S for the civil aviation.
Mode A/C transponders give the identification (Mode A code) and the altitude (Mode C code). Consequently, the ground station knows the 3-dimension position and the identity of the targets.
Mode S is an improvement of the Mode A/C as it contains all its functions and allows a selective interrogation of the targets thanks to the use of an unique address coded on 24 bits as well as a bi-directional data link which allows the exchange of information between air and ground.

2.1.3 Multilateration sensors

A multilateration system is composed of several beacons which receive the signals which are emitted by the aircraft transponder. The purpose is still to be able to localize the aircraft. These signals are either unsolicited (squitters) or answers (SSR or Mode S) to the interrogations of a nearby interrogator system (can be a radar). Localization is performed thanks to the Time Difference Of Arrival (TDOA) principle. For each beacons pair, hyperbolic surfaces whose difference in distance to these beacons is constant are determined. The aircraft position is at the intersection of these surfaces.
The accuracy of a multilateration system depends on the geometry of the system formed by the aircraft and the beacons as well as the precision of the measurement time of arrival.
Nowadays, multilateration is used mainly for ground movement's surveillance and for the airport approaches (MLAT). Its use for en-route surveillance is on the way of deployment (Wide Area Multilateration (WAM)).

2.1.4 Automatic Dependant Surveillance – Broadcast (ADS-B)

The aircraft uses its satellite-based or inertial systems to determine and send to the ATC center its position and other sort of information. Aircraft position and speed are transmitted one time per second at least.
ADS-B messages (squitters) are sent, conversely to ADS-C messages which are transmitted via a point-to-point communication. By way of consequence, the ADS-B system is used both for ATC surveillance and on-board surveillance applications.

2.2 Sensor data processing

As shown in figure 5 hereunder, a sensor data processing is composed generally of two redundant trackers. Radar (including Surface Movement Radar) data are received directly by the trackers while ADS-B and WAM sensor gateways help in reducing the data flow as well as checking integrity and consistency.

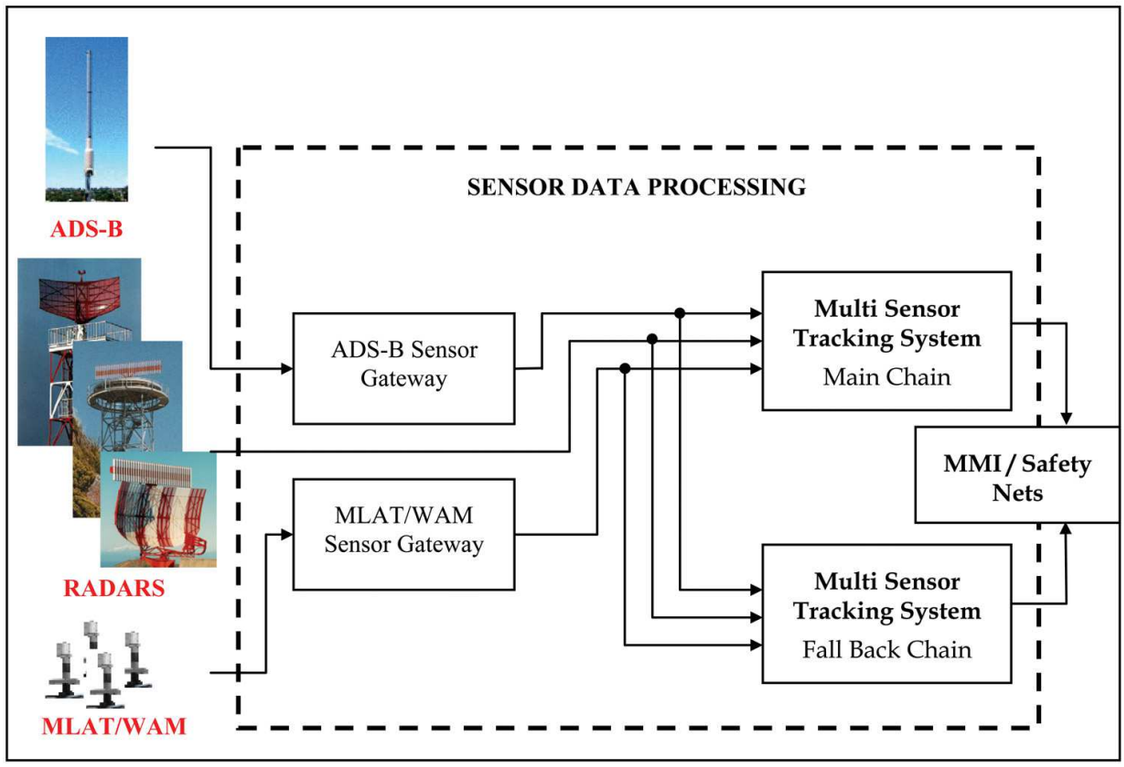

Fig. 2. Sensor Data Processing

As shown in figure 5 above, trackers are potentially redundant in order to prevent from sub-systems failure.

Sensor Data Processing architectures have been shown and discussed in details in (Baud et al., 2009).

3. Multi sensor tracking performance

3.1 Sensor characteristics and scenarios

Radar sensor characteristics are available in table 1.

ADS-B sensor characteristics are available in table 2.

Scenarios that are used to compare the horizontal tracking performance among all possible sensor configurations are composed of straight line motion followed by a set of maneuvers including turn with different bank angles.

These scenarios are mainly derived from the EUROCONTROL performances described in (EUROCONTROL 1997). They have been used to provide relative comparisons. Results extrapolation to live data feeds must take into account the sensor configuration, the traffic repartition over the surveillance coverage and specific sensor characteristics.

RADAR CHARACTERISTICS	PSR	SSR	PSR + SSR
Range	Up to 250 NM	Up to 250 NM	Up to 250 NM
Antenna rotation time	4 up to 12 s	4 up to 12 s	4 up to 12 s
Probability of detection	> 90 %	> 97 %	> 95 %
Clutter density (number of plots per scan)	40		
Nominal measurement accuracy: - Range (m) - Azimuth (deg)	 40 0.07	 30 < 0.06	 30 < 0.06
Measurement quantization (ASTERIX standard): - Range (NM) - Azimuth (deg)	 1/256 0.0055	 1/256 0.0055	 1/256 0.0055
SSR false plots (%): - Reflection - Side lobes - Splits		 < 0.2 < 0.1 < 0.1	 < 0.2 < 0.1 < 0.1
Mode A code detection probability		> 98 %	> 98 %
Mode C code detection probability		> 96 %	> 96 %
Mode C measurement accuracy (m)		7.62	7.62
Time stamp error	<= 100 ms	<= 100 ms	<= 100 ms
Nominal time stamp error (time disorder)	50 ms	50 ms	50 ms

Table 1. Radar sensor characteristics

ADS-B CHARACTERISTICS (1090ES)	NOMINAL VALUE
Range	250 NM
Refresh period	1s
Probability of detection	> 95%
Nominal Position Standard Deviation	10 m
Figure Of Merit	7
Altitude Standard Deviation	25 fts
ADS-B transponder consistency	100%

Table 2. ADS-B sensor characteristics

3.2 Simulation results

Multi sensor tracking accuracy has been evaluated among 5 sensor configurations that are:

- PSR only: radar with 4s revolution period,
- SSR only: radar with 4s revolution period,
- Multi radars configuration including 1 PSR radar, 1 SSR radar and 1 PSR + SSR radar,
- ADS-B only: one ADS-B ground station at 1s update rate,
- Multi sensors configuration that includes both multi radars configuration and the ADS-B ground station.

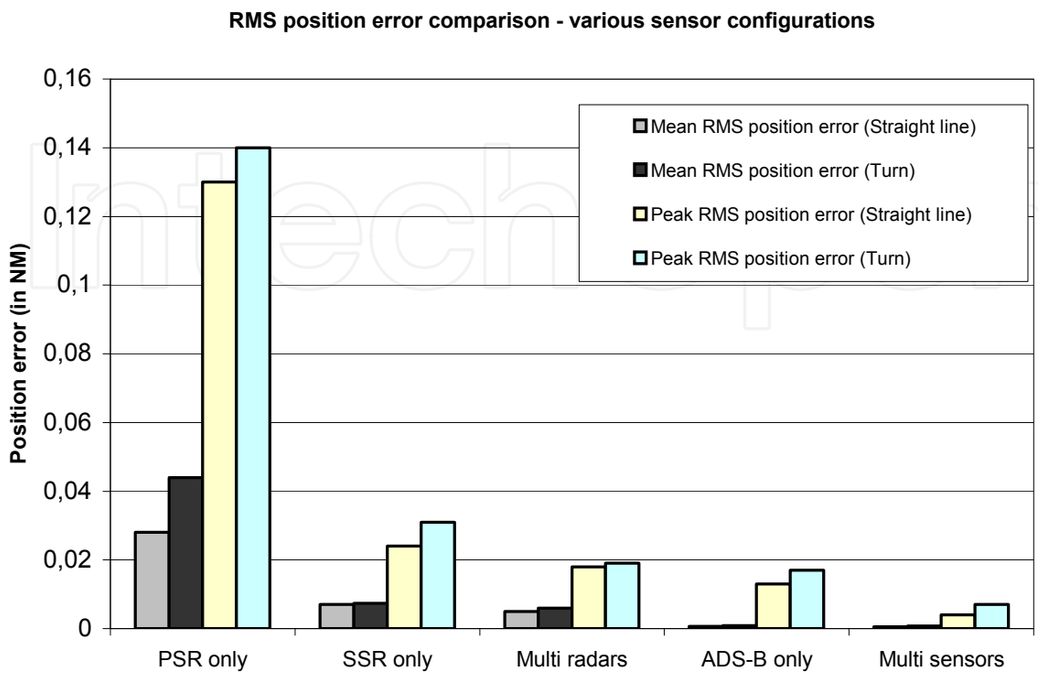

Fig. 3. RMS position error comparison

Multi sensor tracking coverage helps to globally improve the tracking performance in term of:

- Latency metrics: Latency reduced in update/broadcast modes to several hundreds of milliseconds instead of several seconds thanks to:
  - the update rate of new technology sensors (1s) compared to radar sensors (at least 4s and up to 12s),
  - the variable update technique used which does not make any bufferisation of new technology sensors data.
- Continuity/integrity metrics:
  - Possible reduction of multi sensor tracks broadcast cycle thanks to the update rate of new-technology sensors,
  - Quicker track initiation.
  - Bigger coverage areas including airport areas (MLAT) and desert areas (ADS-B) where no radar data are available,
- Accuracy metrics:
  - Improved accuracy even if the multi sensor configuration relies on one ADS-B ground station only, as can be seen on figure 3.

4. Virtual radar emulation – "radar like" solutions

As can be seen in the previous paragraph, introduction of new technology sensors in the tracking systems that are used for Air Traffic Control applications improves the global

performance of the systems compared to what is used at the current time (multi radar tracking systems).
Use of these new technology sensors require an evolution that leads from multi-radar tracking systems to multi-sensor tracking systems.

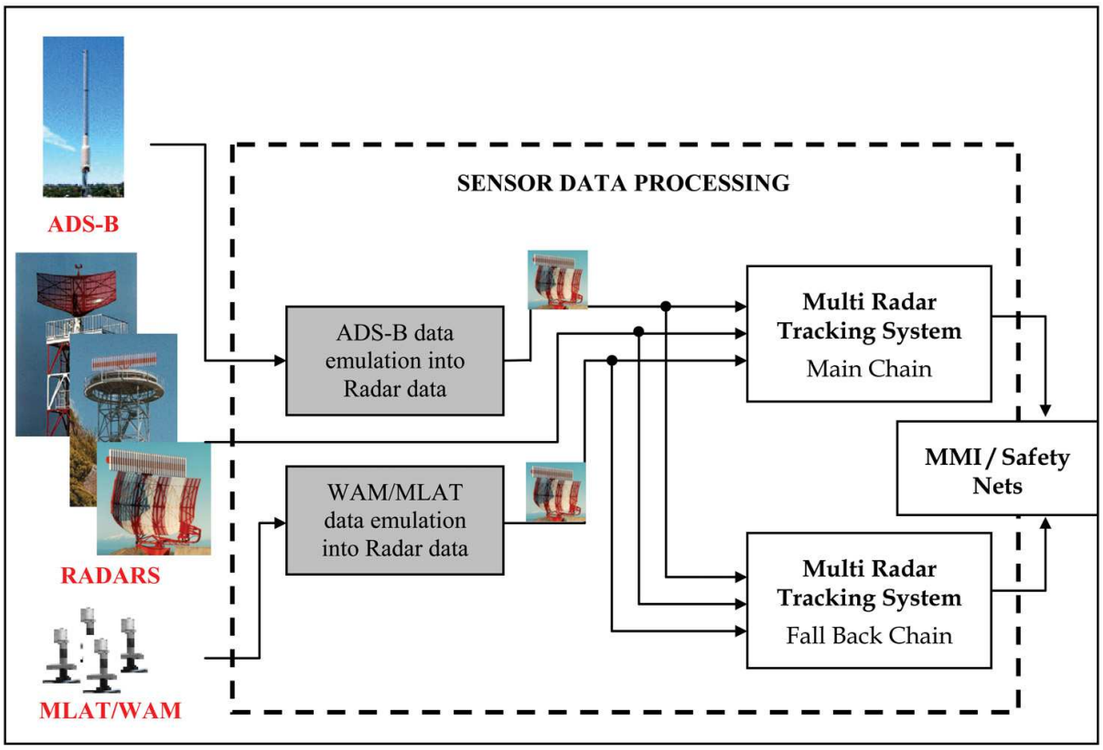

Fig. 4. Virtual radar concept

However, in most cases, the transition from the existing radar based surveillance means (network, radar data processing, …) cannot be done straight away, and the Air Navigation Service Providers mainly ask for an integration of these new sensors into the existing system by a "radar-like" or "virtual radar" approach. Then, decisions could be done to have the WAM/MLAT reports or ADS-B reports appearing as if they are from any radars. This process is explained in details in (Thompson et. Al). This concept can be shown in figure 5.
Most of the advantages of the "radar-like" or "virtual radar" approaches are discussed in (Thompson et. Al) and in (Whitman et. Al).

	"Radar like" approach with new technology sensors as ADS-B and WAM	**Multi radars tracking system**
Multi sensor coverage	Multi sensor coverage allowed: provides coverage where none currently exist.	Only multi radars coverage. When an area is covered by ADS-B only, no control can be done.
Transition from former to new technology	Allow transition and test environment	New technology sensors not used in existing systems

Table 3. "Radar like" solution main advantages

A comparison between a "radar like" approach and an integrated multi sensor fusion with Variable Update technique is done in the following table.

	"Radar like" approach	**Integrated multi sensor fusion with Variable Update technique**
Existing radar data network impacts	Degrade the quality of the ADS-B / WAM report by introducing an additional latency (at least 1s) to buffer the reports. The refresh rate is increased to typically 4s (3 report ignored upon 4) or 12s (11 reports ignored upon 12).	No latency introduced by any radar data network. The refresh rate is the one provided by the sensor itself.
Time stamping	Depending on the radar data format, the time stamping is sometimes not available.	Time stamping available in the ADS-B and WAM standard.
Fitting accurate data into useless radar format impacts	This approach is not able to associate a correct standard deviation to the polar radar coordinates. For Radar, the error standard deviation in range and azimuth are fixed. For ADS-B / WAM report, the standard deviation is not constant and mainly depends either on the satellite configuration / Inertial Navigation System precision/bias or on the geometry of the receivers.	Information available in the ADS-B / WAM standards.
Down-linked Aircraft Parameters (DAPs)	Does not allow the transmission of DAPs information including Mode S data if CD2 or ASTERIX Category 001 /002 is used to transmit ADS-B / WAM data	Information available in the ADS-B / WAM standards.

Table 4. "Radar like" solution discussion

Figure 5 provides a comprehensive comparison of the RMS position error accuracy between three configurations:

- ADS-B data are fitted into a multi sensor tracking system using Multiple Report Variable Update technique,
- ADS-B data fitted into standard radar data and multi sensor tracking system makes use of these ADS-B data as they are radar ones,
- ADS-B data fitted into useless radar data format (introducing high quantization in range and in azimuth: Common Digitizer 2 format) and multi sensor tracking system makes use of these ADS-B data as they are radar ones.

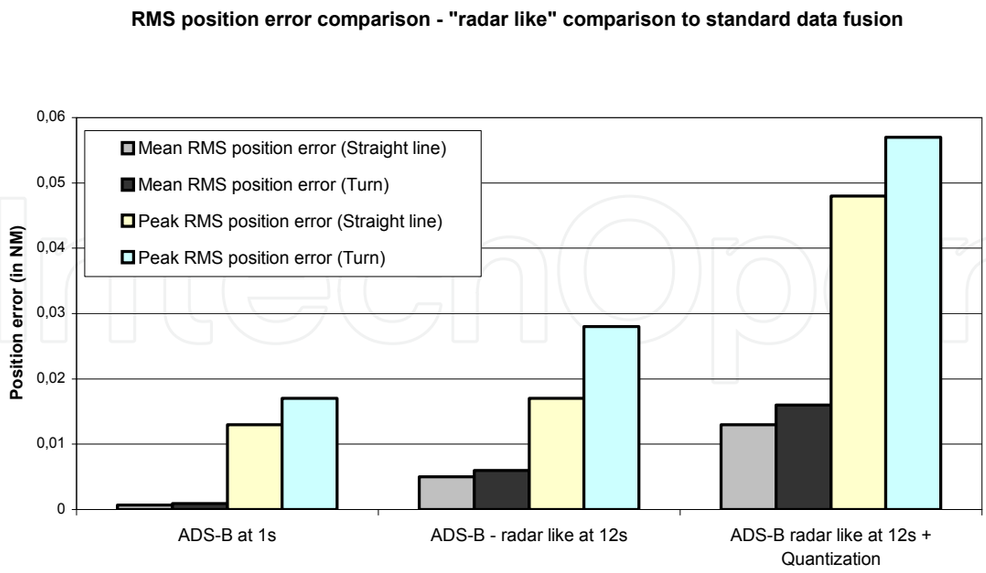

Fig. 5. RMS position error comparison between "radar like" and standard data fusion

By way of conclusion, we can say that:

- the "radar like" solution is interesting, whatever the kind of coverage:
  - when the tracking system is based on a track-to-track data fusion technique, and
  - when the ADS-B data has a high level of integrity.
- the "radar like" solution is interesting only when the area to cover is not yet covered by other kind of sensors when the existing tracking system uses a multiple report variable update technique,
- the accuracy of "radar-like" solution is worse than if we use the available ADS-B standards (see figure 5),
- the gain in term of accuracy is very low when the area is covered by multiple radars.

5. Safety Nets impacts

Safety Nets are functions intended to alert air traffic controllers to potentially hazardous situations in an effective manner and with sufficient warning time so that they can issue appropriate instructions to resolve the situation.
Safety Nets monitoring systems typically include:

- Short term conflict alerts (STCA),
- Minimum safe altitude warnings (MSAW),
- Area proximity warnings (APW).

5.1 Definitions

STCA (Short Term Conflict Alert) checks possible conflicting trajectories in a time horizon of about 2 or 3 minutes and alerts the controller prior the loss of separation. The algorithms used may also provide in some systems a possible vectoring solution, that is, the manner in which to turn, descend, or climb the aircraft in order to avoid infringing the minimum safety distance or altitude clearance.

Minimum Safe Altitude Warning (MSAW) is a sub-system that alerts the controller if an aircraft appears to be flying too low to the ground or will impact terrain based on its current altitude and heading.
Area Penetration Warning (APW) is a tool that informs any controller that a flight will penetrate a restricted area.

5.2 Performance impacts discussion

The most widely used safety net is STCA which is mandatory in many areas and appreciated by air traffic controllers. STCA requires short term trajectory predictions of up to 2 minutes. This is the maximum time over which it is considered valid to predict aircraft paths based solely on surveillance data. The trajectory data are
The utility of safety nets depends on both the reliability of conflict detection and the false alert rate. The false alert rate tends to be highest in the areas where such tools are most needed i.e. in the Terminal Major Areas and particularly during the approach and climb out phases of flight.
Safety nets function directly benefits from the more accurate state vector (position and velocity for both horizontal and vertical axis) provided by any multi sensor tracking system. Indeed, the use of more accurate information and Down-linked Aircraft Parameters such as ADS-B or MLAT/WAM, specifically in Terminal Major Areas, improves the tracking in term of accuracy.
These enhancements of the safety nets ensure safer and more efficient operations, by taking into account the development of new approach and climb procedures and by generalizing the use of user defined routes and closely spaced route networks.
The possibility of using additional information (such as Aircraft Derived Data) for improving prediction (with regard to safety issues) needs to be mentioned, as well as the technical feasibility of adapting safety nets separation parameters to aircraft types.

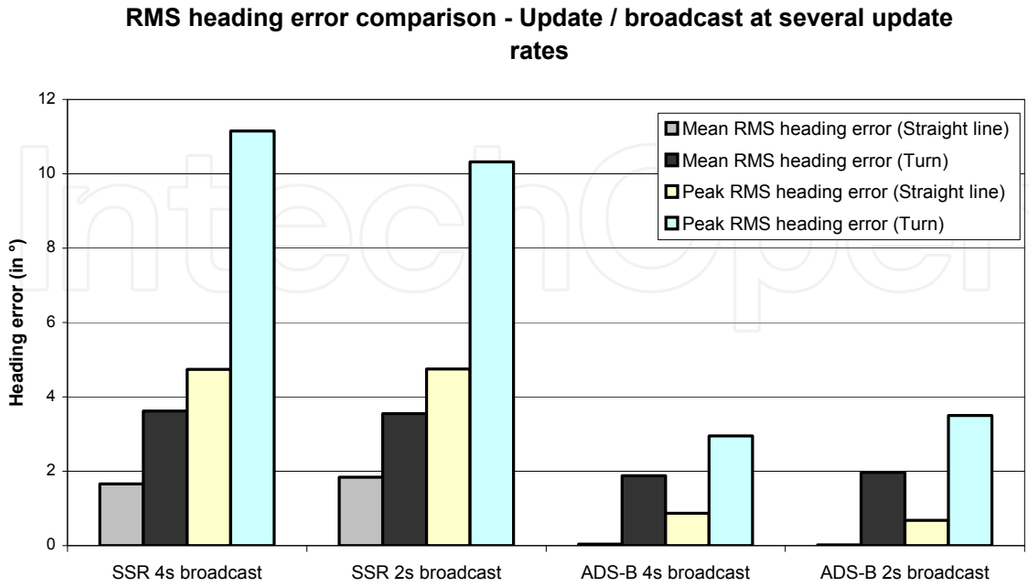

Fig. 6. RMS heading error comparison between update and broadcast at several update rates

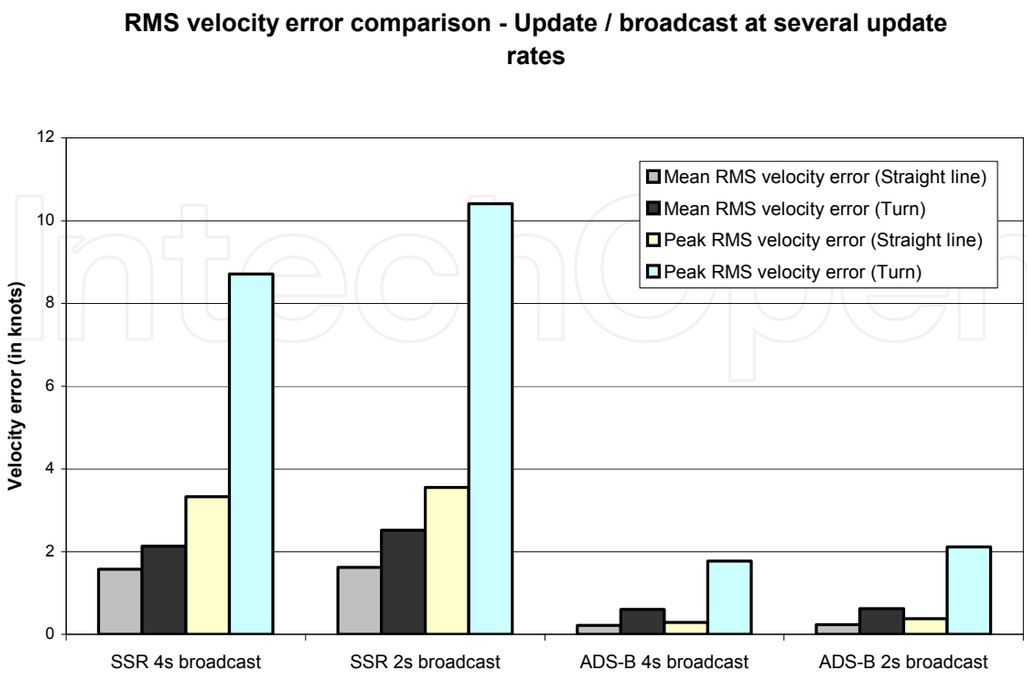

Fig. 7. RMS velocity error comparison between update and broadcast at several update rates

Multi sensor tracking performance helps to globally improve the STCA sub-system performance in term of:

- Quicker STCA detection thanks to the reduction of multi sensor tracks broadcast rate:
  - the update rate of new technology sensors (1s) compared to radar sensors (at least 4s and up to 12s),
  - the variable update technique used which does not make any bufferisation of new technology sensors data.
- Reduction of tolerances required for STCA,
- More accurate multi sensor track velocity vector as can be seen on figures 6 and 7 that leads to less false STCA's, especially for maneuvering aircrafts,
- Transmission of down-linked parameters including rate of turn and trajectory intent information that helps the STCA to enhance and predict the track state vector more accurately.

6. Conclusion

Nowadays, the development of advanced ATM systems is realized by the implementation of advanced means of communication, navigation and surveillance for air traffic control (CNS/ATM).

The definition of a new set of surveillance standards has allowed the emergence of a post-radar infrastructure based on data-link technology. The integration of this new technology into gate-to-gate architectures has notably the following purposes:

- fluxing air traffic which is growing continuously,
- increasing safety related to aircraft operations,

- reducing global costs (fuel cost is increasing quickly and this seems to be a long-term tendency), and
- reducing radio-radiation and improving the ecological situation.

In this context, sensor data processing will continue to play its key rule and its software as well as its hardware architecture is expected to evolve in the meantime. In a previous paper (see (Baud et. al., 2009)), we investigated the past and future of the sensor data processing architectures. In this paper, we have demonstrate the interest to integrate new technology sensors either in existing centers through the use of "radar-like" solutions (suitable for Non Radar Area only) or in future ATC centers in order to improve the global performance of the system.

The accuracy performances that can be seen in this paper have been achieved under the hypothesis that the new technology sensors are really accurate and have a high level of integrity. However, it's not completely the "real world" and we propose to discuss the ways to integrate inaccurate or inconsistent sensor data into multi sensor tracking systems for ATC applications in a future paper.

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