GBAS Interoperability Trials and Multi-Constellation/Multi-Frequency Ground Mockup Evaluation

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***Abstract*— In recent publications the use of different Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS, USA), Glonass (Russia) or Galileo (Europe) for improving the Ground Based Augmentation System (GBAS) had been described [1][2]. Even if not specified in the relevant standards (ICAO Annex 10 [3] and RTCA specifications [5][6][7]) yet, these additional signals offer tremendous potential for improvements regarding GBAS availability, continuity and especially integrity.**

The current planning of GBAS manufacturers and certification agencies foresees a type certificate for GBAS Approach Service Type (GAST) D ground stations in two to three years. GAST-D will then offer CAT-III approach capabilities based on GPS L1 C/A as sole usable GNSS signal. The main challenges are ionospheric anomalies threatening the integrity. GAST-D will thus require a combination of extensive airborne and ground monitoring algorithms. However, with the availability of modern GNSS signals from different core constellations (Multi-Constellation, MC) and on different frequencies (Multi-Frequency, MF), the ionospheric threat can be mitigated almost completely. Within the European SESAR 15.3.7 project, a VDB message definition for MC/MF GBAS has been proposed [1], targeting the usability of additional constellations like Galileo and additional Multi-Constellation and Multi-Frequency services for GBAS CAT-III operations.

This paper describes MC/MF GBAS concepts and discusses the provision of a MC/MF ground mockup development and provision for evaluation flight trials which took place in frame of SESAR project 15.3.7 at Toulouse airport in May 2016. TU Braunschweig (TUBS) provided as sub-contractor to EUROCONTROL the ground mockup software to establish a valid MC/MF GBAS signal-in-space (SIS) for the flight trials. In addition TU Braunschweig performed interoperability trials to test the airborne equipment with signals of different GBAS ground stations. This included Multi-Mode-Receiver (MMR) hardware from Thales Avionics as well as software packages from Japan's Electronic Navigation Research Institute (ENRI) and TUBS. The results of these trials will be described and discussed as well. The paper will close with an outlook to planned future activities.

Keywords – GBAS, Multi-Constellation, Multi-Frequency, Interoperability, Flight Trials

I. INTRODUCTION

Current certified GBAS airborne receivers and ground based installations are limited to CAT-I operations, i.e. precision approach procedures down to a decision height (height above ground at which the cockpit crew must see either the runway or at least the runway approach lights) of 200 ft. With this final visual check the pilots ensure that the aircraft is aligned on the correct path (both glide slope and localizer) and in a safe attitude. If the cockpit crew detects any offsets they either have to conduct corrective actions or initiate the missed approach procedure (i.e. going around). This operational procedure is independent from the underlying precision approach guiding system.

This GBAS service supporting CAT-I operations is called the GBAS Approach Service Type C (GAST-C) and is almost exclusively based on GPS L1 measurements only. While providing high accuracy using differential corrections, the main challenge is to ensure the necessary integrity for this crucial phase of flight, i.e. timely warnings in case of any malfunction.

Besides this GBAS CAT-I service, other GBAS services have been defined based on different operational requirements. On the one hand, the Differentially Corrected Positioning Service (DCPS) is a generic GBAS service to provide a differentially corrected position solution with very stringent integrity bounds. On the other hand, different GBAS approach services have been defined to cover different operational requirements ([6][7]):

- GAST-A: approach service to enable APV-I (Approach Procedure with Vertical guidance) operations
- GAST-B: approach service to enable APV-II operations
- GAST-C: approach service to enable CAT-I precision approach operations
- GAST-D: approach service to enable CAT-III precision approach operations

In this terminology, GAST-C is the legacy GBAS Cat-I service already in operation as described in the SARPs [3], while GAST-D is defined by the SARPs under development [4], DO-246D [6] and DO-253C [7]. In DO-253C, Appendix I, the following explanation can be found with respect to GAST-D: "*Just as with the other service types, GAST-D defines a matched set of standard airborne and ground functional requirements that when combined results in position and guidance information with quantifiable performance. However, GAST-D is different than the other defined services in that some aspects of the airborne functional requirements are not standardized. These non-standard characteristics allow the position domain NSE performance of the system to be tailored to the needs of a specific aircraft implementation.*" This means that in contrast to GAST-C operations, where the GBAS ground station must ensure the integrity of the signal based on a fault-free airborne receiver, the responsibility for meeting the integrity requirements is split between the ground facility and the airborne installation for GAST-D.

Hence, some additional airborne monitoring will be required for GAST-D operations. For CAT-III operations, guidance has to be provided to approaching aircraft even during touchdown and rollout. Thus, in addition to even more stringent requirements on the overall system's accuracy and integrity, it is not sufficient to limit the possible navigation system error (NSE). Instead, the Total System Error (TSE), combining the quality of the guidance system and the quality of the aircraft to follow the commanded path, has to be limited. This is done by an additional monitoring algorithm called "Geometry Screening". This however has to been adapted for each airplane individually. GAST-D airborne installations will thus always have to be certified together with the aircraft itself.

All GBAS services currently defined are based on single-frequency L1 GNSS measurements and are thus susceptible to threats by the Earth's ionosphere. This part of the upper atmosphere can alter GNSS signals significantly. Especially anomalous ionospheric conditions are known to pose a significant threat to GBAS operations. Using single-frequency GNSS signals only, extensive overbounding of the performance and additional monitoring components are necessary to ensure safe GBAS single frequency operations. This has been delaying the GAST-D standardization for years with respect to original time schedules. As of October 2016, the ICAO SARPs validation is going to be closed by December 2016 and will be effective by November 2018.

In recent years, more and more GNSS constellations and signals have become available, with some of these usable for aviation. GPS offers an additional L5 signal next to the legacy L1 signals. Glonass plans to incorporate an additional CDMA signal in the L5 band, too. The new GNSS constellation Galileo (European Union) and BeiDou (China) will also provide multi-frequency GNSS signals from the beginning. Hence, the use of these new components could bring a significant boost to GBAS performance, too.

Multi-Constellation GBAS (incorporating multiple GNSS constellations into GBAS processing) can increase the number of usable differentially corrected satellites enormously. Multi-Frequency GBAS on the other hand has the potential to mitigate ionospheric threats almost completely by eliminating the ionospheric delay. This can be done by combining two GNSS signals from the same satellite on different frequencies. This is why both techniques are addressed in the frame of the European research program SESAR.

Within SESAR several different projects were dedicated to future GBAS Approach Service Types. GAST-D had been in focus of SESAR 15.3.6 while Multi-Constellation and Multi-Frequency GBAS (GAST-E and -F) were in focus of P15.3.7. The airborne aspects have been handled in SESAR 9.12. The current timeframe for operational implementation of GAST-D has a target date for entry into service in the timeframe 2019/2020. For this the required documentation on ICAO level is already at an advanced level. Contributors for the SESAR projects were (besides others) the main manufacturers of GBAS airborne and ground equipment (namely Thales, IndraNavia, Honeywell, etc.). Together with already available and certified GAST-C ground stations interoperability of the airborne GAST-D equipment developments with different western manufactured ground installations had been verified. But no interoperability tests between the developments of Japan (ground station as well as airborne software) and Europe took place so far. These tests are important to prove the robustness and applicability of the GAST-D documents on ICAO level. In order to evaluate the worldwide usability of the SESAR developments and the future requirements for ICAO documents, TU Braunschweig conducted interoperability trials with onboard software developed by ENRI (Electronic Navigation Research Institute, Japan) and the SESAR GAST-D ground station prototypes. These trials were contracted by EUROCONTROL. In addition the backwards compatibility with already certified and operational GAST-C ground stations has been checked, too.

Additionally, an experimental GAST-D capable Multi-Mode Receiver (MMR) developed by Thales Avionics in the frame of SESAR 9.12 has been tested. For evaluation purposes, software-based GBAS solutions have also been checked using recorded data. Next to a tool developed by TUBS, EUROCONTROL's Pegasus toolset had been used as independent GBAS data evaluation software.

First, some flight trials have been conducted by the TUBS using the research aircraft D-IBUF. This twin-engine turboprop aircraft has been used for various GBAS-related research campaigns over the last years. After having been integrated into the aircraft and approved for the flights, the different receivers have been tested at different GBAS ground installations. In Bremen, some approaches have been flown to ensure the compatibility of the GBAS solutions with an operationally approved GAST-C ground facility made by Honeywell. At Frankfurt, one approach has been conducted using the experimental GAST-D ground station manufactured by IndraNavia in the frame of SESAR 15.3.6, which is special, as it is the only one currently using multiple transmit antennas. At Toulouse airport, flight tests have been conducted using the experimental Multi-Constellation / Multi-Frequency GBAS mockup developed in the frame of SESAR 15.3.7.

In a second step the previously described airborne hard- and software (Thales MMR, ENRI airborne software, TUBS airborne software) have been shipped to Japan to test the proper functionality of these airborne developments with a GAST-D prototype ground station manufactured by NEC and operated by Japan's Electronic Navigation Research Institute (ENRI). The results showed a seamless functionality of all tested combinations and therefore proved the interoperability of the different independent development lines. Detailed results of these tests can be found later in this paper.

Within the SESAR 15.3.7 project, future GBAS architectures are being addressed, incorporating more than one core GNSS constellation and more than just one GNSS frequency in order to allow for better ionospheric threat mitigation (especially important for low-latitude regions) and better satellite availability (e.g. for high-latitude installations). As these concepts are more advanced and will be operational only in mid-term future, 15.3.7 focused on basic architecture definition like the operating modes of MC/MF GBAS and a possible VDB formatting [1][9].

However, none of the directly involved partners was able to provide a ground station mockup suitable of transmitting a signal-in-space to support MC-/MF-GBAS in the time available. To fill this gap, EUROCONTROL issued another Call for Tenders [10] and contracted TU Braunschweig as they already had demonstrated the broadcast of MC/MF GBAS data and the use of this data in flight trials in autumn 2015[11]. The experimental GBAS ground facility simulation software used for this was adapted to support these new efforts. In a joint experiment together with Thales and the DSNA, the TUBS GBAS ground station mockup was installed at Toulouse airport in order to provide a Multi-Constellation / Multi-Frequency signal-in-space for SESAR evaluation flight trials. These trials took place in May 2016 with the participation of Honeywell's research aircraft (Falcon 900) as well as the TUBS research aircraft (Dornier 128-6, as part of the before-mentioned interoperability flight trials), see Figure 1.

Figure 1. Honeywell Falcon and TUBS Dornier at Toulouse Apron

This paper will describe the test setup of TUBS with the different components and the achieved results. The work was mainly performed by TUBS GBAS and flight test teams as subcontractor to EUROCONTROL in close cooperation with ENRI's GBAS team and the other partners involved.

II. USED EQUIPMENT

For the trials different pieces of equipment have been used. The following chapter will describe the different components.

A. *Flight Trials in Europe*

For the interoperability and MC-/MF-flight trials different equipment has been installed in the research aircraft (see TABLE I.). The Dornier aircraft was equipped with a standard Rockwell-Collins (GAST-C) MMR as well as a SESAR prototype GAST-D MMR developed by Thales. Additionally, a multi-constellation multi-frequency GNSS receiver as well as a VDB receiver had been installed to collect the raw GNSS and VDB data for online and offline processing purposes. Two different software packages were running in parallel: the GAST-D experimental software developed by ENRI in Japan [12] and the airborne MC/MF software package developed by TU Braunschweig.

TABLE I. EQUIPMENT OF RESEARCH AIRCRAFT

	Equipment	Purpose
Hardware	RC MMR 925-430	Test of interoperability and compatibility issues and baseline for the trials
	Thales MMR TLS2016	Test of interoperability of SESAR prototype
	Javad GNSS receiver	Reception of GNSS raw messages (GPS L1 & L5, Galileo E1 & E5a, Glonass)
Software	ENRI GAST-D Software	Test of interoperability issues of software algorithms developed in Japan
	TUBS GAST-D Software	Test of interoperability issues of software algorithms and baseline software

In Braunschweig (being the home base of the research aircraft), initial tests of the installation had been performed after having received the approval of airworthiness. During these tests the equipment had already been tested with the SESAR GAST-D prototype manufactured by Thales Air Systems. In addition, the MC-/MF-ground station software of TUBS had been tested, too. GAST-C approaches had been flown in Bremen (Germany) where a certified GAST-C station (Honeywell SLS4000) is installed. At Frankfurt airport a prototype of the SESAR GAST-D prototype of IndraNavia was used. Besides the GAST-D-signal-in-space the Frankfurt environment has in addition the unique characteristic that an operational GAST-C station is operating in parallel to the experimental GAST-D station and the SESAR prototype station is sending its signal-in-space via two different VDB transmitters in order to provide an improved VDB coverage.

One approach on Frankfurt's runway 25L has been performed on 29/04/2016 here (see Figure 2.).

Figure 2. Approach Frankfurt 25L

Finally the TUBS/ENRI flight experiment team participated at the evaluation flight trials of SESAR 15.3.7 which took place from 17/05/2016 to 20/05/2016 at Toulouse airport (see Figure 3. and Figure 4.). There the signal-in-space has been based on a ground station mockup developed by TUBS in combination with a VDB data telegram proposal developed by TUBS as well (see [1] and [9]).

Figure 3. Approach Toulouse 32L

As already mentioned before and listed in Table 1 different pieces of (airborne) equipment had been used during the Toulouse trials. On ground only the MC-/MF-ground mockup was used. The purpose of these trials was the validation of the developments inside SESAR 15.3.7. The software package of TUBS was installed in the hardware setup at Toulouse airport (provided and maintained by DSNA). With this setup the originally planned verification flights of the Honeywell airborne development could take place and had been finished successfully. In addition TUBS performed interoperability trials to prove that the development by ENRI was also compatible with the SESAR prototype(s). These interoperability tests were needed to validate the SARPs and documents prepared and issued on ICAO level which are the baseline for worldwide developments.

In total, 32 approaches have been conducted throughout three research flights in Toulouse as shown in Figure 4. Only one approach had to be extended due to other traffic. During all other approaches the aircraft intercepted the final approach segment at distances between 6 and 12 NM.

More detailed results can be found in chapter III but in general the interoperability of all airborne units with the MC-/MF-ground mockup was given.

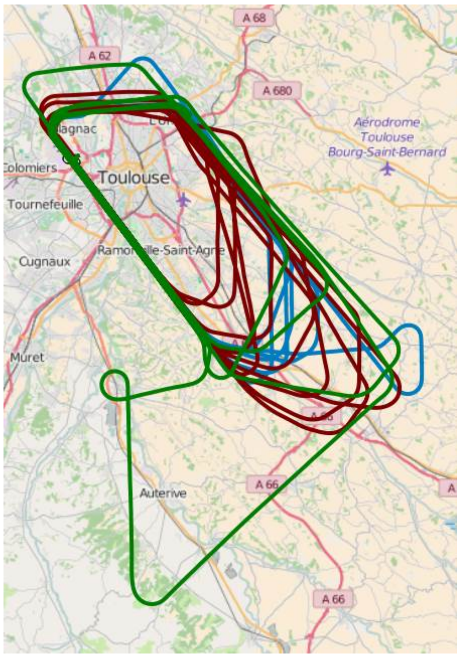

Figure 4. Flight Patterns Toulouse

B. *Static Trials in Japan*

In Japan, GBAS ground station equipment (hard- and software) as well as airborne components have been developed in recent years independently. ENRI developed together with NEC a GAST-C ground station prototype which had been installed at Kansai International Airport (KIX). This installation was already tested in different campaigns with ENRI's experimental aircraft (with a Rockwell-Collins GLU-925 MMR installed), an experimental aircraft of Japan's Aerospace Exploration Agency (JAXA, equipped with a Rockwell-Collins GNLU-930 MMR), as well as Boeing 787 aircraft operated by All Nippon Airlines (ANA) and Japan Airlines (JAL). Based on this GAST-C ground station prototype a follow-on development of a GAST-D prototype was developed and installed at Ishigaki New International Airport (ISG). This airport is located at the Island of Ishigaki in the south-western part of Japan (24.4°N, 124.1°E, Figure 5.). The special challenge of this low latitude location is the ionospheric disturbance characteristic to the low magnetic latitude region which is called plasma bubble.

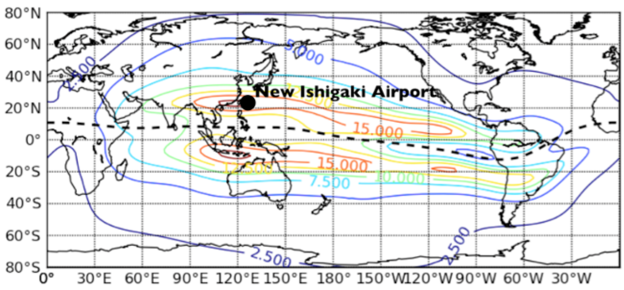

Figure 5. Location of the New Ishigaki Airport. Typical distribution of the ionospheric delay at the L1 frequency (1.57542 GHz) at 03 UT is also plotted.

ENRI also developed a GAST-D airborne experimental subsystem. It consists of hardware commercially available devices and software installed in a PC. The software installed on the PC includes major airborne integrity monitors based on the RTCA DO-253C [7] and DO-246D [6].

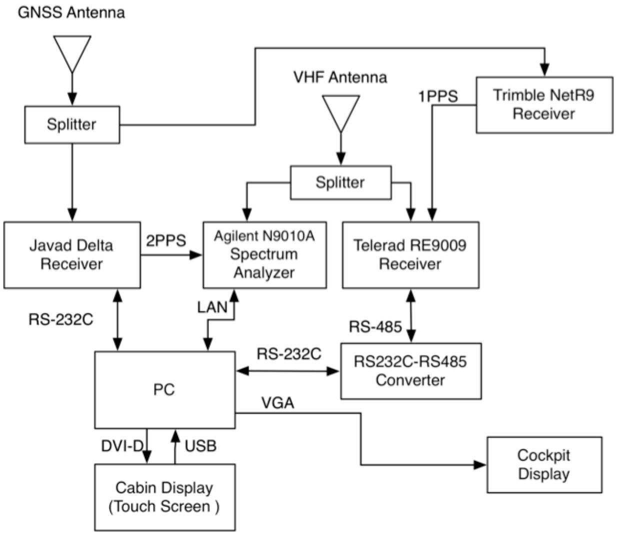

Figure 6. Block diagram of hardware of the ENRI GAST-D airborne experimental system.

In order to test the SESAR prototype airborne equipment with the experimental ENRI/NEC GAST-D ground installation, static tests have been conducted at new Ishigaki airport in June 2016. All tests have been conducted during daytime so that the measurements are not affected by plasma bubbles.

The GNSS receive antenna was located close to a TSR (Terminal Surveillance Radar) building of Japan's Civil Aviation Bureau (JCAB). The equipment itself was installed inside this building. The used antenna position as well as a virtual FAS block is shown in Figure 7. This FAS block has been broadcast by the ground installation in order to receive valid indications by the airborne receiver.

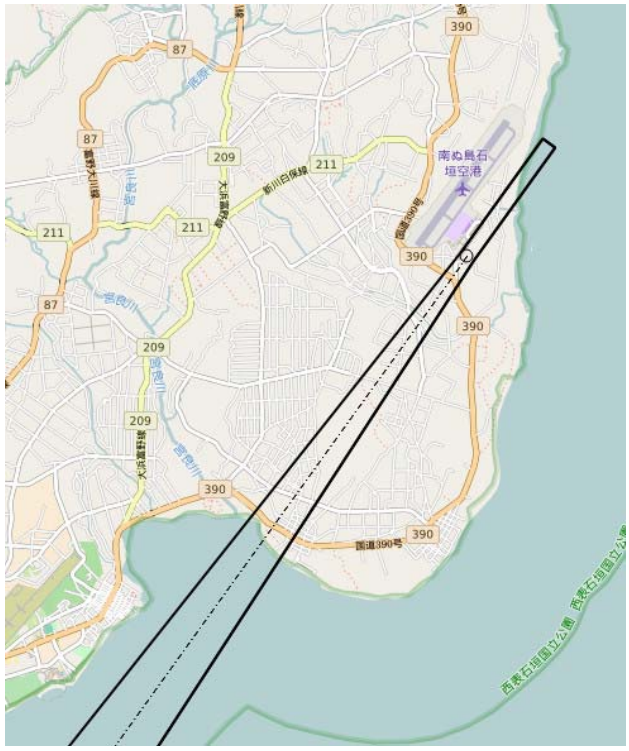

Figure 7. Map of Ishigaki airport, test site (circle) and approach definition

C. Interoperability Matrix

Multiple approaches had been performed at different GBAS ground installations in order to test the interoperability of all components (see TABLE II.). The PEGASUS toolset has been used in parallel for offline evaluation with all the mentioned systems.

TABLE II. INTEROPERABILITY MATRIX

Airborne / Ground	SESAR MMR prototype Thales	ENRI GAST-D software	TUBS GAST-D software	TUBS MC-/MF- software
Honeywell GAST-C	BRE[a]	BRE	BRE	BRE
Thales GAST-C	BRU[b]	BRU	BRU	BRU
SESAR GAST-D prototype IndraNavia	FRA[c]	FRA	FRA	FRA
SESAR GAST-D prototype Thales	BRU[b]	BRU	BRU	BRU
TUBS MC-/MF- ground mockup	TLS[d]	TLS	TLS	TLS, BRU
NEC/ENRI GAST-D prototype	ISG[e]	ISG	ISG	ISG

a. Bremen, Honeywell SLS-4000, operational

b. Braunschweig, Thales experimental & TU Braunschweig/DLR experimental

c. Frankfurt, IndraNavia SESAR prototype, experimental

d. Toulouse, Thales Hardware and TUBS software

e. Ishigaki, ENRI/NEC, experimental

III. GBAS Ground Facility Mockup

As part of the subcontract between EUROCONTROL and TU Braunschweig [10], a GBAS ground facility simulation developed by TU Braunschweig has been extended in order to allow broadcasting a VDB signal-in-space. This mockup is based on commercial-off-the-shelf (COTS) PC hardware and is running on a Linux operating system. The ground facility simulation can be configured flexibly using an XML file to include up to four GNSS receivers and to generate VDB messages for different services.

The mockup supports the VDB message types MT1, MT2 and MT4 for GAST-C, MT3 and MT11 for GAST-D as well as MT42 and MT50 for GAST-E/F. The message update rates, the respective message content and the message broadcasting scheme can be configured flexibly, too.

For the flight trials in May 2016, this GBAS ground facility mockup has been set up at Toulouse airport using several components of the existing GAST-D prototype there and additional hardware provided by the industry partners. It used two existing Multipath-limiting GNSS antennas (MLA) with specific low-noise amplifiers (L5-capable) and GNSS receivers (Septentrio PolaRx receivers). The existing serial RS485 lines have been used to connect the GNSS receivers to the mockup via an RS485 to Ethernet converter. The generated VDB data has then been broadcast using an existing Telerad VDB transmitter connected to a VHF transmit antenna. The overall setup is shown in Figure 8. .

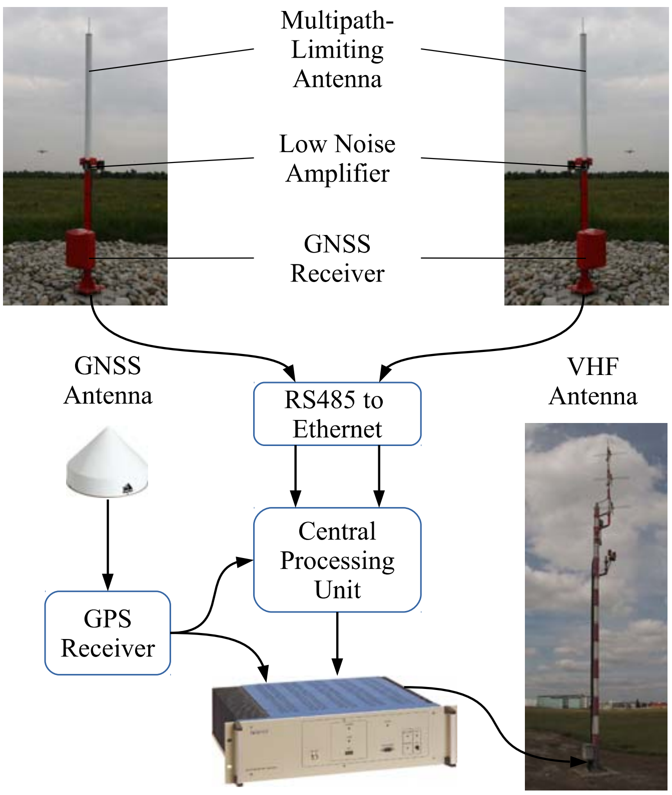

Figure 8. Components of the GBAS Ground Facility Mockup

For a TDMA-based transmission like VDB, coherent timing between all involved components is mandatory. Thus, all central components have been synchronized using a common Pulse-Per-Second (PPS) signal from an additional GNSS receiver. This signal has been used (after changing the respective voltage levels) by the central processing PC as well as the Telerad VDB transmitter. This way, a valid VDB broadcast could be achieved.

This experimental broadcast was continuously active from May 16th to 19th 2016. During this period of time, a dual-VDB transmit antenna scheme for GBAS service types C, D and F has been simulated. The broadcasting scheme of the different messages is shown in Figure 9. .

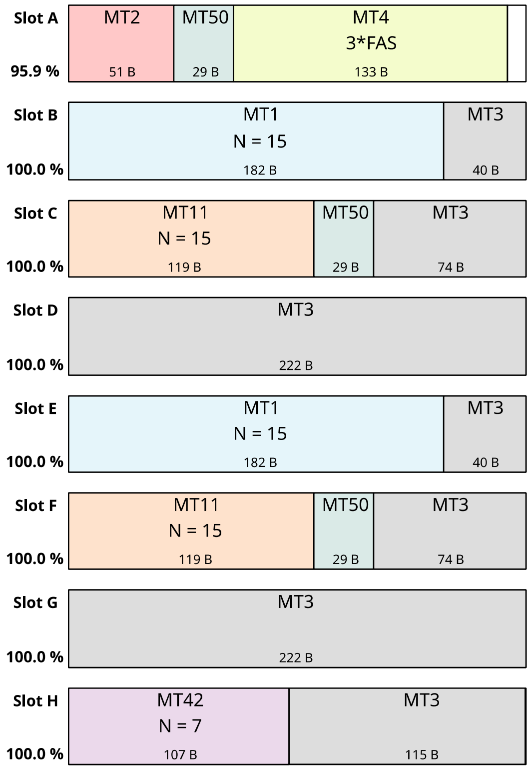

Figure 9. Timing of the different VDB messages for the Toulouse trials

IV. Data Evaluation and Comparison

The main purpose of the conducted test campaigns was to prove the feasibility of MC/MF GBAS according to the proposed VDB formatting and processing, especially with regards to the backwards compatibility with the existing GBAS services and the VHF Data broadcast.

In order to qualify the correct operations, one approach on Runway 32R in Toulouse has been used to compare the guidance information from different independent GBAS solutions as an example. Four distinct solutions have been excerpted or calculated from the recorded on-board data:

- Rockwell-Collins GLU-925: This Multi-Mode-Receiver (MMR) is capable of GBAS CAT-I

(GAST-C) and has been analyzed by its ARINC 429 output.

- ENRI software: This experimental GBAS software developed by ENRI (Japan) implements the GBAS Approach Services C and D and allows live processing of the received GNSS and VDB data. A Javad GNSS receiver and a Telerad VDB receiver have been used.
- PEGASUS: The navigation toolbox PEGASUS has been developed by EUROCONTROL and is one of the main references for GBAS processing worldwide. Even though a MC/MF implementation is being developed, GAST-D is the highest service used here.
- TriPos: This navigation framework has been developed by the Institute of Flight Guidance at TU Braunschweig and includes experimental GBAS processing for GAST-C, GAST-D, GAST-E as well as MC/MF.

All GBAS solutions were able to provide valid GBAS approach guidance for their respective approach service all the time. Of course, a performance assessment is not meaningful due to the experimental ground mockup. Nevertheless a comparison of the different GBAS services allows validating the correct overall operation.

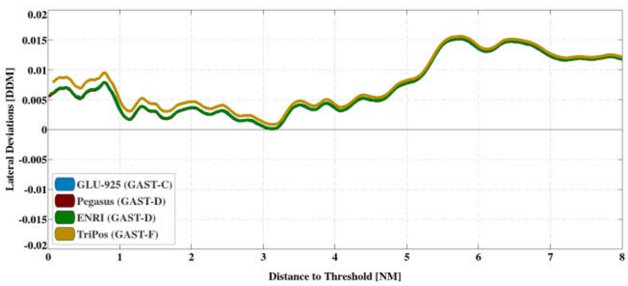

Figure 10. Lateral Deviations for a Single GBAS Approach

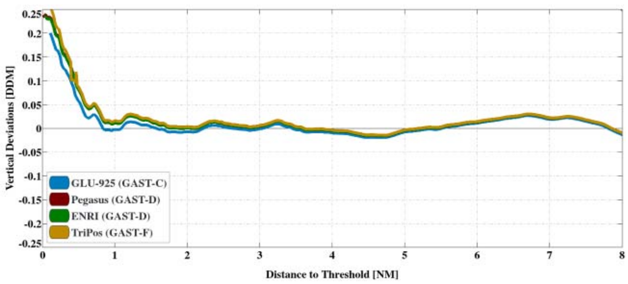

Figure 11. Vertical Deviations for a Single GBAS Approach

The most straight-forward way to compare the results of these GBAS airborne solutions is to simply compare the guidance information (i.e. the data which is displayed to the pilot). Figures 10 and 11 show respectively the lateral and vertical deviation outputs against in one of the approaches conducted on 18 May 2016. They are plotted over the distance to threshold. Please note the different scales of vertical axes in these two figures.

These approaches have not been flown coupled to the autopilot, but have been flown manually under Visual Flight Rules (VFR). Thus, the deviations itself fluctuate. However, the differences between the shown plot lines are negligible for most of the approach. Even small positioning differences can result in larger deviation differences close to the threshold due to the increased sensitivity. Thus, minor differences are only visible close to the runway, and exist particularly between the GAST-C/D solutions and the experimental MC/MF solution.

The MC/MF positioning is based on the Ionosphere-free combination of L1 and L5 signals. While Galileo satellites always broadcast signals in both frequency bands, not all GPS satellites are transmitting L5 signals currently. This results in a significantly lower number of used satellites and thus also a worse positioning accuracy. However, the differences between the different achieved service types and algorithms are negligibly small and the general usability of the new GAST-F processing is shown, even though many aspects have not been finally assessed. With the legacy GBAS services working well with this VDB broadcast, the general backwards compatibility was demonstrated as well. With the addition of more multi-frequency capable GPS and Galileo satellites, the overall performance of the new GBAS services is expected to increase gradually in the future.

V. CONCLUSIONS

The results of the interoperability trials presented in this paper prove that the draft ICAO SARPs are mature and stable enough to allow independent developments worldwide for the upcoming GBAS services. Especially for GAST-D this result is a major milestone towards a publication of the final standardization documents.

In addition the paper showed that future Multi-Constellation and Multi-Frequency GBAS operations are possible while maintaining backwards compatibility. Of course, as additional messages are broadcast using the same VHF data link, the VDB capacity can be a challenging constraint for future GBAS services. The conducted trials show that the requirements can be met nevertheless. These results have been achieved by a multi-national research group from Germany (TU Braunschweig) France (DSNA/DTI) and Japan (ENRI) with the support of EUROCONTROL.

In addition the project "GBAS Mock-up Datalink Facility (GMDF)" showed that even a small but focused research group can fill gaps in major programs with their high flexibility. The GMDF team was able to compensate a last minute change of the work plan and minimized the respecting consequences. The broadcast of a Multi-Constellation/Multi-Frequency GBAS signal-in-space helped to achieve the goals of SESAR project 15.3.7.

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Figure 12. DSNA, ENRI and TUBS flight test team

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