Initial GBAS Experiences In Europe

Andreas Lipp, EUROCONTROL
Alfredo Quiles, Pildo Labs
Mercedes Reche, Pildo Labs
Winfried Dunkel, DFS
Sylvie Grand-Perret, EUROCONTROL

BIOGRAPHIES

Andreas Lipp received a "Master of Science" degree from the Georgia Institute of Technology and a "Dipl.-Ing." degree from the Technical University Braunschweig in 1992. He then worked as research engineer and project leader at the Institute of Flight Guidance and Control of the TU Braunschweig in the field of satellite and integrated navigation systems, focusing on high precision positioning and integrity for satellite navigation systems. He joined EUROCONTROL, the European Organisation for the Safety of Air Navigation, in 1997, where he works at the Experimental Centre on integrity aspects of satellite navigation. He is currently responsible for the GBAS Validation and Standardisation activities, as well as supporting the GBAS operational and safety studies and GNSS Tools activities within EUROCONTROL’s Navigation Domain.

Alfredo Quiles is Project Manager at INECO (Madrid). He received his MSc in Aeronautical Engineering in 1997, from the UPM (Madrid). He worked in ESA giving support to EGNOS and Galileo programmes, and in 2000 he joined Thales Avionics Ltd (London) to work on the validation of the SQM concept for EGNOS RIMS-C. In July 2002 he joined Pildo, where he worked until August 2005 acting as a project manager and technical consultant for different EUROCONTROL projects related to the Operational Validation of GBAS.

Mercedes Reche obtained her MSc in Telecommunication Engineering from the Universitat Politecnica de Catalunya in 2002. She started to work on Satellite Navigation in 2003 with CNES. Since October 2004 she has been working for PiLDo Labs, giving technical support in activities related to EGNOS and GBAS Operational Validation.

Winfried Dunkel graduated as an engineer in aerospace technology at the Technical University of Braunschweig in 1989. He then worked as research and flight test engineer at the Institute of Flight Guidance and Control of the TU Braunschweig where he finished with the doctor degree. Since 1995 he is working in the satellite navigation department of the German Air Navigation Services DFS Deutsche Flugsicherung GmbH. As project manager he was responsible for DFS GBAS Project at Frankfurt airport. From 1999 to 2001 he was DFS Galileo Programme Manager and working as Technical Leader for the audit of safety-of-life applications and requirements in the Galileo Architecture Support Team (GAST) of the European Commission. Since then he is again responsible for the DFS GBAS programme and technical project manager of the GBAS Bremen project.

Sylvie Grand-Perret graduated as a general engineer from Ecole Nationale Supérieure De Techniques Avancées (ENSTA - PARIS X ) in 1987. In parallel she obtained a Diplome d’Etudes Approfondies for research studies undertook at the Ecole Polytechnique (X)/ ENSTA common research center. She first joined the Office National d’Etudes et de Recherche Appliquées (ONERA) to work on the Ariane 5 program. She then joined THALES avionics as a system architect to develop the THALES/SMITHS Flight Management System (FMS) for the Airbus fleet. In addition she initiated activities on the new concept of an interactive cockpit. In 1999 she joined EUROCONTROL Experimental Center to work on the Airborne Separation Assurance System (ASAS) applications developments in two European Projects AFAS and MA-AFAS. In 2001 she joined EUROCONTROL’s Navigation program, where she is now responsible for the development of landing and take off (LATO) activities.

ABSTRACT

The main objective of this paper is to show the first results of experimental GBAS activities in the context of the other EUROCONTROL GBAS activities. It focuses on the tool set defined together with member states and developed by EUROCONTROL. Together with detailed interface and data format definitions this tool set
(available for air navigation service (ANS) providers and other interested parties) ensures comparable results based on the same assumptions and forms a basis for a harmonized evaluation of GNSS SIS performance in Europe. These baseline results can then also be used for support to the definition of GBAS CAT II/III standards.

Since, in contrast to the US, past experimental activities with systems encompassing the final ICAO standardized GBAS definition are limited in Europe, the paper addresses the current and planned activities by or in cooperation with EUROCONTROL, designed to complement the tests already conducted in the US.

The GBAS experiments were conducted together with the German Air Navigation Services Provider DFS at Frankfurt airport. Although describing first experimental results only, the paper gives an initial insight into the methodology used in GBAS validation. It allows an outlook to future trials involving more detailed investigations regarding system interoperability and requirements validation for future CAT III GBAS systems, putting these trials into context of the other GBAS activities currently ongoing in Europe.

**INTRODUCTION**

The current EUROCONTROL GBAS activities are coordinated and directed by the EUROCONTROL “Landing and Take Off (LATO)” Focus Group with representatives of the EUROCONTROL stakeholders, including aircraft manufacturers, airlines, air traffic service providers, certification authorities and other parties. The LATO groups treats all aspect of Precision approach and Landing, including those related to ILS and MLS, but mainly focuses on GBAS. It addresses operational, safety and technical aspects.

GBAS activities are also coordinated with FAA activities in this area in the recently formed FAA-Europe “GBAS Working Group”. This group, with recent additions of representatives from Russia and Australia provides a forum for information exchange covering all aspects of technical, operational and safety elements of GBAS introduction and can be seen as a GBAS equivalent to the Interoperability Working Group (IWG) active between SBAS providers.

In both groups, aspects of GBAS CAT I introduction, which is seen as a necessary step towards the final goal are treated in detail, while progress toward GBAS CAT II/III is limited to the activities supporting and complementing operationally ICAO, RTCA and EUROCAE standard developments.

A number of States have initiated the deployment of prototype ground stations and EUROCONTROL is supporting them in the validation and certification process as well as in the operational aspects of GBAS deployment. The purpose of this paper is to present the results of the initial GBAS experiments realized in Europe by EUROCONTROL and DFS.

**DFS GBAS ACTIVITIES**

DFS has installed a first SCAT I ground station of DASA/NFS at Frankfurt airport in 1998 together with a measurement data recording and monitoring system MDES [10]. The FAA certified SCAT I ground station was replaced in the year 2000 by the current Honeywell Beta LAAS station. After a firmware upgrade this prototype GBAS ground station should be ICD compliant to the current standards [6]. The purpose of these experiments was to test this station for the first time with an ICAO SARPS [1-4] compliant GBAS receiver. The results should help to improve the ground station and to define a new GBAS monitor in the just started GBAS Bremen project. This nationally sponsored project is planned to install a GBAS ground station at Bremen airport in 2007 and finish operational GBAS trial with partners like Lufthansa in 2008.

**EUROCONTROL GBAS ACTIVITIES**

The GBAS activities performed by EUROCONTROL focus around three main areas:

- **Operational aspects**, including ATC phraseology, procedure description, operational concepts, aspects of transition, and mixed-mode operations. Here, EUROCONTROL plays a harmonizing role between the detailed work done in its member states and the need for standardization at international level. With GBAS and MLS, for the first time in history, precision approach operations can be performed by a choice of systems installed in parallel, necessitating significant changes in ATC operating concepts to support precision approach mixed landing-mode operations safely. After finalizing the GBAS operational concept for CAT I, the work is currently ongoing on development of an operational concept for GBAS CAT II/III, harmonization of ATC procedures in mixed landing-mode operations as well as investigations into protection requirements, such as the Obstacle Free Zone.

- **Safety aspects** are treated extensively, since recently developed European legislation requires both a quantitative safety assessment of newly introduced systems (ESARR’s [16] and related EC directives) as well as assessment of the navigation equipment’s contribution to the overall ATM safety. This is compounded by high level strategies (ATM 2000+ [15]) demanding an increase of individual system safety to maintain low accident rates despite increasing traffic levels. In this area
EUROCONTROL supports its stakeholders by not only providing generic safety assessment documents (Safety Policy, Safety Plan, Functional Hazard Analysis, and Preliminary System Safety Analysis) for GBAS, but also demonstrates their application to a few selected pilot installations. The current work will see the completion of the generic documents for GBAS CAT I for the end of 2005, with application to pilot sites starting in 2006.

- Technical aspects, which will be the main focus of this paper, are designed to support the standardization of GBAS systems, initially for CAT I and now more and more focusing on Cat II/III, while building a pool of experience on system capabilities. In Europe individual organizations typically do not have the resources to fully investigate all aspects of a new navigation system, so EUROCONTROL tries to support common methodologies to evaluate and compare results provided by individual stakeholders, develop and maintain tools and material assets common to the necessary investigations and support experiments performed to validate aspects of the system. For GBAS this strategy translates into intensive support to standardization, notably the development of CAT II/III requirements by EUROCAE as well as their harmonization with other organizations such as RTCA and ICAO. Once requirements are defined, their validation necessitates the provision of assets needed for investigations, such as site surveys and initial tests, as well as a harmonized set of tools and support to the execution and evaluation of experiments. Individual results are then presented and discussed in the frame of the LATO group to share experience and to serve as inputs to the Operational and Safety activities. The PEGASUS toolset has thus been extended with GBAS-specific tools under the “PEGASUS-MARS” designation and now provides additional PEGASUS modules for the assessment of ground station siting, performance and data quality as well as the evaluation of static and dynamic data gathered using typical avionics. It allows SARPs (Standards And Recommended Practices) and MOPS (Minimum Operational Performance Specification) compliant post-processing of both the performance of satellite navigation signals-in-space and their augmentations. Development activities associated with PEGASUS are nearing completion and it is now time to start using the tools to assess the performance of the GNSS Signals-in-Space that are becoming available. The European SBAS system, EGNOS, has recently begun broadcasting a signal on a stable basis and EUROCONTROL is embarking on the process of signal-in-space validation using the PEGASUS tool.

For GBAS a number of ground-stations have been deployed and several ANS providers have requested the use of PEGASUS to assess the performance of their ground-stations, airborne systems and total system performance, as well as support their future certification activities. The PEGASUS toolset has thus been extended with GBAS-specific tools under the “PEGASUS-MARS” designation and now provides additional PEGASUS modules for the assessment of ground station siting, performance and data quality as well as the evaluation of static and dynamic data gathered using typical avionics. It allows SARPs (Standards And Recommended Practices) and MOPS (Minimum Operational Performance Specification) compliant post-processing of both the ground station and airborne GBAS components. Its open architecture and modular design allow both assessment of existing systems and extrapolation of the performance needs to future (e.g. CAT III) requirements.

This was done by co-location of dual frequency GPS receivers with the MMR and at the same time with the ground station receivers. This data was post-processed using the PEGASUS simulation toolset. Finally an evaluation using an algorithm with proposed modifications linked to ionospheric issues is provided.

PEGASUS TOOLSET

Originally requested to provide support on the validation of Aircraft-Based Augmentation Systems (ABAS), EUROCONTROL had developed and operated a satellite navigation data analysis toolset under the name of SAPPHIRE from 1995 to 2000 [9]. The experience gained in this project has been transferred starting in 2001 to a new generation of tools that is called PEGASUS [17], initially designed to support validation of Satellite Based Augmentation Systems (SBAS). This set of tools is designed to assist ANS providers and users in evaluating the performance of satellite navigation signals-in-space and their augmentations. Development activities associated with PEGASUS are nearing completion and it is now time to start using the tools to assess the performance of the GNSS Signals-in-Space that are becoming available. The European SBAS system, EGNOS, has recently begun broadcasting a signal on a stable basis and EUROCONTROL is embarking on the process of signal-in-space validation using the PEGASUS tool.

The following sections describe the application of the PEGASUS toolset to static and dynamic test data recorded at Frankfurt Airport and provide first validation results. They address:

- the performance of the Ground Station,
- the reception of the VDB receiver at ground level,
- the performance of a GBAS MMR under these conditions and
- the comparison of simulated GBAS ground station and simulated GBAS user receiver with the performance of the real equipment.

Figure 1 gives an overview of the elements of PEGASUS. It can be divided into 4 main functions:

I. Data conversion from manufacturer proprietary data formats into a harmonized, public format [12] and initial testing of data quality.
II. Algorithmic functions related to airborne processing, reference track and error calculation as
well as ground station processing and signal analysis in the case of GBAS.

III. Graphical and report presentation functions, ranging from a quick-look facility, interactive graphic facilities of typical evaluations to predetermined automated reports including textual and graphical statistical evaluations.

IV. Support tools, including the handling of campaign datasets for multiple files, automatic sequencing of processing steps, scheduled execution and data selection and management functions.

The setup shown in Figure 2 shows these elements. As a reference, dual frequency GPS receivers from NovAtel and Septentrio were installed in parallel to all ground station receivers (RSMUs) and the MMR. The existing DFS Measurement Data recording and data Evaluation System MDES [10], provided complementary static data. The setup could be monitored and controlled via network from the DFS headquarter.

Figure 1: PEGASUS Toolset

A more detailed description of PEGASUS can be found in [13].

EXPERIMENT SETUP

The measurement campaign together with DFS was designed to provide a first set of results from prototype equipment acquired both by DFS and EUROCONTROL.

DFS had been operating a Honeywell SLS-3000 Beta LAAS prototype GBAS ground station for some years, upgraded from a SCAT I design and had monitored its performance on a continuous basis using the Measurement Data recording and data Evaluation System MDES [10]. However, no operation with current airborne equipment had been attempted.

EUROCONTROL had recently acquired a prototype version of the Rockwell-Collins Multi Mode Receiver (MMR) GLU 925-330 and had completed an initial series of static functional tests. However, no dynamic tests outside of those performed by Boeing [14] had been attempted, notably in a configuration without full aircraft integration. A recently acquired independent VDB receiver also had not yet been tested in conjunction with a GBAS ground system.

Figure 2: Experiment Setup at Frankfurt Airport

Figure 3: Geographic Locations of System Elements

Figure 4: Ground Station Installation with the three Reference Receiver (RSMU) Locations
Figure 3 shows the location of the system elements on Frankfurt International airport and Figure 4 shows details of the GBAS ground station installation.

After an initial verification of the system functions in March 2005, a ten day static test was performed, with the MMR-rack installed in the MDES location, followed by three days of dynamic tests on the airport.

**STATIC INVESTIGATIONS**

As DFS has already acquired significant experience with the operation of the ground station, the static experiments were mainly designed to test the post-processing options of the PEGASUS tool. The setup enabled both the analysis of broadcast ground station data and the simulation of a ground station as well as a comparison of both.

Because of limited knowledge about the ground station reference receivers (called RSMU) it was not possible to use its data as input for the PEGASUS ground station simulation. In addition the passive RSMU antennas did not allow splitting the antenna signal for a second receiver. Therefore Septentrio PolaRx2 dual frequency GNSS receivers with their own antennas were installed in parallel to the existing RSMUs.

This setup enabled statistical investigations on the VDB data, determination of a noise profile and recreation of the station outputs using a limited sample of measurements. The noise profile was then generalized and used to simulate a GBAS ground station only using ephemeris information.

**VDB statistics**

The SARPS and MOPS include strict rules on minimum and maximum transmission rates for individual messages. Content rotation of the Type 1 range corrections is also specified. PEGASUS provides a tool to analyze messages and assess their conformity with the standards. Due to the upgrade from a SCAT system, small differences were found that have to be fixed by the ground station manufacturer. Nevertheless both PEGASUS and the MMR were able to function normally. The VDB investigations included an analysis of propagation time of changes in the constellation, where the ground station was found to be conforming to the integrity requirements at all time, while needing a few seconds more for re-start of transmissions. On the airborne side, several seconds more are required after such an event to resynchronize and reuse the affected satellite(s) in the position solution.

**Sigma and B-Value Analysis**

Of all the parameters broadcast by the ground station, the B-values and Sigma_PR_GND require the most intensive analysis. The B-values indicate the differences in signal quality between individual reference receivers, while Sigma_PR_GND provides an overall indication of the ground station measurement quality. They are both key to the calculation of the protection level onboard the user receiver and determine availability and integrity of the system for the desired approach operation.

While simulating a GBAS ground station, there are multiple methods of determining an approximation of the values to transmit. Figure 5 provides an overview of the techniques used in this study.

A 24h sample of static data was used to statistically analyze the VDB broadcast values of the ground station and compare them to the curves for specific ground station classifications (Ground Accuracy Designator - GAD). Although this interval is relatively short for a characterization of the station, it offers a good compromise between computational effort and result quality. The initial broadcast values are shown in Figure 6. These were then averaged over elevation.

**Figure 5: Comparison of Sigma_PR_GND Estimations**

**Figure 6: Broadcast Sigma_PR_GND (m)**
Another method available through PEGASUS is the determination of a Sigma characteristic from the recorded B-values, seen in Figure 7. In comparing the results (Figure 8), agreement for low to medium elevations is very good, while the number of data points at high elevations is insufficient to provide a reliable estimate.

![Figure 7: Simulated Sigma_PR_GND – Raw Data and Statistical Analysis](image)

Another area of the static investigations was the comparison of measured and simulated pseudorange corrections, which have shown very good comparability as visible from Figures 9 and 10. However, the simulation provided slightly higher noise in the results (Figures 11 and 12).

![Figure 8: Comparison of broadcast and simulated Sigma_PR_GND](image)

![Figure 9: Histogram of Measured Pseudorange Corrections](image)

![Figure 10: Histogram of Simulated Pseudorange Corrections](image)

![Figure 11: Statistics of Measured Pseudorange Corrections](image)
The PEGASUS toolset thus shows a good modeling potential, albeit with somewhat conservative noise estimates. The potential to simulate station behavior, based on a limited set of initial measurements.

In summary, the static investigations have shown a normal behavior of the ground station and a good modeling potential, albeit with somewhat conservative noise estimates. The PEGASUS toolset thus shows a good potential to simulate station behavior, based on a limited set of initial measurements.

Figure 12: Statistics of Simulated Pseudorange Corrections

Ground Station Position Domain Analysis
Using the PEGASUS post processing tool and the raw data from a survey grade receiver, a 24h data set of the ground station corrections have been processed for the following position domain results.

The Stanford diagram shows periods of unavailability, which are also visible as spikes in the Timeplot in Figure 14. They result from regular ground station signal losses every two hours, an effect only present in the ground system prototype used, since its design is based on a S-CAT 1 system. As the histogram of vertical error shows (Figure 15), this has no influence on the error distribution.

In summary, the static investigations have shown a normal behavior of the ground station and a good modeling potential, albeit with somewhat conservative noise estimates. The PEGASUS toolset thus shows a good potential to simulate station behavior, based on a limited set of initial measurements.

Figure 13: Vertical Stanford Diagram (PEGASUS, VDB)

Figure 14: VNSE and VPL Timeplot

Figure 15: VNSE Histogram

DYNAMIC INVESTIGATIONS

In preparations for the dynamic tests, the local conditions had to be taken into account. Since the density of airport operations would not permit extended occupancy of the runways, multiple FAS data sets had to be prepared for measurement tests on taxiways. This posed an issue in FAS data generation, since no dedicated surveys were possible. The chosen method of retrieving coordinates from a calibrated airport map has proven too inaccurate for actual operations, although sufficient for the initial purpose. In the vertical plane two issues were to be seen:

- Movement on the airport surface would have provided deviations only in the “fly-up” direction. A vertical offset was chosen to correct this.
- The Glidepath Intersect Point (GPIP) was not chosen at the beginning of the taxiway, but towards the end, allowing us to “fly” in the segment towards the threshold.
Figures 16 and 17 show these modifications.

**Figure 16: Supplemental FAS Data for Tests**

Initial investigations had shown that the MMR was able to function even with these modifications, although further experiments, using FAS designations reserved for helicopter operations (parameter runway number set to zero) were unsuccessful, since the MMR is designed for air transport aircraft applications.

**Figure 17: FAS Offset Parameters**

Figure 18 shows the data evaluation process employed. A truth track was established using carrier-phase processing with the survey receiver data, allowing access to all three main error components:

- Total System Error (TSE), as the difference between truth track and desired track (from FAS).
- Navigation System Error (NSE), as difference between MMR indicated track and truth track.
- Flight Technical Error (FTE) defined here as difference between indicated and desired track and therefore equivalent to the deviation output.

Of the multiple runs, only two will be presented in this paper – one on one of the runways and one on a taxiway.

**Figure 18: Data Evaluation Process**

**Runway Experiment**

The track of the runway experiment (Figure 19) shows entry from a holding position, travel roughly along the centerline and exit to another holding position.

**Figure 19: Track for Runway Experiment**

As vertical deviations are only available until the threshold (Glide Path Intercept Point – GPIP), the full runway length was not used. Figure 20 shows the necessity of adapting the FAS for the driving tests to obtain more complete results in the vertical direction.

Interesting for the performance of the post-processing tool is the comparison of the protection levels generated by the MMR with those from the post-processed solution in Figure 21. The number of satellites tracked is slightly different, leading to an offset, but further differences are visible in the smoothness and in the behavior after constellation changes; effects which are currently still under investigation.
The post processed position solution however, was very close to the MMR generated deviations, as Figure 22 shows. Only a very small timing issue is visible in the vertical (Up Track – UT) track deviations depending on vehicle speed. Horizontal deviations (Cross Track – CT) are not influenced.

**Taxiway Experiment**

Use of the specific FAS on the taxiways allowed for a longer vertical guidance period and a transition of the full vertical deviation spectrum. However, the NSE remained small, as Figure 23 indicates. For the horizontal NSE, shown in Figure 24, the results are even better.

**Long Term Evaluation**

As the 24h static dataset evaluated for Figure 25 indicates, the results of Figure 23 and 24 are representative of the MMR performance. The data losses are due to the ground station design, as explained earlier. The Stanford diagram in Figure 26 confirms this and both diagrams show good cohesion with the PEGASUS processed data in Figures 13 and 14.
Due to the ionospheric storms late in 2003, discussions arose whether changes to the GBAS pseudorange smoothing time constant could alleviate the ionospheric error contribution in a storm situation. Under normal conditions, a higher smoothing time will reduce the noise on the position determination and is therefore desirable. However, under ionospheric storm conditions this smoothing introduces a residual error depending on the difference in ionospheric conditions between aircraft receiver position and ground station position. These differences are undetectable by either receiver and therefore not included in the protection level calculations, potentially causing a loss of integrity. Reducing the time constant directly reduces the ionospheric error contribution.

Following a suggestion at a recent LATO meeting, the possibility to reprocess both ground- and airborne segments with PEGASUS was employed to generate the results with both a standard-conformal 100s smoothing as well as with a 50s time-constant.

As the reference day had a calm ionosphere, the difference in the results should mainly show the noise increase due to reduced smoothing – see Figure 28 as compared to Figure 29. Comparison with Figure 26 shows the similarity with the MMR performance, while the significant differences to Figure 13 results in the use of apparently more stringent plausibility checking on the VDB data by the MMR.

The difference in performance is negligible and it will be useful to explore this method in more detail. Future investigations will include the modeling of ionospheric errors to provide the improvement under different threat scenarios.

DFS has recorded ground station reference receiver data and single as well as dual frequency GPS receiver data during ionospheric storms since 2000. As soon as PEGASUS is able to process the recorded RSMU raw data.
data the PEGASUS capabilities can be used for the investigations of ionospheric issues.

CONCLUSIONS

The experiments described have been a first step to gain practical experience with a combination of ground and aircraft GBAS equipment. After having earlier performed static tests jointly with the French STNA and a Thales ground station, the experiments described here have ascertained the compatibility with a Honeywell ground system for equipment very similar with the one already certified for a Boeing aircraft and in certification with Airbus. They have also been able to describe limitations of both air and ground systems and provide valuable “lessons learned” for the upcoming, more involved tests. The GBAS components of the PEGASUS tool have been validated and are currently being improved in line with the requirements from the tests. With the detailed PEGASUS data format description [12] and the tool set [17] all installations and experiments can provide comparable results and contribute to a technical and operational GBAS validation.

OUTLOOK

EUROCONTROL is continuing its GBAS activities both in support of extension to new operations, such as the standardization of CAT II/III and the introduction of CAT I systems. This comprises further work on GBAS operational concepts, but also local support to experimental activities such as those performed by DFS in Bremen and by AENA in Malaga. For these sites, the application of the more generic safety case material is planned as well. Late in 2005, first flight tests are envisaged to complement the ground test results presented in this paper. The ongoing work also comprises activities to verify how the ICAO goal of fully transitioning to satellite based navigation systems in aviation can be achieved.

DFS has started the development of an independent GBAS monitor for data recording and performance monitoring. Initial VDB field strength simulations and measurements are used as preparation for the GBAS Bremen frequency coordination. The improved simulation and frequency coordination tools are used to check if GBAS flight trials with an experimental aircraft to an airfield close to Frankfurt are possible. The airfield Egelsbach is located approximately 12 km from the VDB transmitter. Depending on the real VDB antenna characteristics and the geometry it should be possible to use this airfield for initial GBAS flight trials instead of the crowded Frankfurt airport. In 2006 the site survey and installation preparation for a GBAS ground station at Bremen airport will support the operational GBAS trials with airliners in 2007 and 2008.

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Contact Information:

Andreas Lipp, EUROCONTROL Experimental Centre, +33-1-6988-7618, andreas.lipp@eurocontrol.int

Winfried Dunkel, DFS +49-6103-707-2252, winfried.dunkel@dfs.de