NAVAID INFRASTRUCTURE ASSESSMENT FOR RNAV IN TERMINAL CONTROL AREAS

Juan J. Navarro (1), F. Moreno (1), Miguel A. Salamanca (1), Enrique Velasco (2), Manuel Portillo (2)

(1) AENA. División de Navegación y Vigilancia. Josefa Valcarcel 30, 28027 . Madrid. Spain. jjnavarro@aena.es.

(2) INECO. Division CNS. Madrid. Spain. evelasco@ineco.es

ABSTRACT

RNAV procedures with tight accuracy requirements are now being implemented (e.g. RNAV-1) to obtain specific safety and efficiency benefits. For evaluating the suitability of the available infrastructure to support these new procedures, a combination of analysis, flight inspection and/or other operational data and expert judgment is performed in a cooperative and iterative manner.

This paper focuses on software tools like COVERNAV, which has been developed by AENA/INECO to conduct an initial analysis of the capability of the available DME facilities to support the envisaged procedure. This tool is based on a baseline FMS implementation [3] and a geometric analysis taking terrain limitations into account. In particular, COVERNAV includes a 3D terrain model with sufficient resolution and accuracy to predict theoretical visibility of navaids along the procedure, including an analysis of the subtended angles and other geometric constraints. Other specific COVERNAV features, aiming to ease the coverage assessment by the ANSPs and to prepare flight inspection, are discussed.

INTRODUCTION

RNAV procedures are being implemented on many airports across Europe and USA, promising a more efficient use of the limited runways capacity and airspace constraints.

P-RNAV is the operator and aircraft approval requirement for RNAV procedures in ECAC Terminal Airspace. Terminal Airspace procedures that require P-RNAV approval are designed following common principles that ensure that procedure design and execution are fully compatible. Additional to the minimum performance and functional requirements appropriate for Terminal Airspace RNAV operations, P-RNAV approval includes navigation data integrity requirements and flight crew procedures.

P(recision)-RNAV defines European RNAV operations which satisfy a required track-keeping accuracy of ±1 NM for at least 95% of the flight time. This level of accuracy can be achieved using DME/DME and/or GPS. It can also be maintained for short periods using IRS (the length of time that a particular IRS can be used to maintain P-RNAV accuracy without external update is determined at the time of certification).

Air Navigation Service Providers (ANSP) has the responsibility to provide infrastructure (e.g., navigation aids) to support all procedures, including RNAV. According to JAA TGL 10, section 4c)[1]:

"*The design of a procedure and the supporting navigation infrastructure (including consideration for the need of redundant aids) have been assessed and validated to the satisfaction of the responsible airspace authority demonstrating aircraft compatibility and adequate performance for the entire procedure. This assessment includes flight checking where appropriate.*"

From the previous statement three main points, regarding the navigation infrastructure, are taken out and are discussed henceforth:

1) The navigation infrastructure must support the procedure. As the service volume is given by the boundaries of its procedure design surfaces, the infrastructure assessment should include these surfaces in an appropriated manner. In the vertical dimension, infrastructure must be assessed for the published minimum altitude. In general, it is sufficient to flight inspect the RNAV procedure centerline, except when

coverage of required facilities is expected to only partially cover the RNAV service volume [2].

2) It must be ensured that navigation aids meet Annex 10 performance requirements (i.e. accuracy and minimum field strength) within their coverage boundaries. To this regard, the term Designated Operational Coverage (DOC) is used to declare those boundaries.

3) Demonstrating aircraft compatibility: The assessment must ensure that any approved aircraft is able to get a valid position solution along the entire procedure. To this end, the baseline FMS defined into the recently published PBN Manual impose some constraints which must be taken into account: (1) For determining valid DME pairs (2) For extending the DOC, if this extension is required, either omni-directionally or on a sector basis. It should also note that avionics behavior could impose exclusion of some DME facilities from the infrastructure assessment (e.g. co-channel facilities within line of sight).

INFRASTRUCTURE ASSESSMENT

The basic approach to the infrastructure assessment is for the ANSP to ensure that a minimum set of qualifying DME is available. The DME/DME RNAV procedure can only be implemented if a suitable minimum set of DME facilities within DOC range along the procedure is confirmed.

The final goal of the infrastructure assessment is to identify essential, critical and harmful DMEs.

By the set of essential DMEs, ANSP guarantees at least the existence of a position solution at any point along the proposed procedure. Once a preliminary set of DMEs has been qualified from a list of DMEs facilities which are within the line of sight of the procedure, all possible combinations of pairs of DMEs at each point are identified and qualified if the subtended angle constraint and the P-RNAV accuracy requirement are met (i.e. 0.866 NM). From these qualified DME pairs, a minimum set of DMEs can be identified as essentials.

Essential DMEs are published in the state AIP and their signals are considered to meet signal-in-space accuracy tolerances and the minimum field strength within DOC range along the procedure under evaluation.

An essential DME is critical when an outage will disable DME/DME RNAV positioning. If only one valid pair of supporting DME exists, both DME facilities are considered critical to the procedure. If a particular DME is common to the list of all supporting DME pairs, that DME is critical as well. The infrastructure assessment needs to identify the number of critical DME facilities that support a procedure.

If an authority decides that critical DME facilities are not acceptable, alternatives are to either base the procedure on GNSS only or to require inertial capability in addition to DME. The acceptance of such measures will depend mostly on the anticipated user fleet equipage levels.

In addition to identifying a minimum set of qualifying DME (i.e. essentials) that are within DOC range along the procedure under evaluation, it is considered that DME signals meet signal-in-space accuracy tolerances everywhere along the procedure these signals are received regardless of the published coverage volume. Thus, ANSP should identify DME signal with multipath errors. When such errors exist and are deleterious to the navigation solution ANSP may identify such DMEs (harmful DMEs), as not appropriate for the procedure (to be inhibited by the flight crew) or may not authorize the procedure on DME/DME.

It should be noted that errors resulting from field strength below the minimum requirement for receiving signals outside the DOC are considered receiver errors, which are under the responsibility of the RNAV system. This must ensure the use of facilities outside the DOC do not cause erroneous guidance. Including reasonableness checks or adjusting the FOM to the DOC may accomplish this.

Any critical or harmful DME should be clearly designated on the procedure chart and in the AIP [2]

THE ROLE OF FLIGHT INSPECTION

Flight Inspection information is primarily required by ANSPs to ensure all of the DME that are within DOC range along the procedure provide signals in compliance with Annex 10.

Though a preliminary coverage analysis is usually conducted by using a software tool to identify DME facilities that meet the requirements and constraints identified above, it must further be confirmed by flight inspection information in order to ensure that stable and accurate DME signals are available with sufficient field strength.

If any DME behavior is suspicious to provide a misleading signal outside of DOC it is desirable to conduct flight verification to check accuracy tolerances.

Signal quality needs to be verified, in particular, if a procedure is in a location where there has not been any flight inspection, and/or multipath effects are expected due to the nature of the surrounding terrain (e.g. mountainous or coastal areas). In this case, signal reflections/diffractions can occur which distort the time delay measurement. This error could be more deleterious consequences if the direct signal is victim of fading or shadowing effects

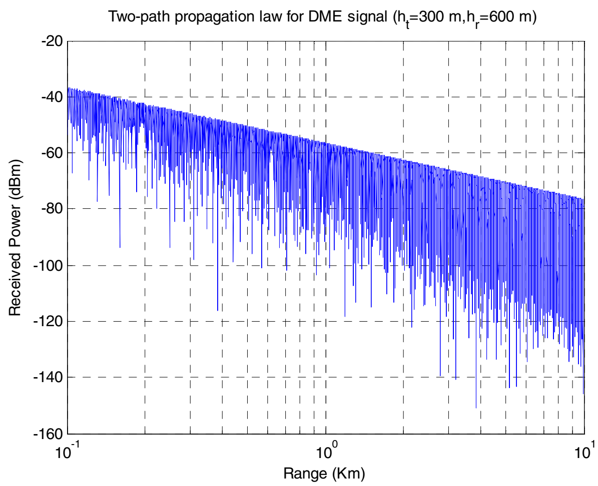


Figure 1. Two-path propagation law for DME signal (R=–1)

On the other hand, some or all of the flight inspection may be omitted if sufficient experience /evidence exist with the adequate performance of a specific DME or set of DMEs in a particular airspace. However, in areas where many DME within DOC are available, the burden to check all such DME may become excessive. This can be the case at large aerodromes with high-density operations. Based on available flight inspection data, evidence, experience and expert judgment by the engineering authority it is possible to reduce the amount of flight inspection with a monitoring of aircraft track keeping during the initial operations phase [3].

USE OF SOFTWARE TOOLS: COVERNAV

While the assessment could be conducted using manual analysis and flight inspection, the use of a software tool is recommended in order to make the assessment more efficient. The software tool should be tailored to allow evaluating the infrastructure to meet the requirements imposed by the P-RNAV navigation specification.

In general, RNAV assessment tools should include a 3D terrain model with sufficient resolution and accuracy to allow predicting the line of sight visibility of navaids along a procedure service volume, including an analysis of their respective subtended angles and a variety of other geometric constraints. Note that the accuracy of the terrain model in the near field of the DME antenna can have a significant impact on the accuracy of the line of sight prediction.

Covernav Features

COVERNAV has been developed by AENA/INECO to conduct an analysis of the capability of the available DME facilities to support the envisaged procedure. This tool is based on a baseline FMS implementation [2] and a geometric analysis using a highly optimized line-of-sight coverage computation based on a very accurate terrain elevation model (e.g. DTED1).

Main Covernav functions are:

- **Coverage Redundancy Analysis:** Number of DMEs in the user's line of sight ..

- **RNAV Area Analysis:** Performance parameters in a specific area are computed at a flight level as selected by the user.

- **RNAV Route Analysis:** Calculation of performance parameters along a procedure introduced by the user.

Coverage Redundancy Analysis

Coverage calculation is performed by taking equidistant radials through the 360º azimuth range, as shown on Figure 2.

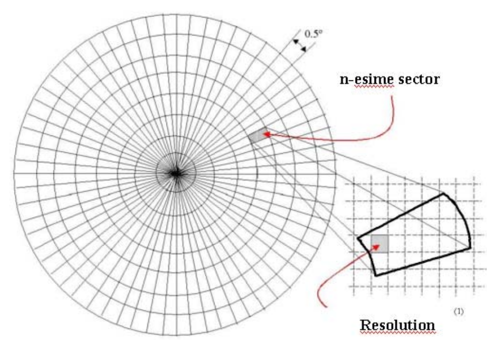


Figure 2. Calculation method

Three different methods for line-of-sight evaluation are available, depending on the preferred time/quality trade-off.

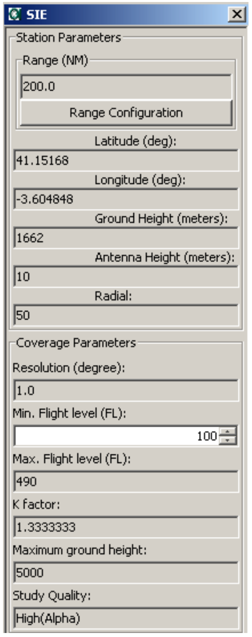


Figure 3. DME facility and coverage parameters setting

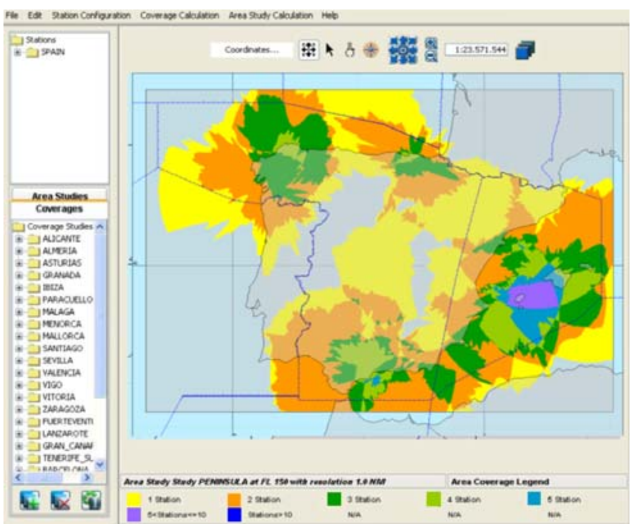


Figure 4. Coverage redundancy analysis

RNAV Area Analysis

Area RNAV analysis estimate performance parameters at a predefined area, at specific flight level, in a DME-DME RNAV navigation environment, meeting certain requirements entered by the user.

Some parameters provided by COVERNAV are:

- **Position Estimation Error**

$$2\sigma_{DME1/DME2} \le 2\frac{\sqrt{\left(\sigma^2_{DME1,air}+\sigma^2_{DME1,SIS}\right)+\left(\sigma^2_{DME2,air}+\sigma^2_{DME2,SIS}\right)}}{\sin(\alpha)}$$

Where: σ_{SIS} = 0.05 NM (or larger value if required),

σ_{air} is MAX {(0.085 NM, (0.125% of distance)},

α = subtended angle (must be within 30° to 150°).

- **Reliability:** Continuity performance is evaluated based on the individual facility's MTBOs inputted by the users.

- **Pairs:** The number of DME pairs meeting required PEE for the study.

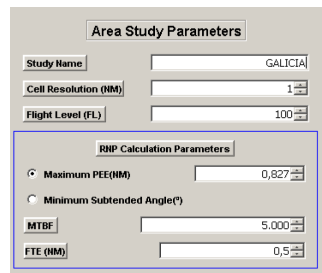


Figure 5. RNAV parameters setting

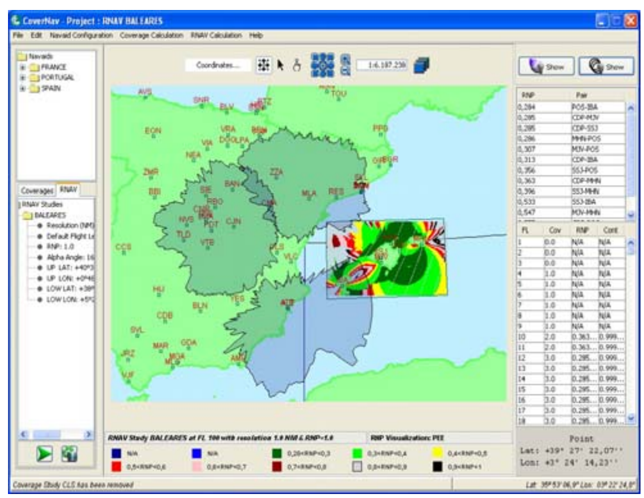


Figure 6. RNAV Area Analysis (PEE)

RNAV Route Analysis

Performance parameters assessment along the designed procedure is necessary for final procedure validation, to guarantee P-RNAV requirements compliance.

- **Easy route insertion:** creation of new waypoints by clicking on the map, importing data from CSV files or manual entry of coordinates.
- **Resolution, Accuracy and Continuity values setting.**
- **Easy understanding of the study results:** which are displayed at the graphics, showing the variation of each parameter along the route.

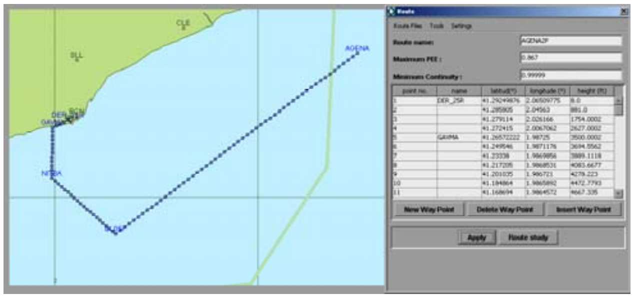


Figure 7. Definition of a SID procedure

Figure 8 indicates DME signal visibility along the procedure in terms of the minimum received signal altitude.

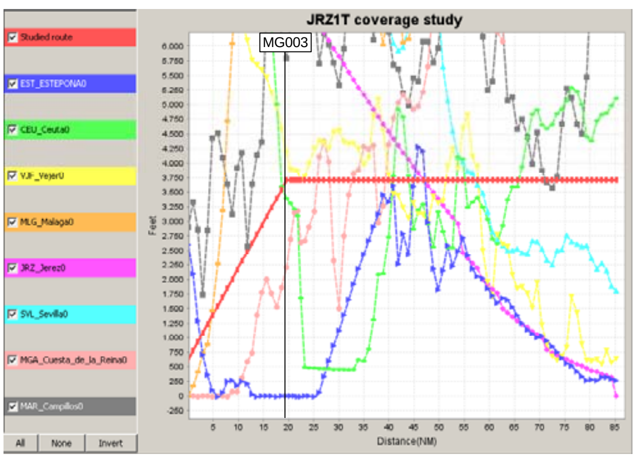


Figure 8. DME Visibility along procedure (red line)

COVERNAV determines all possible DME pairs at a given 3D point. This information, along with the profile DME visibility, permits to elaborate a DME list to be flight inspected in an efficient way.

PEE	Pair
0,294	LRA-VES
0,325	LRA-VGO
0,355	EON-VES
0,398	STG-VES
0,447	EON-VGO
0,54	STG-VGO
0,583	STG-LRA
0,776	EON-LRA

FL	Cov	PEE	Cont
154	3.0	0.58...	0.99...
155	3.0	0.58...	0.99...
156	3.0	0.58...	0.99...
157	4.0	0.29...	0.99...
158	5.0	0.29...	0.99...
159	5.0	0.29...	0.99...
160	5.0	0.29...	0.99...

Figure 9. DME pairs at 42º51’22”N, 7º11’21”W at FL160

VALIDATION CASES

This section discussess on how DME signals and P-RNAV procedures have been qualified in an efficient manner by using COVERNAV.

Study Case

The following validation case study shows how COVERNAV is used to assess the DME/DME infrastructure supporting P-RNAV departures from Barcelona (e.g. AGENA 2P SID) as depicted in Figure 10

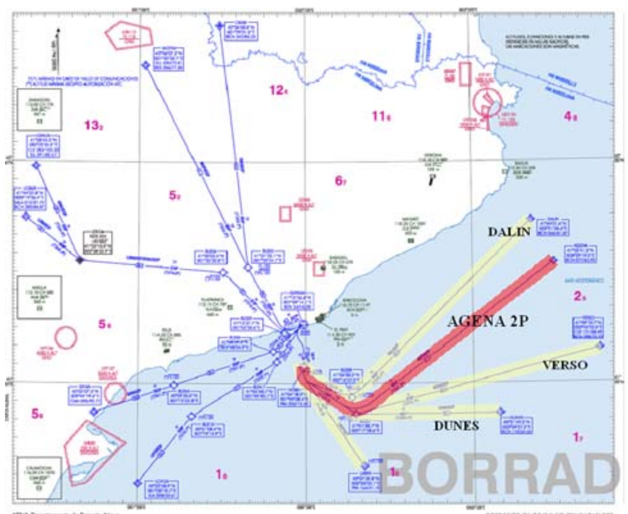


Figure 10. Barcelona RWY 25R SID Proposal Chart

Figure 11 shows the theoretical visibility of the DME facilities along AGENA procedure; the red line represents the vertical profile of the route. The rest of lines stand for the minimum altitude at which the DME is in the user’s line of sight. Note that a particular DME is visible where the minimum line-of-sight altitude is below the vertical profile of the route.

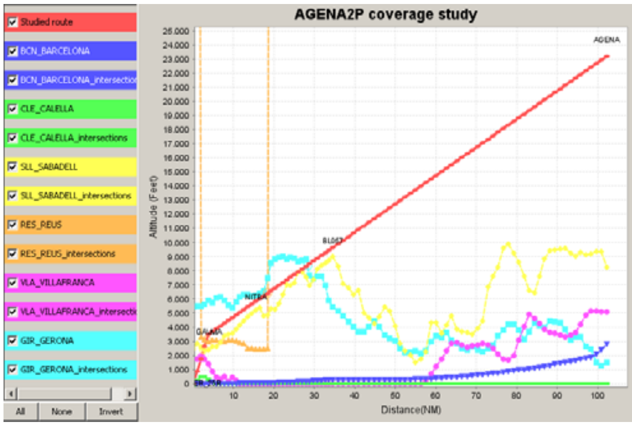


Figure 11. DME visibility along AGENA2P

The portion of the procedure where any DME is visible was screened out by COVERNAV to be inside the DOC as shown in figure 11 for REUS DME.

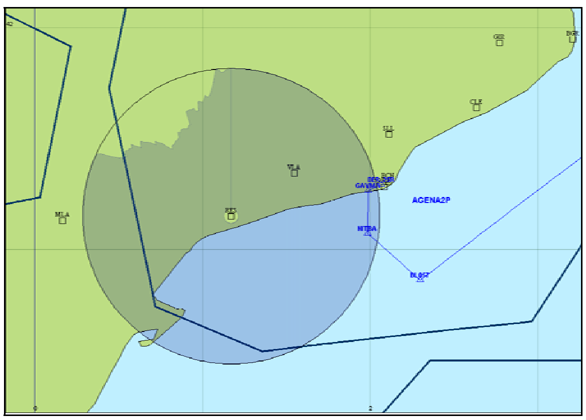
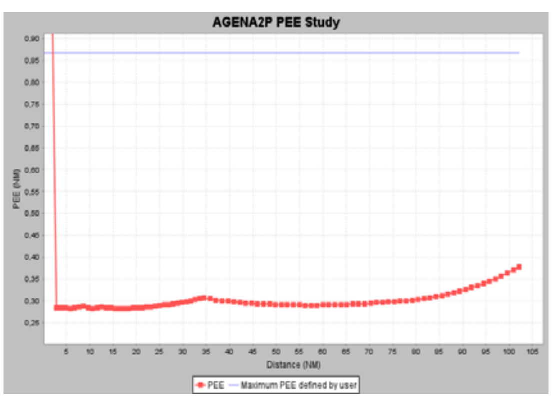


Figure 12. Current published DOC for REUS DME facility (40NM)

Figure 13 shows accuracy and continuity performance met by the visible DMEs set. PEE curve is obtained by selecting the best accuracy pair of DMEs.



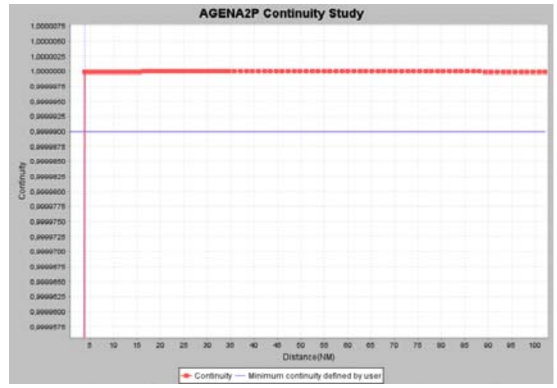


Figure 13. Accuracy and Continuity Performance plots along AGENA2P

From the Figure 13, it was concluded and confirmed by FI there was not proper DME/DME infrastructure to support the initial leg of the procedure, which was published as conventional one.

The following DMEs were found to be essential for AGENA2P: BCN, CLE, SLL, VLA and GIR.

In order to optimise the number of inspection flights, the essential DMEs for AGENA were flight inspected in different procedures due to the coverage communalities (i.e. similar and closely procedures in similar terrain pattern) as defined in Table 1. This assumption is easy to validate in our example since they are departures towards the Mediterranean Sea. On the other hand , it should be noted that current F.I. equipment are not suited in scanning mode to perform field strength measurements, thus there is a limited number of DME signals that can be recorded per flight (i.e. 2 in this example).

PROCEDURE	DME RECORDING
DALIN2P/Q	**SLL**/BGR
AGENA2P/Q	RES/**GIR**
VERSO2P/Q	**VLA**/CDP
DUNES2P/Q	**CLE**/PRA
LARPA2P/Q	**BCN**/POS

Table 1. List of DME signals to be recorded per procedure

The visibility plots from COVERNAV can be very useful to provide some insight into the assumption of coverage communalities as shown in Figure 15 for the SLL DME case.

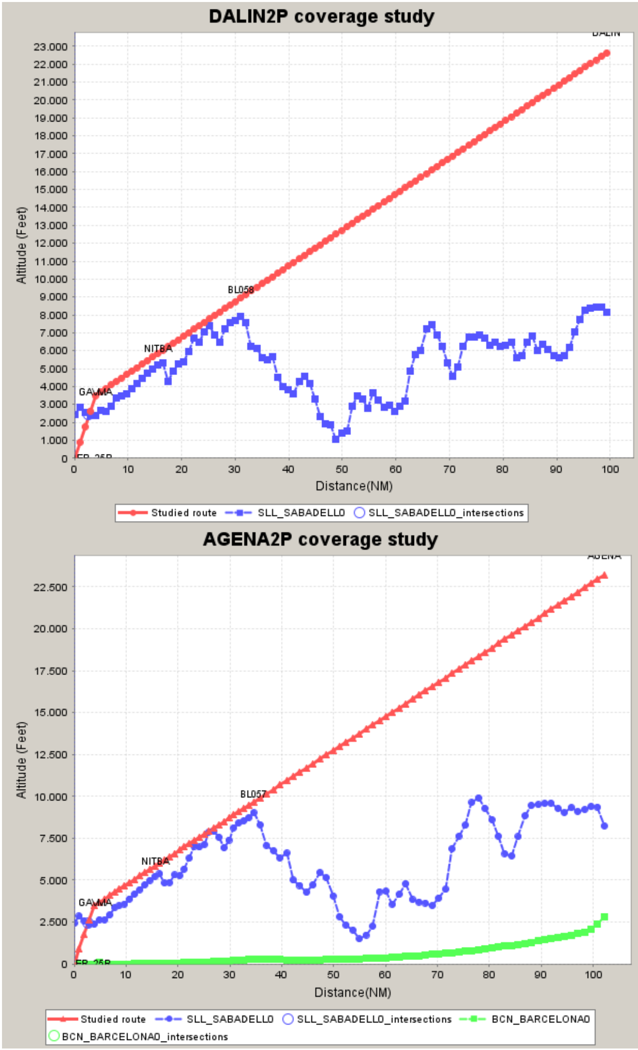


Figure 14. SLL DME communalities between DALIN2P and AGENA 2P

Finally, simulation results were confirmed by F.I. recordings.

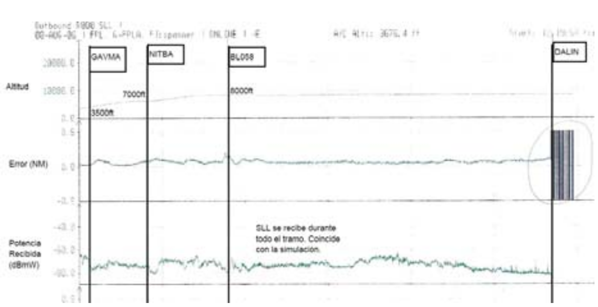


Figure 15. Flight records of SLL along DALIN2P

Qualifying DMEs

COVERNAV has been validated by using an extensive list of existing flight records. Any specific issues, such as AGC unlock in certain areas or DME signal reflections in mountainous or coastal areas have deserved special attention. The intention of the following examples is to indicate the degree of confidence we can put on COVERNAV tool.

Next figures show the simulation and flight inspection results for Madrid-Barajas ZMR1D SID. Simulation results correlate well with F.I. measurements shown in figure 17 but are a little bit pessimistic (i.e. on the safety side). The record also shows that the F.I receiver uses the RBO signal below the minimum field strength requirement of Annex 10. This event is also true for aircraft avionics.
Nevertheless, it should be noted that current flight inspection systems are generally not suited to determine exact limits of coverage. This is due to the fact that it is not possible to get an accurate field strength measurement by automatic gain control (AGC) voltage calibration, as well as because angles of incidence from different DME ground transponders vary greatly. Consequently, simple calibrations of the horizontal antenna gain pattern cannot be more accurate than approximately 10dB. For field strength measurements accurate to 3dB, 3D installed gain pattern and antenna voltage calibration needs to be employed.

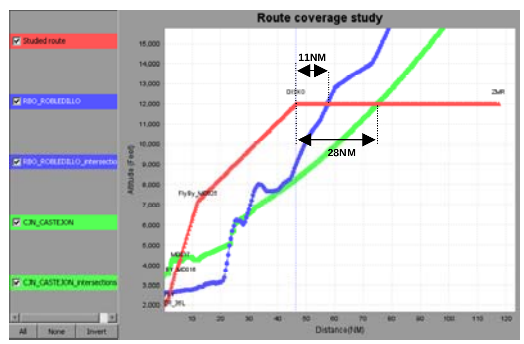


Figure 16. ZMR1D SID Simulation

Figure 15 shows simulation and flight inspection results for the VFD DME in the TURPU1D SID procedure from Pamplona airport. That DME is located in a rich terrain environment. According to the theoretical analysis and for the published minimum altitude of the procedure, the VFD visibility is only marginal and the facility was not included in the DME/DME coverage assessment. However, this signal was flight inspected in order to verify any deleterious behavior as it could be received by the aircraft avionics. Again, there is a good correlation between simulation and flight inspection.

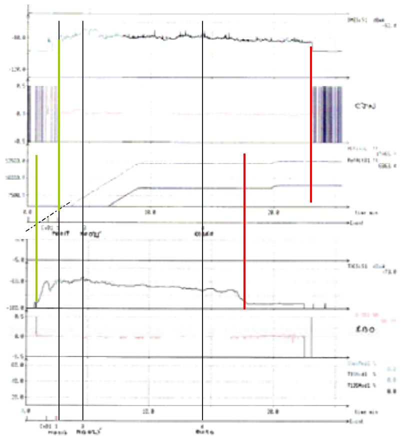


Figure 17. F.I. record and simulation for CNJ and RBO DMEs

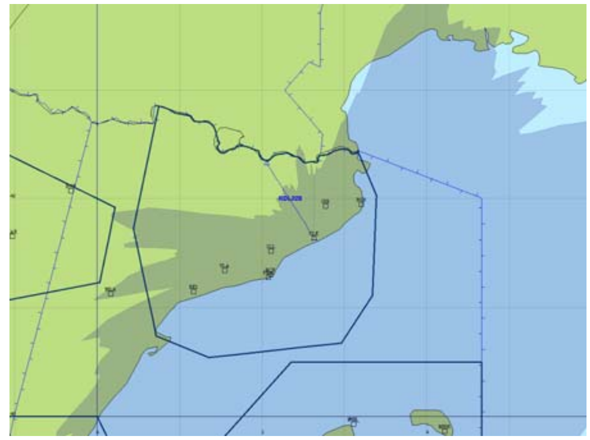


Figure 19. CLE Coverage at 12500 ft (MSL)

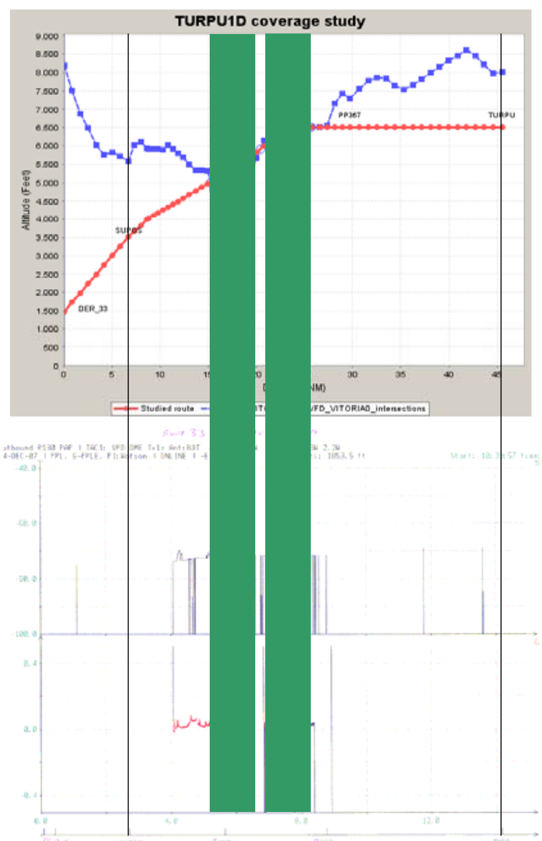
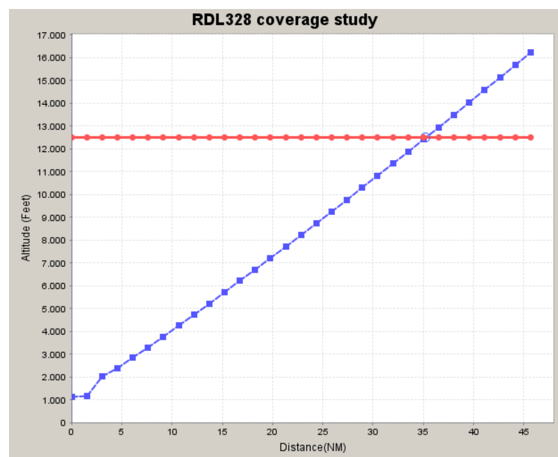


Figure 18. F.I record and simulation for VFD DME



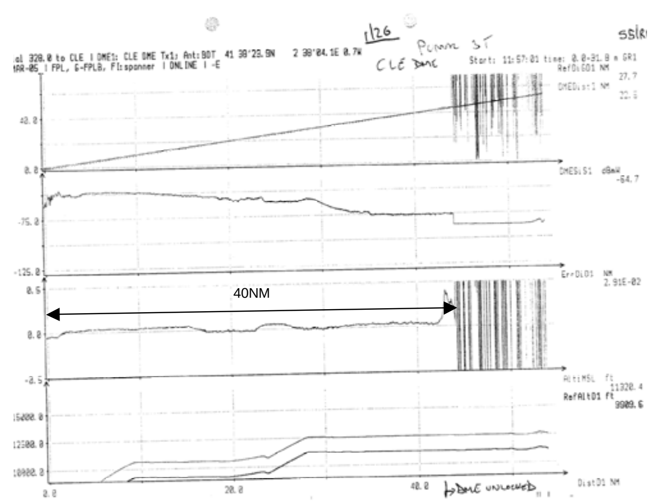


Figure 20 . Flight Inspection records for CLE in R328º

Figures 19 and 20 show DME coverage simulation and flight inspection results respectively for the CLE VOR/DME facility along the 328 º radial as an example of very rich terrain. As a consequence this facility provides a very irregular coverage. A good correlation between simulation and measurements is noted. At 40 NM, DME interrogator unlocks do occur.

As it was said, for a DME to be suitable for P-RNAV , the signal needs to have sufficient field strength and be free of excessive distortions.

The signal quality needs to be verified in location where fading and multipath effects could be expected, such as coastal areas. This is the case of the POS DME along the LARPA SID over the Mediterranean Sea as depicted in Figure 21.

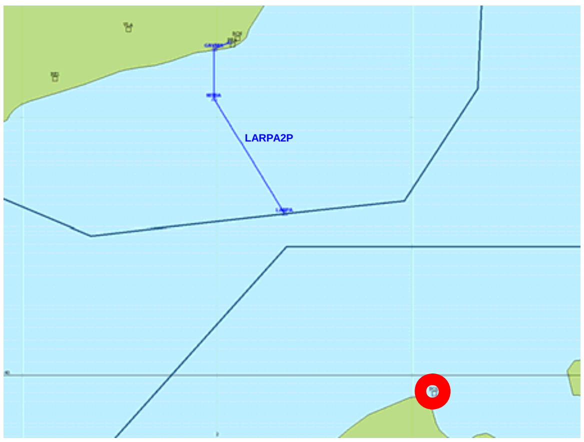


Figure 21. LARPA SID for Barcelona TMA

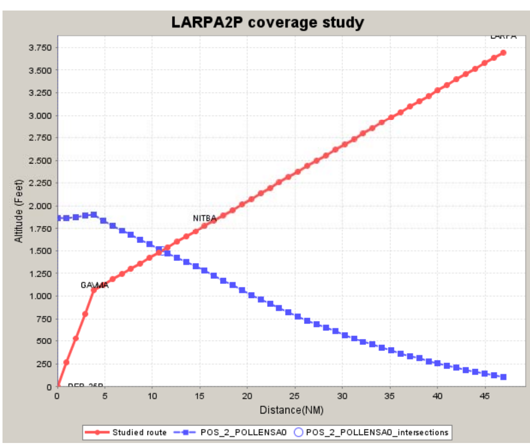


Figure 22. POS DME visibility along LARPA

Flight inspection measurements in Figure 23 show the typical propagation pattern due to reflections from the sea without any significant multipath errors, and farther from the station, AGC gets unstable, jumping back and forth due to the searching process, with unlock events. Despite COVERNAV cannot predict these events, the simulated coverage was confirmed by the F.I measurements as indicated in Figure 23 with a yellow strip.

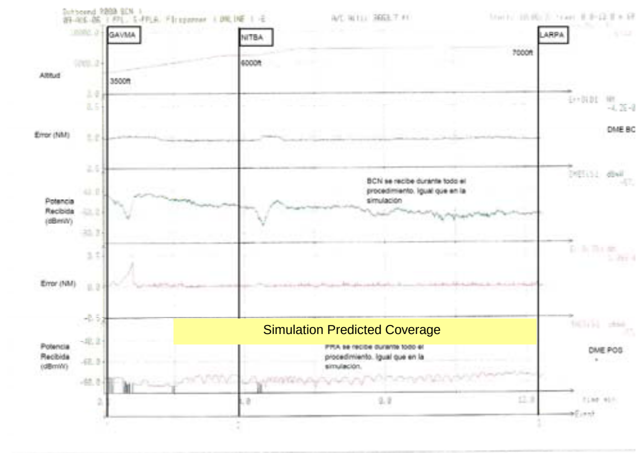


Figure 23. Flight inspection records of POS DME along LARPA.

CONCLUSIONS AND FUTURE WORK

With the introduction of RNAV procedures in Terminal Areas, DME is becoming into a multi-ranging navigation system. However, DME coverage assessment process and signal-in-space quality verification need to be properly performed.

To help for that, a simulation tool for analyzing the ability of the DME facilities to support P-RNAV procedures. Different examples cases show a high correlation level between the simulation data and measurements.

More than 200 P-RNAV procedures have been validated by AENA until now by using COVERNAV and flight inspection information, many of them in very rich terrain and coastal areas.

It is important to say that not deleterious signal behavior leading to misleading information has been detected. In fact, it should be considered rare phenomena. However, any propagation problem such significant multipath reflections need to be identified. COVERNAV will be upgraded to include an electromagnetic propagation model, though the need for flight information would not be eliminated. On the other hand, flight inspection equipment would aid in identifying (and removing) the causes of propagation distortions by including additional capabilities.

ACKNOWLEDGMENTS

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