A Standardizeable Framework Enabling DME/DME to Support RNP 1

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ABSTRACT

The continued disruption of GNSS signals in the airspace has highlighted the need for RNP services based on terrestrial sources. Given the prevalence of DME in many complex airspaces and terminal areas, the target of DME/DME supporting RNP 1 is desirable. The route to adoption, however, has not been as straight forward as originally envisioned. One reason for that delay has been the threat from multipath-induced errors. This paper proposes a way of detecting and excluding multipath-affected measurements, and it predicts the achievable navigation performance, after multipath exclusion.

1 INTRODUCTION

The European Organization for Civil Aviation Equipment (EUROCAE) has tasked its Working Group 107 (WG-107) with developing a Minimum Aviation System Performance Specification (MASPS) to support Required Navigation Performance (RNP) services, based on Distance Measuring Equipment (DME). The target performance is RNP 1, which has a Total System Error (TSE) of 1 NM [1]. A key constraint to the work is that the new standard ought to require no more than the minimum amount of changes needed, with respect to the state of the practice, to reach this target.

To comply with RNP 1, the avionics must guarantee a TSE below 1 NM with a 95% confidence, as well as a TSE of 2 NM with 99.99% confidence. Making DME-based navigation compliant with RNP 1 can be achieved by demonstrating its Navigation System Error (NSE) stays below 0.866 NM (1603 m) [1], which accounts for a Flight Technical Error (FTE) of .250 NM (assuming flight director or autopilot guidance), to achieve the required TSE of 1 NM. This argument assumes that the Path Definition Error (PDE) is zero, which is established common practice.

In addition to the actual navigation accuracy, the avionics must also support performance monitoring and alerting. The proposed framework will implement this capability by monitoring redundant measurements. Prior work [2] has demonstrated that it is safe to assume no more than one measurement will be affected by severe multipath at any given time. Furthermore, DME has suitable protection features against nominal levels of multipath (within the accuracy error budget) with an associated long-term performance record.

The strategy for severe multipath mitigation is based on modeling fading in the vicinity of DME ground transponders, as proposed in [2]. Fading or obstruction of the direct signal path in combination with a sufficient multipath reflector has been shown to have the potential to cause severe multipath. The ability to predict fading results in an ability to predict the location of severe Out Of Tolerance (OOT) multipath occurrences in 3-D space, thereby allowing adequate trajectory design that is free of OOT multipath, as well as adequate tuning of DME channels in the FMS. The key result is that no more than one unmodeled OOT multipath will occur at a given time.

2 OBJECTIVE

The stated objective of the multipath task force of EUROCAE WG107 is to identify ways of making navigation errors due to multipath tractable for the purposes of RNP 1. Over the lifetime of the task force it has seen a variety of proposed approaches to deal with multipath errors, with varying effectiveness and from a range of technical complexity.

Two central themes are common to most of the proposals:

- A methodology for detecting and excluding out-of-tolerance ranging errors due to multipath
- A way of providing sufficient diversity of measurements, after the exclusion of affected measurements

The methodology described in this paper achieves these two objectives with a set of proposed modifications to the way on-board avionics handle DME interrogators. The first modification is to enforce that DME interrogators coordinate which channels they tune, bringing increased redundancy to the position solution, compared to conventional DME/DME. The second modification is to continually monitor the consistency of all ranging measurements, using a Fault-Detection and Exclusion (FDE) method that is similar to Receiver Autonomous Integrity Monitoring (RAIM).

In addition to the changes in the on-board architecture, the proposal includes modeling radio propagation in the vicinity of every ground transponder relevant to implementation of RNP procedures (generally in high capacity TMAs), with the aim of predicting signal fading. This fading prediction was developed by [2] and provides a way of predicting where multipath errors are likely to occur. The same methodology can be leveraged to indicate areas that are likely to be free of multipath. Using this approach, combined with adequate (or "smart") tuning of ground transponders, guarantees that the airborne interrogators do not tune transponders with a high probability of multipath at a given location. This, in turn, supports the claim that no two DME channels will be affected by OOT multipath simultaneously.

3 RANGING PERFORMANCE

For the purposes of modeling the coverage of DME signals in the airspace, a ranging error with a zero mean and a standard deviation of $\sigma_r = 180$ m provides a conservative model. This is consistent with both, the applicable standard [3], as well as recent results from real-world measurement campaigns [2].

In addition to the nominal error, driven by the 180 m standard deviation, the only source of out-of-tolerance (OOT) measurements is multipath. This assertion is consistent with the findings of [2], where no more than a single OOT measurement could be identified at any point in time.

For the broader integrity case it is important to note that the transponder facilities are equipped with executive monitors, which reduce the risk of a signal-in-space fault from an operational DME facility to below the integrity risk in question of 10^{-4}.

4 NAVIGATION PERFORMANCE WITH CONVENTIONAL DME

Conventional DME/DME receivers tune a minimum of two different transponders at a time. Given that the tuned channels are subject to a constrained on the subtended angle $30° \leq \theta \leq 150°$, this leads to a horizontal Dilution of Precision (DOP) value between 1 and 2. Notionally, such figures would suggest that with a $\sigma_r \leq 180$ m and a DOP ≤ 2, the position-domain horizontal error would have a standard deviation of 360 m at worst.

For an integrity risk of 10^{-4}, the horizontal error to be considered would be four times the standard deviation, or 1440 m. However, it is important to bear in mind that with only two measurements, the computation of two estimates (latitude, longitude), has no redundancy associated with it, from which integrity checks could potentially be derived.

5 PROPOSED MODIFICATIONS TO ACHIEVE RNP 1 ACCURACY

From the reasoning above it becomes evident that integrity can only be computed if redundancy, or spatial diversity, can be enforced. Given that aircraft operating DME/DME services are expected to have redundant DME interrogators available, one logical place to enforce such diversity is in the tuning of DME channels.

The solution to the problem can be to expect the redundant on-board Flight Management Systems (FMS) to coordinate the tuning of DME channels. With this constraint enabled, this paper shows, in later sections, that the interrogator can track up to five distinct channels simultaneously. This leaves enough redundancy for at least one single OOT measurement to be detected and excluded, should a statistical anomaly be present.

5.1 Detectability of Multipath Events

Ob-board performance monitoring and alerting (OBPMA) is a required function of RNP systems, and allows real-time knowledge on whether the RNP system is operating according to its required performance. This includes monitoring the total system error (TSE), which is comprised of a navigation system error (NSE), flight technical error (FTE), and path definition error (PDE). PDE is typically neglected in performance analyses, and monitoring of the NSE and FTE can be accomplished, for example, with a RAIM-like algorithm and lateral navigation display indicator, respectively [4]. FTE refers to the aircraft's ability to follow the defined path, therefore this paper focuses only on the NSE and predicts a level of performance monitoring by applying a RAIM-like algorithm to the DME navigation infrastructure of Germany.

For a given RNP designation, the TSE 95% lateral accuracy requirement is identical to the RNP designation in nautical miles. For example, RNP 1 is a specification requiring TSE accuracy to be no worse then 1 nautical mile 95% of flight time. OBPMA monitors accuracy performance according to this requirement. Additionally, OBPMA must monitor whether the probability of TSE exceeding twice the RNP designation (e.g. 2 nautical miles for RNP 1) is greater than the required maximum of 10^{-5}. These accuracy and OBPMA limits are allocated to the various TSE error components, and the portion of the OBPMA limit allocation to the NSE is referred to as the horizontal alert limit in this paper.

A RAIM-like algorithm can compute a level of horizontal protection that bounds the NSE monitoring capability to within a certain probability. By comparing this horizontal protection level (HPL) for a given region and assumed navigation infrastructure, one can analyze the feasibility of implementing RNP procedures for that region and navigation infrastructure.

5.2 HPL Equation

As there is no single standard RAIM algorithm, this paper uses a more conservative version of the method in [5], which is already fairly conservative for en-route operations [6], to compute the HPL. The HPL is a function of a navigation infrastructure measurement error characteristics, the transmitter geometry for a particular space-point, and the false alert and missed detection probabilities. The HPL equation used in our analysis is given by

$$HPL = \max\left(H_{slope,i}\right)\sqrt{\lambda_{mdb}} + k\sigma_{max} \qquad \textbf{(1)}$$

where $\max\left(H_{slope,i}\right)\sqrt{\lambda_{mdb}}$ is described in detail in [5] and $k\sigma_{max}$ is the maximum horizontal error uncertainty σ_{max} inflated by k to correspond to an ellipse bounding the NSE to $1 - P_m$ probability.

5.3 Resulting Navigation Performance with Monitoring

The HPL was computed using (1) for discrete points at FL100 (an altitude of 10,000 ft) over the region of Germany. Current DME stations were used as the assumed navigation infrastructure. As DME avionics have limited tracking capability, this process was repeated for various station selection assumptions. The top-left plot in Figure 1 shows the HPL results in the case that there is no limit on the number of stations that can be tracked. The top-right plot shows the HPL performance in the case that only five stations are tracked and the station selection method simply chooses the five nearest. The bottom plot of Figure 1 shows HPL performance in the case of only four stations tracked selected in an optimal manner.

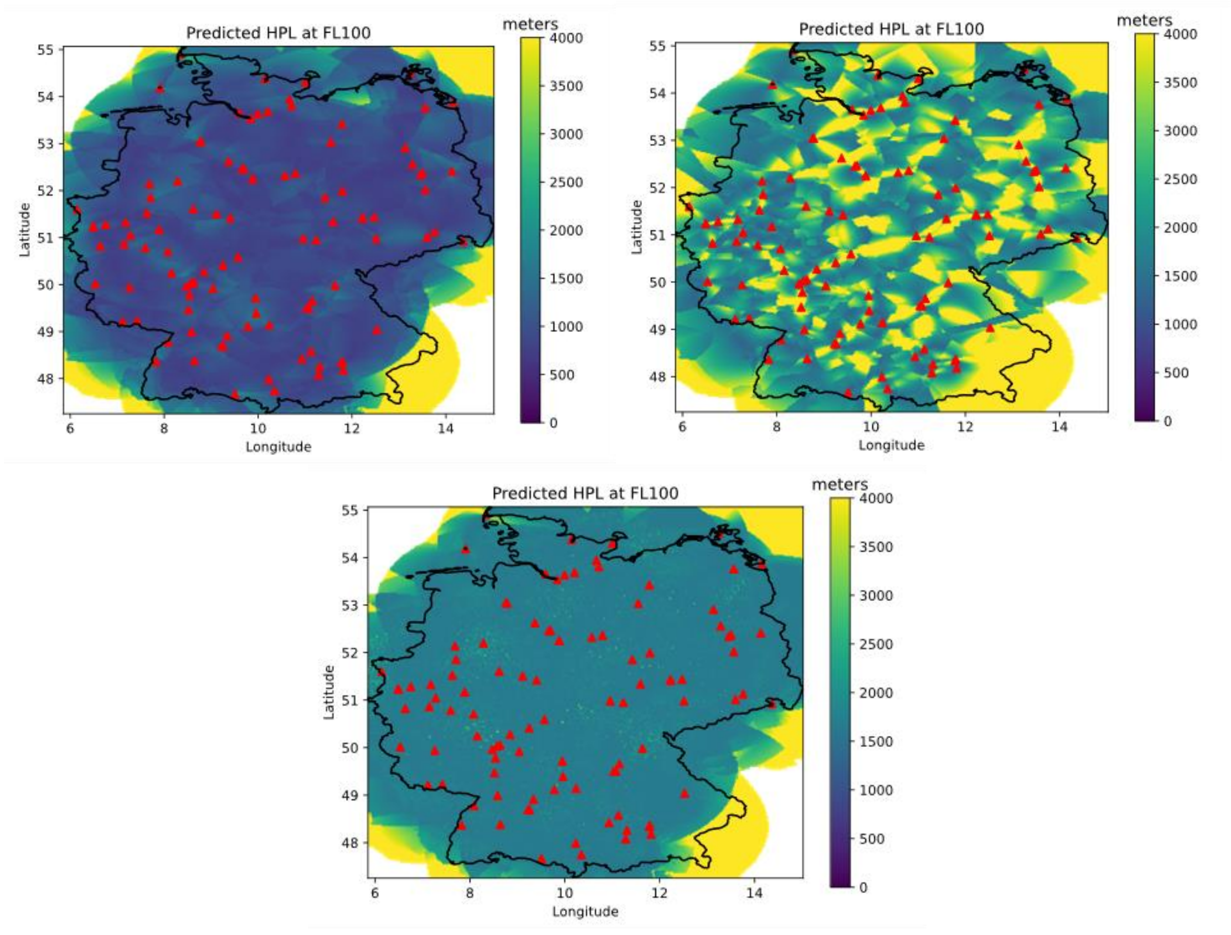

Figure 1 - (top, left) HPL results for all stations in view. (top, right) HPL results for five nearest stations in view. (bottom) HPL results for four optimal stations in view.

The optimal four stations were found using a brute-force method and is intended to show the ceiling of any proposed station selection method. Looking at the all-in-view HPL plot, the DME infrastructure provides a HPL of at least 1500 meters, or 0.81 nautical miles, over most of Germany. The optimal-four plot likewise shows that most of Germany is covered by an HPL of around 2000 meters or 1.08 nautical miles. Assuming all other requirements are met, this would imply that DME has the potential to allow RNP 1 operation at FL100 for most of Germany if the entire OBPMA budget was allocated to NSE. If the auto-pilot resulting in a 95% FTE of 0.250 NM is used, the remaining 0.866 NM in the TSE budget can be allocated to the 95% NSE. Twice this value, 1.73 NM, is then considered the horizontal alert limit. From the plots, it is clear that both the all-in-view and the optimal four can meet the OBPMA requirement for NSE monitoring given the specified conditions.

6 PROPOSED REQUIREMENTS TO BE INCLUDED IN MASPS

The following modifications to conventional DME/DME that can lead to RNP 1 performance will be proposed to EUROCAE WG-107 for consideration. It will be up to the working group to approve or modify the proposed changes in a way that is practical to all stakeholders.

- Under the **assumption** that:
    - Large outliers due to OOT multipath occur on at most one channel at a time
- The **airborne equipment** should:
    - Have at least two DME interrogators with at least three channels each
    - Feed measurements from BOTH/ALL interrogators into at least one FMS
        - May feed measurements from all receivers into all FMS
    - Manage channel tracking to ensure sufficient diversity of ground transponders
        - May manage channel tracking to ensure maximum diversity of ground transponders
    - Implement consistency-based monitoring of observables in snapshot (RAIM-like)
- The airborne equipment may:
    - Implement time-domain monitoring of observables
- **ANSP / Procedure Design / Flight Inspection** should:
    - Assert that waypoints are in fading-free zones, giving them a vertical scope of validity
    - Ensure sufficient ground stations to suit redundant geometry

7 FUTURE WORK

The recommendations of this paper will be submitted to EUROCAE WG-107 in the hope that the members will endorse them. If an endorsement takes place, the pathway to a future aviation standard is likely set. Alternatively, the WG may decide to only adopt a subset of the recommendations, in which case there will be at least one round of iterations.

Should this methodology become part of a MASPS document, it will enable a more robust implementation of RNP services. This new generation of RNP would not be affected by the loss of GNSS services, making them more widely available and accessible than currently possible.

In addition to the standardization work, it will also be critical to continue developing new methods against disruption from OOT multipath events. These may include making DME transponders more robust to multipath, for example with better signal processing, or it may include fundamental changes in the architecture, such as establishing an automated reporting method for OOT multipath events.

8 SUMMARY

This paper proposes a way of making DME/DME services compliant with the RNP 1 specification. The main contribution is a proposed set of changes to the standard on-board architecture, in how DME interrogators and flight management systems are interconnected. The proposal includes a strategy for dealing with OOT multipath events and a prediction of RNP 1 coverage over Germany, under the proposed new methodology.

9 REFERENCES

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