Quantifying DME-N Multipath in the Context of PBN

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INTRODUCTION AND GENERAL CONTEXT

The number of GPS outages likely caused by radio frequency interference reported by aircraft operators in the European region has reached a historic high in 2018 and 2019. The issue continues in 2020 / 2021 despite a reduced numbers of flights (and subsequently also a reduced number of reports). While various efforts are underway to counteract this trend, the most suitable back-up navigation infrastructure to maintain Performance Based Navigation (PBN) operations currently is DME/DME area navigation. This can be referred to as “short term A-PNT” (Alternate Positioning, Navigation and Timing), where longer term options consider evolution towards using new technology.

PBN specifications make a distinction between RNAV and RNP specifications, where the latter provide on-board performance monitoring and alerting, which implies a recognized level of integrity. While DME/DME can support RNAV5 and RNAV1 applications, the support of RNP1 is subject to State approval. EUROCAE Working Group 107, “DME Infrastructure supporting PBN Positioning” was created in 2018. The deliverables of the group are to update EUROCAE Document ED-57, Minimum Operational Performance Standard for DME (Ground Equipment), and to write a new MASPS. This Multi-DME-focused Minimum Aviation System Performance Standard will be consistent with the RNP/RNAV MASPS (ED75 / RTCA DO236, covering aircraft avionics) and provide a basis for States to approve DME infrastructure for PBN as described in the ICAO PBN Manual. This will enable a more robust RNP service in locations where this is required. In other locations where RNAV applications are used, it will improve the reliability of DME-based RNAV1 service as well. This is desirable because with increasing use of GPS, aircraft will only rarely navigate using DME. Therefore, these measures ensure that when DME/DME service is needed due to a GPS outage, the expected performance can be provided.

For accurate and reliable operation based on DME/DME positioning, it is necessary to assess and limit all system error components. This includes not only the ground and aircraft equipment, but also the propagation channel. In the case of DME/DME supporting PBN, this conventional ranging source needs to be compared to GNSS, where the development of error budgets and integrity mechanism has received much more rigorous attention. For GNSS navigation, an airborne multipath envelope has been determined through extensive in-flight data collection. Due to the space to air propagation, there is no further significant multipath apart from reflections off the aircraft fuselage (noting that PBN does not cover landing, roll-out or taxi operations). In the case of DME and terrestrial propagation, however, multipath is a potentially much more significant ranging error source. WG107 is aware of several significant multipath cases and is working towards assessing them in the context of providing "integrity assured" ranging with DME. While various current DME techniques provide a multipath-limiting function, typical integrity considerations like bounding nominal errors and monitoring for off-nominal conditions have not received much attention so far. WG107 seeks to quantify the threat space and then define suitable assurance methods such that sufficient confidence exists that DME-usage in a given airspace is free from excessive (integrity-relevant) multipath effects.

A first finding of the group was that the traditional two-ray model may not provide a sufficiently conservative multipath error envelope. Of particular concern are cases where the direct path is attenuated, while the aircraft is receiving a significant and consistent reflected signal. The temporal and spatial behavior of the multipath scenario is also of interest, since ranging errors need to be translated into corresponding positioning errors. Only this will allow making decisions on whether this will lead to unacceptable errors in flight guidance from an integrity point of view.

The desired integrity levels for DME supporting RNP are such that bounding errors based on empirical data alone is difficult, even if conventional navigation aids can rely on a long operational service history. During 2021, a dedicated data collection campaign was flown in France, Belgium and Spain to collect multipath data especially at low altitudes and in places with known anomalies. The collected data and associated findings are presented in this paper. While further analysis still needs to be performed, the current thinking of WG107 with respect to the assessment and bounding of DME range integrity when subject to multipath is presented, together with an outlook on what possible assurance methods involving flight inspection could be envisaged.

INTRODUCTION TO DME MULTIPATH

Multipath propagation can induce large errors to range measurements in terrestrial radionavigation systems. While many authors have attempted identifying a practical overbound, or other ways of managing the effects for navigation with integrity [1], [6], [9], [7], [10], some open questions remain. One of the remaining challenges is the treatment of rare, but relatively severe (i.e. several multiples of the standard deviation), off-nominal ranging faults.

Empirical observation has shown that multipath errors are worse at low elevation angles [6] and become more manageable at 3° and above [9]. Below that 3° figure, the errors tend towards a non-Gaussian / heavy-tailed distribution with changing biases. Above that value the error tends more towards Gaussian behavior.

The established literature on Distance Measuring Equipment (DME) suggests that a hard bound, on the order of a few hundred meters, can be identified for multipath-induced errors [5]. This concept is rooted in the use of a two-ray model as the basis of multipath errors. Ample evidence exists to disprove the existence of a hard overbound at a few hundred meters [7], as multipath errors can reach six hundred or more meters. In fact, a careful read of [5] shows that the authors make no such claim. However, other authors have used the error model to argue for bounding DME multipath errors, for example at 180 m.

Following the discussion of [7] it is evident that no hard theoretical bound can be constructed on the maximum ranging error due to multipath for snapshot DME measurements. This argument extends to any radionavigation system based on time-of-flight or time-of-arrival measurements. In the case of DME supporting PBN, DME provides ranging data while the position computation occurs in the Flight Management System (FMS). FMS use reasonableness checks based on time history to exclude large range errors as required per [2]. An unpublished study by a major aircraft manufacturer concluded that large step and fast ramp errors could be detected by reasonableness checks, but that slow ramps were a challenge. However, the performance and effectiveness of such reasonableness checks are not known. Therefore, it would be advantageous to achieve a multipath range error overbound without taking credit for reasonableness checks.

As part of the effort of formalizing DME as a navigation technology to support RNP operations, it is useful to establish that unusually large multipath faults are rare occurrences. The evidence discussed in this paper presents first steps towards providing evidence that large DME multipath faults can be considered to be rare enough to support RNP operations.

BACKGROUND: RNP

Required Navigation Performance (RNP) is a class of airspace operations that is particularly desirable for the high level of automation it enables. The implementation requirements, defined in [3], include provisions for several RNP Types, each of which is indicated with a number, which in turn represents the required Total System Error (TSE) expressed in nautical miles. As such, an RNP 1 operation can be guaranteed to stay contained to within 1 NM of the operation centerline with a probability of 95% and within 2 NM with a probability of 99.999%.

These reliability figures make RNP attractive for airspace where a high degree of automation is necessary. The high degree of automation is particularly attractive in congested airspace, where trajectory-based operations would generally bemore fuel efficient and have lower emissions than traffic subject to tactical deconfliction. Such automation puts an additional burden on the reliability of the navigation solution and its resulting path containment.

MULTIPATH FAULT MODEL

The aforementioned shortcomings of the two-ray model can be addressed by accounting for more reflections than one. In the classic two-ray situation, no multipath error should ever exceed a hard bound; as presented in [4], this bound would be 240 m for an attenuation of 6 dB between the direct and the reflected rays. Instances of DME errors greater than 240 m occur when the reflected ray is attenuated less than 6 dB, relative to the direct ray. It is also possible for the direct ray to be attenuated, which can make the reflected ray stronger, thus leading to potentially large multipath faults.

According to [9], the following reasons can lead to an attenuated line-of-sight (LoS) ray:
1) Shadowing of the ray, such as from foliage or other occlusions
2) Misalignment of the antenna gain, for example due to aircraft banking
3) Destructive interference from a reflector (in particular from ground)

A drop in LoS power, coupled with a strong reflected ray, can lead to a situation where it is the reflected, not the LoS ray, that has the higher power. In the absence of a direct signal, the receiver will likely identify the reflected signal as genuine, leading in theory to very large error magnitudes (unbounded). We can, however, assume that reasonableness checks will detect excessively large errors, such that for RNP containment, the main concern is about errors which exceed the ones limited by the presence of a direct signal, leading to path deviations which are significant enough to compromise operational route spacing objectives while at the same time not being easy to detect.

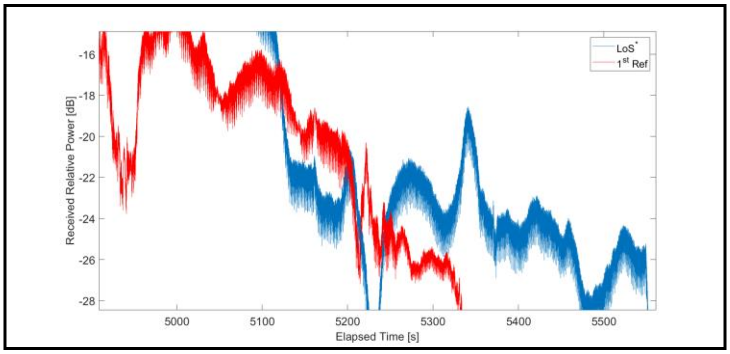

Figure 1. Received signal power on the LoS and first reflected rays.

The plot of Figure 1 shows a snapshot from the results of a channel sounding experiment, detailed in [6], where airborne equipment allowed modeling the transfer function between a ground DME antenna and an airborne DME receiver. Note that the reflected can, on occasions, be stronger, leading to such increased multipath errors.

METHODOLOGY: DATA ANALYSIS

A potential integrity case for RNP based on DME/DME could be to demonstrate that multipath errors leading to TSE exceeding the specified limit (two times the accuracy value) without annunciation are “rare”, meaning less likely than 10^{-5} [4]. This probability value must hold true per flight hour, which would imply that all possible routes below a certain altitude would require flight-inspection to be authorized for RNP. Alternatively, if a suitable analysis methodology can be found, it would be possible to authorize RNP trajectories in areas that have not yet been flight-inspected. A more balanced approach would be to perform an initial engineering analysis to identify areas which may be vulnerable to multipath including direct signal attenuation, followed by a more targeted and reasonable flight inspection effort. To quantify the likelihood of rare multipath errors requires a definition of “anomalous” multipath, as a differentiating feature of “nominal”, fault-free multipath. In an effort to assess whether large multipath faults are rare occurrences or not, and characterize the multipath threat, EUROCONTROL commissioned a DME multipath study comprised of two phases: in-flight data collection followed by data analysis and threat model derivation. The data collected for this purpose serves as the basis for the initial analysis presented in this paper (the full data processing and theoretical analysis is still to be executed). In addition, the paper briefly describes other DME range anomalies that have been studied by the members of the EUROCAE WG-107.

DATASET

A previous in-flight DME data collection was executed in 2016 in cooperation with the Flight Inspection team of DSNA-DTI, with the following main objectives:

- Assess the maximum usable range of DME
- Assess the actual accuracy of the DME range and in particular the dependency with the distance

Therefore, the tuning plan was defined in order to record mostly far away transponders. The results of the analysis were presented to IFIS 2016 [11]. This time the data collection (performed also by the DSNA-DTI FI team) was focused on logging data received relatively close to the transponders and at low altitudes, an environment which is more prone to multipath and other propagation anomalies. Thus the data was recorded mostly during ILS flight inspections and other flight tests executed in various TMAs in France and Belgium. Up to 10 DMEs in view were tuned simultaneously using an EDS300 device. In order to maximize the size of the dataset, logs have been generated also during ferry flights but again selecting with priority the ground stations in close range. During the ferry flights, a good number of stations in the neighboring countries were also recorded. A flight in the proximity of the Swiss border was also executed in order to capture potential anomalies of the cross-border DMEs that may be caused by the terrain rich environment. The data was analysed in search for large errors and other signal in space anomalies. The last part of the campaign was dedicated to the investigation of some of the known abnormal cases and other potential multipath cases detected by the preliminary data analysis. During these targeted flights, the EDS300 was used in single-channel mode and the video base band signal and the RF I/Q data were recorded at the same time.

ANALYSIS RESULTS

Overall assessment

The aggregated dataset, including the data recorded during the flights targeted on special case investigations was processed and analysed in a similar way as for the 2016 data collection to characterize the overall error distribution. After excluding all the invalid records, those measuring a co-channel range or logged in search or memory mode, a total number of approx. 6.2 million records were retained. The histogram of the range error distribution is shown in Figure 2, while the computed data characteristics are:

- Mean: 5.61m
- Standard deviation: 103.69m (0.056NM)
- Skewness: -4.828
- Kurtosis 316.95

This error distribution confirms that in general the actual accuracy of the DME ranges is two times better than the performance required by the ICAO Annex 10 SARPS (0.2 NM - 95% / 2σ). Note that the analysis was performed on a dataset which includes a number of biased, ILS-collocated DMEs. The presence of these biased stations can be observed in Figure 3 together with other special cases, all subject to varying degrees of multipath:

1. One particular DME installation at the end of the runway, with a large bias introduced for zero range indication at threshold (2250m bias).
2. GP collocated DMEs biased for zero range indication at threshold (approx. 300m bias).
3. Anomaly associated with a TACAN
4. Same ILS/DME frequency (interlocked) used for 2 parallel runways, the runway in service was unknown, the position of the u/s DME was used as reference.
5. Potential multipath errors recorded for ILS collocated DMEs which use directional antennas, outside of the service area (opposite to the approach direction)

The presence of the biased DME/ILS stations and the large positive errors, although in a low proportion relative to the size of the dataset, explains the high kurtosis factor. Note that in the above list only case 3 & 5 represent potential multipath cases. Unfortunately, it was not possible to investigate further the TACAN anomaly (case 3); however, it is unlikely that this constant error of approx. 300m is due to a multipath reflection. Case 5 appears to be a multipath issue facilitated by the directive radiation pattern of the transponders; this is similar to a direct path shadowing scenario. A more detailed analysis of this case is presented in one of the following chapters. It is important to highlight the fact that case 5 is the only severe anomaly (range errors higher than 1000m, up to 3.500m or 2NM) detected so far in the data logged during this extensive in-flight data collection campaign, and that the anomaly is found outside the transponders service volume.

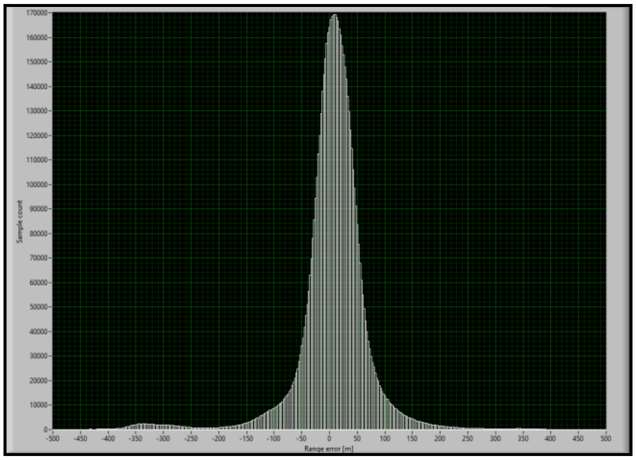

Figure 2 Overall range error distribution

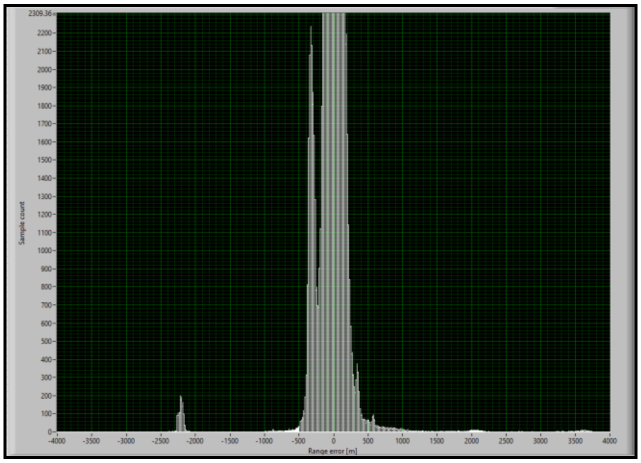

Figure 3 Range error distribution - tails detail

A good number of additional large range errors were recorded but these can be described as:

- Measurement outliers (isolated, short duration records)
- Small sets of consecutive measurements, recorded over several seconds at coverage limit or in coverage gaps.

At this time, this type of transient anomalies (illustrated in Figure 4, where different colors are associated to different DMEs) have not been further investigated. The following sections present an analysis of the 3 main scenarios affecting the direct path that could generate large multipath errors, i.e. destructive interference, shadowing/occlusion by ground obstacles and shadowing at aircraft level (e.g. due to high banking angles), on the basis of the recorded data and the evidence and assessments performed by different other authors.

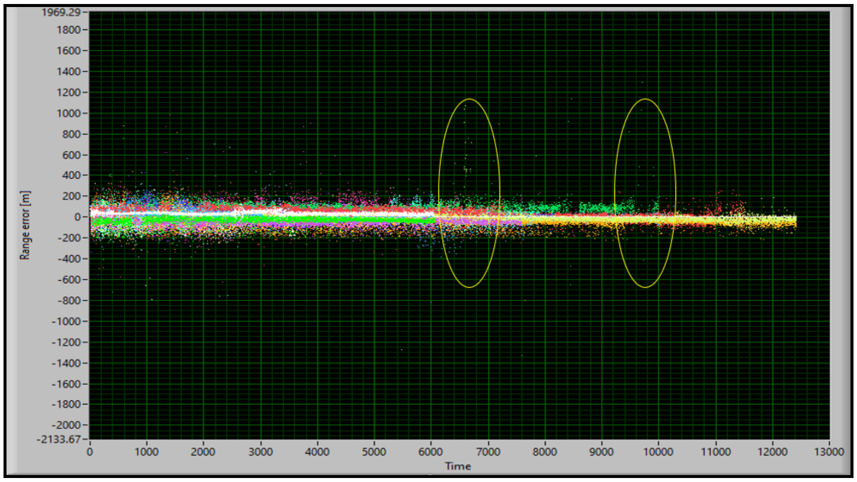

Figure 4 Transient large range errors

<u>Destructive interference</u>

<u>DME FTV – Fuerteventura</u>

During the commissioning flight of a new STAR in GCFV airport, an anomaly in the signal received from DME FTV was detected. As it can be seen in Figure 5 , the power density falls below -90 dBW/m2 from 23 NM to 26 NM of the flight record (approximately 55 NM DME range), at 5000 ft. Considering that the power density increases again after this segment (further from the station), the problem seems to be caused by longitudinal multipath on the terrain. In the impacted segment the range error shows a “scalloping” effect but doesn’t exceed 0.2 NM in absolute value. Note that FTV DME is installed in close proximity to the shore and that the impacted radial is flown over the sea.

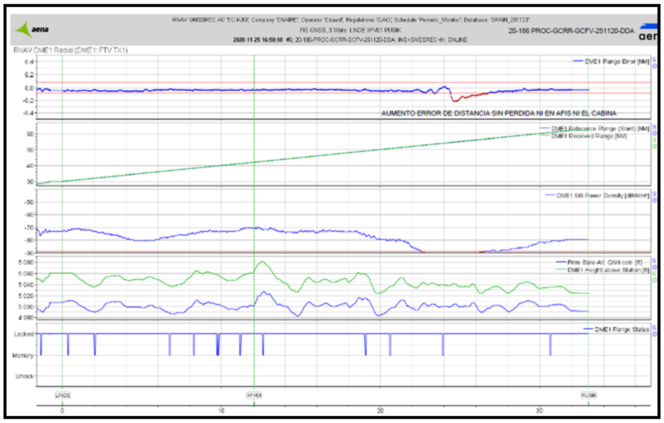
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Figure 5 Anomaly in flight inspection results for DME FTV

INECO has analysed the signal in space propagation by means of the software AREPS, which applies the parabolic equations technique. The simulation has shown a deep and narrow radiation null which intersects the flight altitude in the impacted area. This case was discussed in WG-107 and EUROCONTROL has decided to investigate this case further using an application which models the radio waves propagation also based on the parabolic equations method, implementing the Wide Angle Parabolic Equations – WAPE (application created by Christophe Visee – EUROCONTROL). The simulation using the specific antenna radiation pattern, height above ground, and terrain profile has returned similar results, identifying a number of fading areas which correspond to the recorded power density variation (Figure 6). Note that in addition to the substantial fading at approx. 55 NM DME range, a number of less strong fading areas are predicted closer to the station, matching the variation of the recorded signal strength. The analysis has considered also different other factors that may influence this fading phenomena, such as antenna height above terrain (leading also to a different height above mean sea level), tide height and wave height. The results illustrated in Figure 7 and Figure 8.

From these results it can be concluded that strong fading of the DME signal-in-space is possible, and the existance and position of the nulls is determined by several factors:

- Antenna height above ground
- The configuration of the "ground" (in this case comprising two different areas: ground and water surface)
- The reflection index and the smoothness of the reflecting surface

In this particular case it appears that the flight inspection was executed in a worst case multipath scenario: low tide and calm sea.

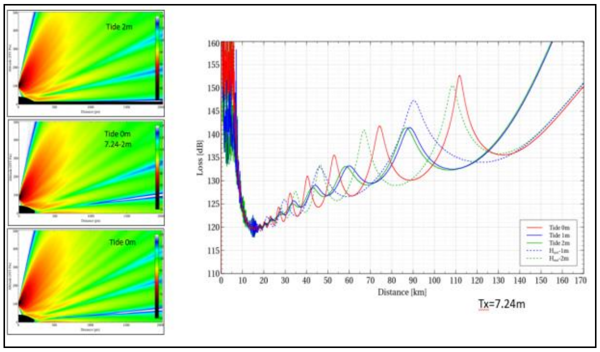

Figure 7 Propagation loss for different tide and antenna heights

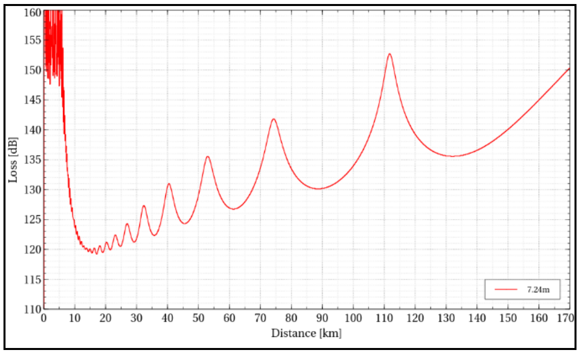

Figure 6 Simulation of propagation loss (WAPE)

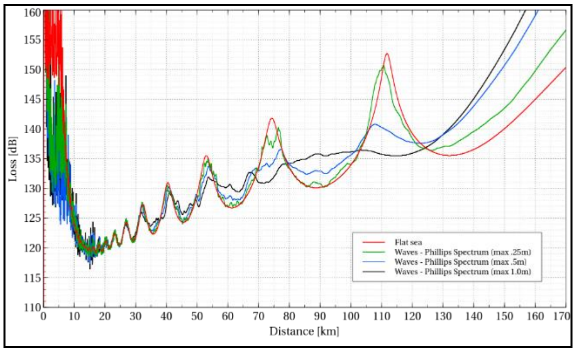

Figure 8 Propagation loss for different wave height

This anomaly was also investigated by another member of WG-107, Ralf Eichhorn – DFS. The method used to estimate the impact of the ground reflection on the signal in space was the two-ray model over a smooth Earth which returned a similar attenuation pattern. This proves that this method can also be very effective to identify fading, especially where the terrain is relatively flat and for propagation over water surfaces. The Rayleigh Roughness Criterion was proposed in order to assess the smoothness of the reflecting surface and the capacity to generate the specular reflections considered by the model. In addition, three-ray model analysis (adding a lateral multipath) showed that a large aircraft holding for departure could have produced a signal with higher strength than the direct signal in the fading area, which may explain the range error in Figure 5.

DME CNA – Cognac

One particularity of the FTV case is that the fading is observed for the signal propagation over the water, which in case of a calm sea generates a specular reflection, similar to the "smooth Earth" scenario. For propagation over land, the terrain profile may be a factor of critical importance that has to be carefully considered.

Another potential fading case discussed in WG-107 is the DME CNA (Cognac), where a fast and short drop of the received signal was observed on radial 154 during the flight inspections performed over several years at 5000 feet and also 7000 feet AMSL. For both altitudes and all measurements the null appears at an elevation angle between 1.2° and 1.3° (see Figure 9) Range errors up to 500m were also detected within this null.

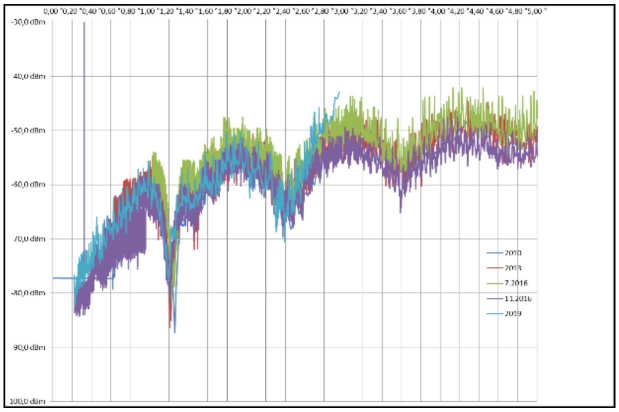

Figure 9 Signal strength versus elevation angle

The station was recorded several times during the ferry flights in the new data collection campaign, at different ranges and azimuths, but no propagation issues or out of tolerance range errors have been detected (each time the measurements were made at elevation angles higher than 1.3°).

The signal in space propagation for CNA DME was also investigated using the parabolic equations method. Multiple simulations were executed for the problem radial and other radials using different combinations of the following input parameters:

- Terrain model:
  - DTED 1
  - Smooth Earth
- Radiation pattern:
  - Gaussian distribution with a HPBW of 6 degrees and tilt of +3 deg.
  - RTCA typical DME pattern (named RTCA 1 in this document)
  - RTCA typical TACAN pattern (named RTCA 2 in this document)

The different antenna patterns were used on one hand because the real radiation pattern was not available and on the other hand in order to assess the sensitivity of the results to slightly different patterns. In all simulations the actual antenna height above ground was used (5m) and the presence of the VOR counterpoise was also modelled (30m diameter, 3m above ground). It is not in the scope of this paper to discuss these results in detail, nevertheless, the main findings are summarized as follows.

The simulation using the RTCA 1 and the Gaussian patterns succeeded to predict accurately the position of the fading zone. However, both the terrain profile and the vertical radiation pattern of the antenna have a substantial impact on the resulting signal in space radiation lobes and on the presence and the elevation angles of high loss fading areas. In what regards the radiation pattern, it is key to use a correct gain model at elevation angles around zero degrees, which determine the level of energy radiated towards and reflected by ground. This high sensitivity of the results to the input parameters requires the use of precise input parameters in order to obtain reliable simulation results.

For this ground station, a targeted investigation flight was planned. It was decided to inspect during this flight other radials in addition to radial 154, looking for additional fading areas, and at the same time attempting a first partial validation of the prediction model. For this purpose the propagation loss was simulated for all azimuths around the station at the altitude of 7000 feet AMSL (see Figure 10). The flight plan was defined on the basis of the simulation results and included a number of radial and orbital flight segments, which intersect the predicted fading areas at the specified altitude (represented at horizontal and vertical lines in Figure 11). The signal level measured by one of the FIS receivers (dBm) is shown in Figure 12 (using DEMETER software).

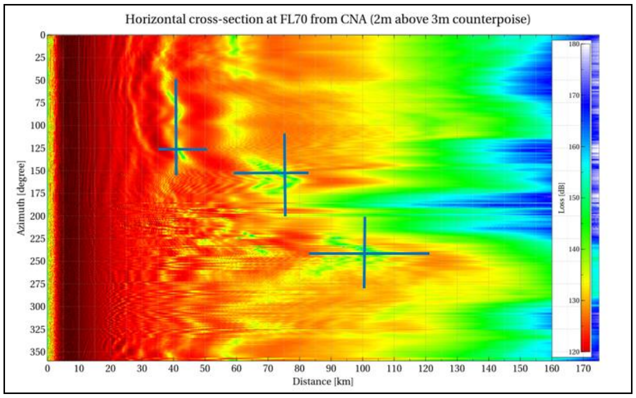

Figure 10 Propagation loss - horizontal cross section

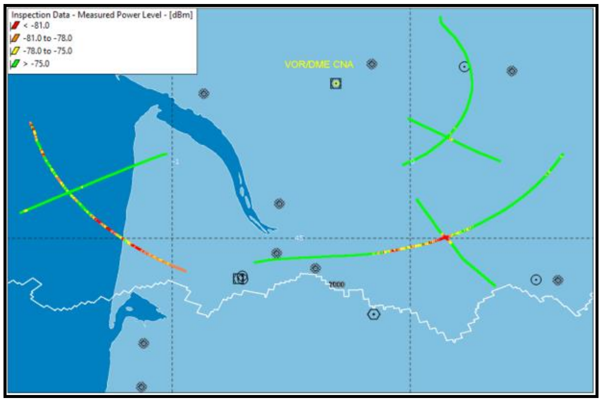

Figure 12 Measured signal level

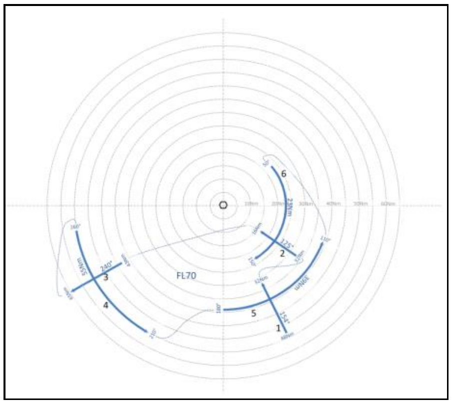

Figure 11 Targeted flight plan

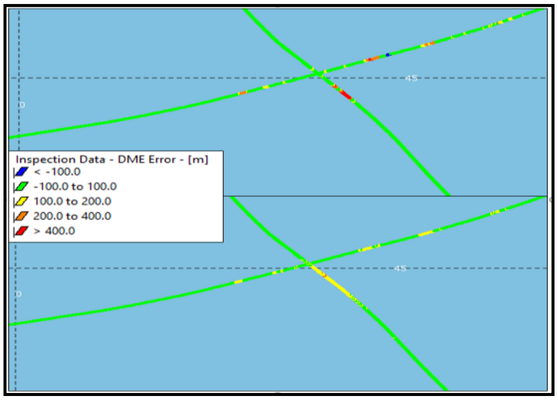

Figure 13 Range error (two different interrogators)

When comparing the recorded signal level with the predicted propagation loss it is observed that:

- The fading on radial 154 at around 40 NM is confirmed and in addition the high propagation loss predicted up to 175 deg on the 40 NM orbit (Run # 1&5) is also confirmed
- Run #4 (orbit at 55 NM) detected only intermittent and less severe signal drop around radial 240 (not fully confirming the predicted fading area), instead a more severe than expected fading was found between radials 210 and 235)
- Runs #2&6 detect a small size fading area on radial 125 at approx. 23 NM (as predicted) but they don't confirm the potential additional issues around radial 75. Note though that the size of the predicted problem area in this case is very limited and the distance to the station is low, therefore the field intensity has a large margin.

Overall, it can be concluded that the simulations have successfully identified the existence of additional fading areas, although the location prediction may not be exact. To be noted though that the simulations are based on AMSL altitudes, depending on the atmospheric conditions in the day of the flight, the flown altitude might have been slightly different. All runs have been flown inside the radio line-of-sight predicted on the basis of the same terrain model (white contour in Figure 12).

The main purpose of the data collection being the analysis of the multipath threat, this aspect was also investigated. In Figure 13 the range error measured by two different DME interrogators, is plotted using the specified color legend. Even where the power density dropped slightly below -89dW/m^2, the receivers were able to maintain tracking but the range measurement error was within 100m increasing up to 400m in Run #4 in the main fading area and slightly above 500m in Run #1 & 5 (around radial 154). It is noted that the interrogators are using different technologies (analog vs. digital signal processing) and behaved slightly different.

The preliminary analysis of the I/Q data recorded during this flight was also attempted. This analysis identified many instances of what appears to be multipath replies, in some cases even multiple echoes but with amplitudes less than half of the direct path reply. These echoes were detected so far only in areas where the interrogators have measured the range accurately. An example is provided in Figure 14 and Figure 15 that show the reconstructed amplitude and phase of the RF signal. An echo with a delay of approximately 7µs can be clearly observed. For each pulse pair the phase of the signal is practically constant but also different between the pairs. However, the analysis of the main fading area on radial 154 was not conclusive. If the range error was produced by a lateral multipath source it could be expected that the destructive interference due to fading would be different (or not existing) for the echo replies and therefore affecting less their magnitude. However, this hypothesis could not be confirmed, even if according to the datasheets the sensitivity of the data acquisition device is better than the sensitivity of the FIS interrogators; in this area all the direct and/multipath reply pulses appear to be below the noise level. The lack of multipath evidence combined with the different behavior of the interrogators suggest that the range errors may be due to the limitation of the signal processing at levels which are below the required sensitivity. The analysis of the I/Q samples and the video base band records will be continued to further investigate the potential presence of multipath signals in the fading areas.

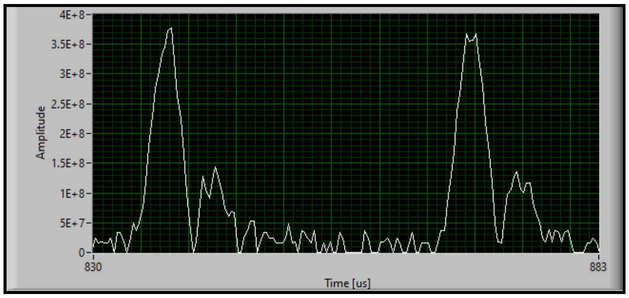

Figure 14 Amplitude of reply pulses

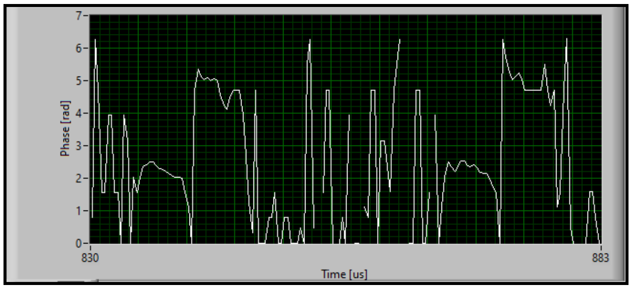

Figure 15 Phase of reply pulses

Two other targeted flights were executed to investigate what appears to be destructive interference observed for two Spanish DMEs, also when the signal propagates over the sea. Although the fading areas were confirmed, the propagation loss is less substantive such that the signal doesn't drop below the minimum threshold and the range errors do not exceed the tolerance limits. For these sites the propagation loss was not analyzed with the simulation tools.

Direct path shadowing

As described in in the Overall Assessment section, some areas of high DME range errors were detected in Paris - Charles de Gaulle Airport (CDG) in areas out of the service volume of two DME/ILS (PNE and CGE), which serve runways 09L and 09R. These large errors were recorded opposite to the approach direction. Although this is not a real direct path shadowing case, it can be considered that the directive radiation with a high front to back gain ratio may mimic well this scenario. Figure 16 shows the magnitude of the range errors recorded in track mode for PNE. The signal is well tracked, with errors within the tolerance in the western sector, while in the eastern sector the signal is tracked intermittently with very large errors that reach almost 2NM in the southeast extremity of the flight path. Similar results are recorded in the CGE logs. One other relevant aspect is that everywhere where the replies are tracked, the field strength of the signal is also at least few dB above the minimum threshold, which suggest that the reflected signal should arrive from a large reflector with a high reflection index.

The number and the variety of locations and magnitudes of the range errors recorded allow an estimation of the location of the potential reflector(s). For each of these measurements, based on the magnitude of the error, the aircraft location and the transponder location, an ellipse will describe all the possible locations of the reflector. The intersection of the set of ellipses will then indicate the most likely location. However due to the measurement uncertainty, and if multiple multipath sources exist in the area, these ellipses may not have one common intersection point. One different approach for the same analysis is to generate a heatmap on the basis of all measurements using a grid computing approach. For each node of the grid and each ellipse a probability index is computed based on the distance from the point to the ellipse. The overall probability index is then computed as the aggregation of all individual indices, and quantifies the probability that the multipath source is located in that node. The heatmap is then generated based on the magnitudes of the aggregated probability index for all grid points.

When this method is used to process the data recorded for these 2 DMEs, the heatmap shown in Figure 16 is obtained (red colour indicates the highest probability). A smaller scale view of the same heatmap is shown in Google Earth view (Figure 17) and may help identifying the potential multipath sources. It is interesting to note that DME CGN is located practically in the hotspot of the heatmap. The possibility that the multipath is due to the re-radiation of the CGE and PNE replies by the CGN antenna was not investigated but should not be excluded. The large metal hangars located around 700m to 1000m south of CGE are also potential multipath sources. Unfortunately the targeted flight planned for the recording of additional in-flight data (including I/Q samples and video base band signals) was postponed several times due to traffic and meteo conditions. The analysis of this case will be further developed once this additional data is available. These preliminary results indicate though that in an airport environment where multiple reflection sources are usually present as well as obstacles that can occlude the direct path, the multipath signals may lead to substantial DME range errors.

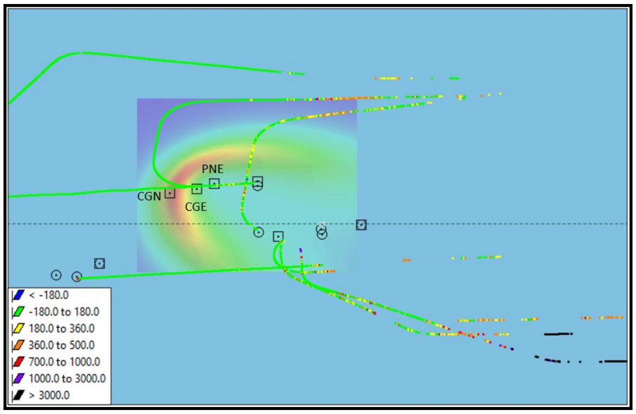

Figure 16 Range errors outside main radiation lobe

Figure 17 Multipath source location heatmap

Misalignment of the Antenna gain (aircraft banking)

During flight inspections on radials of various DMEs by the Japan Civil Aviation Bureau (JCAB) in Japan, range anomalies were found in two particular cases [12]. The anomalies were reproduced in further flights, leading to the assumption that they could be multipath effects. Assessments conducted by Electronic Navigation Research Institute (ENRI) by means of simulations lead to the identification and localization of potential reflectors, which are terrain formations. The magnitude of the error after filtering high frequency components reaches 0.02 NM, respectively 0.04 NM and thus the error is within the tolerances. In one case two reflectors were identified. As already explained above, this situation can lead to the case that the direct signal is strongly attenuated by one reflector and thus the second reflector can lead to an unacceptably large range error. This case however was not observed during the flight inspections. There may be several reasons for this, e.g. the attenuation of the direct signal may be too weak or the aircraft did not fly through the area where the above geometry leads to large range errors.

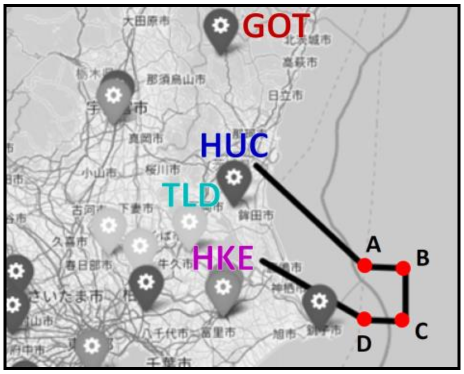

Figure 18 STAR RJAA SWANP N (ENRI)

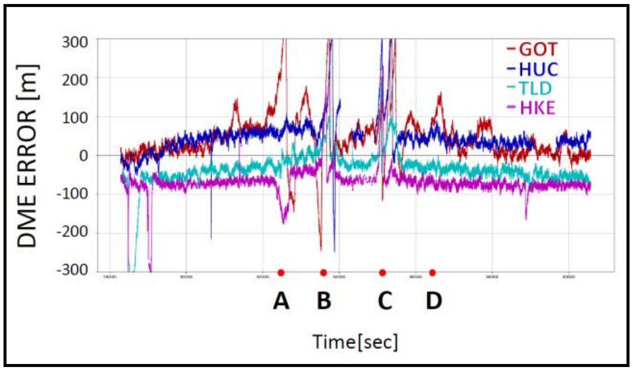

Figure 19 DME range errors during turns

Further DME measurements recorded during flight inspections along STARs in the Tokyo airspace were evaluated to identify range anomalies. It was observed that the DME range errors increase during turns. Furthermore, there seems to be a correlation between the range errors and the bank angles. The following two figures illustrate the observations. Figure 18 shows the STAR RJAA SWANP N and the DMEs GOT, HUC, TLD, and HKE that were investigated. At the points A to D turns take place. Figure 19 shows the DME range error plotted against the time of flight and the times where turns occur. The errors during the turns can reach errors of well over 0.1 NM.

In a further analysis, the aircraft was modeled to derive the antenna radiation pattern by means of simulations. In particular, the directivity of the antenna for $\theta < 90°$ are of interest. As expected, several nulls occur in these areas. Therefore, during the turn, a geometry can occur where the direct DME signal incident angle is coincident with an antenna null and is thus strongly attenuated. As a result, the reflected DME signals become prominent and lead to larger range errors as shown in this example.

CONCLUSIONS

A substantial low altitude DME range data set was collected to support the analysis of the multipath threat to the integrity of the positioning solution based on DME. The preliminary analysis of the data indicates that in general, the 95% bound of the range error distribution is substantially better than the limit specified by ICAO SARPS. It also shows that large range errors (e.g. higher than 500m / 0.25NM) are indeed rare events, of short duration, observed in general at the limit of the line-of sight. The assessment of the I/Q samples indicate that the presence of multipath signals is not unusual, especially close to the ground stations, however this phenomena by itself doesn't lead to DME range faults if the direct path propagation is not impacted. The same analysis has confirmed two of the threats identified in the literature [9] which may impact the direct propagation path to a point where a reflected signal becomes predominant and could be tracked by the DME interrogator: destructive interference due to the ground reflection and the occlusion of the line-of-sight (in the case studied the direct path signal is attenuated due to directive antenna radiation, but the impact can be extrapolated to the line-of-sight occlusion case). Evidence that confirms the third threat (i.e. shadowing of the aircraft antenna due to high banking angles) was provided based on the flight inspection data collected and analyzed by ENRI-JCAB.

Although the analysis is not complete and the activity will continue in the framework of EUROCAE WG-107, some initial conclusions and recommendations may be formulated in order to prevent and mitigate substantial DME range anomalies:

a. The vertical radiation pattern of the ground station may contain a deep null at low elevation angles (around 1 deg.) due to the radio waves reflection from the ground plane. The position, size and attenuation in this null are determined mainly by the antenna gain pattern, the terrain profile and the antenna height above ground. This fading phenomena may be predicted using radio propagation simulation tools. Adjusting the antenna height is a first measure to be considered to avoid or mitigate this issue. Targeted flight inspections are recommended where the signal fading is predicted by simulation and to validate the solutions implemented.
b. Radio propagation assessments should be performed when selecting a new DME site and the antenna height above ground.
c. The airspace in the aerodrome vicinity are in particular prone to lateral multipath due to the presence of large reflectors (buildings, metal hangars, etc).
d. The use of antennas with directive radiation patterns in the horizontal plane is not recommended for DMEs intended to support RNAV operations
e. Thorough flight inspections should be considered for DMEs installed in airport perimeters when new RNAV SIDs/STARs are introduced, in particular if these procedures don't overlay with other conventional procedures supported by the station and if radio propagation simulations are not performed.

Finally, we invite the flight inspection community to report to the authors' significant cases of DME multipath, as described in this paper, for further investigation. This will be a significant help towards establishing DME as a sensor to support RNP procedures in terminal areas and in making these operations robust to GNSS outages for the large majority of air transport aircraft equipped with DME RNAV capabilities.

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