Demand-based Placement of LDACS Ground Stations to Achieve RNP 0.3 Accuracy for APNT

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BIOGRAPHY

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ABSTRACT

Regions with dense air traffic has lower separation between aircrafts to maintain the throughput. Terminal area generally requires high throughput and some of the airports need to maintain $3-$ nmi separation between two aircrafts. To provide $3-$ nmi separation RNP 0.3 is required. In this paper we propose two possible ways to fulfill RNP 0.3 NSE requirement using LDACS as an alternate system. The first way is to use LDACS in standalone configuration and the other way is to use a hybrid configuration, where position solution is obtained using LDACS combined with DME.

The results show that both the proposed methods, standalone and hybrid configuration fulfill RNP 0.3 NSE requirement. Where standalone configuration is more accurate than hybrid, due to the low ranging error of LDACS system. For our analysis the surveillance data for terminal area of Munich and Frankfurt airports were used. In standalone configuration 5 LDACS stations for Frankfurt and 6 LDACS stations for Munich are sufficient to fulfill RNP 0.3 NSE requirement. In hybrid mode both Frankfurt and Munich only need 3 LDACS stations.

INTRODUCTION

Air-Traffic Management (ATM) modernization as developed under SESAR [1] in Europe, is enabled by future technologies for Communications, Navigation, and Surveillance (CNS). GNSS combined with Space Based Augmentation Systems (SBAS) and Ground Based Augmentation Systems (GBAS) cover not only the en-route airspace, but extend its application towards a continuous gate-to-gate navigation, including approach, landing and take-off. Nonetheless, apprehensions about the impact of GNSS service outages remain. Consequently, alternate means for providing Position, Navigation and Time (APNT) services during GNSS outage are being explored.

A possible solution for Alternative Position Navigation and Time (APNT), is to use terrestrial navigation aids such as DME or DME combined with Inertial Reference Unit (IRU). As the DME ranging error is much greater than that of GNSS (signal-in-space error for DME is about 182 m at 68 nmi [2]), DME/DME based position solution fails to meet the requirement of RNP 0.3 [3]. Hence, there is a need of alternate terrestrial system to support RNP 0.3.

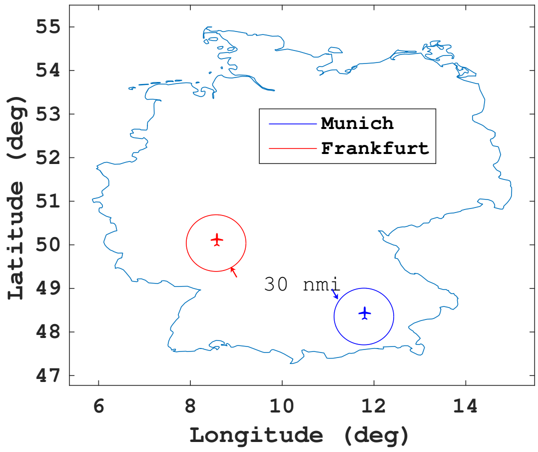


Figure 1

Figure 2: Terminal area (30 nmi) of Munich and Frankfurt airports

Results published by Vitan et al. [4] using data recorded during flight shows that DME/DME or multi-DME approach position solutions has HPE of 0.3 nmi. Hence, DME/DME or multi-DME approach can support RNP 0.5, but not RNP 0.3 [4]. To assess the DME/DME based horizontal position solution, terminal area (30 nmi radius) of Frankfurt and Munich airport is considered, as shown in figure (1).

The major contribution to Total System Error (TSE) comes from Flight Technical Error (FTE) and NSE. Assuming the FTE to be constrained within FAA requirements [5], a system with small ranging error would provide better position solution meaning smaller NSE, hence satisfying the RNP 0.3 requirements.

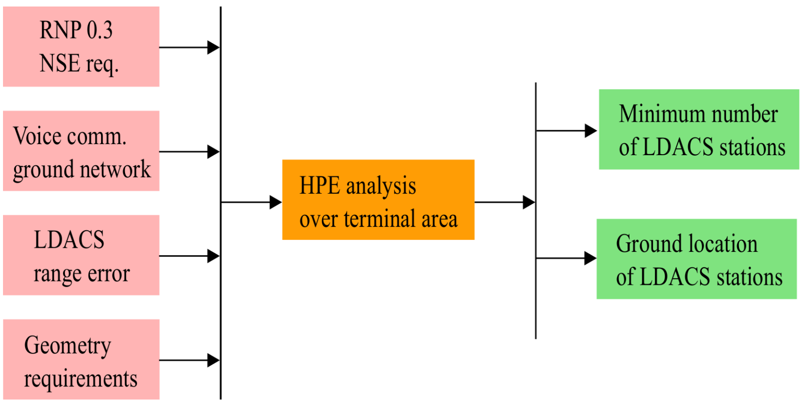


Figure 3: Functional work flow

One way of achieving RNP 0.3 in the absence of GNSS is to place LDACS based ranging sources [6]. Flight trials have shown that, LDACS has a ranging uncertainty of 10 m standard deviation [7], therefore for a given dilution of precision (DOP), LDACS can provide more accurate position solution compared to DME. As placement of new stations is a slow and cumbersome process, we are proposing two methods. First method is to use LDACS in standalone configuration, and the second method is to combine LDACS with DME to obtain a hybrid position solution. In hybrid configuration, the gradual inclusion of LDACS stations can be exploited by strategically placing them, such that measurements from existing DME ground stations combined with LDACS, provides a position solution matching the performance requirements of RNP 0.3, as suggested for Modular APNT [6].

The integrity and timing requirements are not considered here because the LDACS positioning integrity and timing service have not yet been investigated. Therefore, the demand based placement of LDACS standalone and hybrid (LDACS + DME) architectures in this paper will be determined by using the accuracy requirements alone. Overview of the process followed to place the LDACS stations is shown in figure (3). The method uses an exhaustive process to select the minimum number of LDACS stations and their ground locations. The optimization is performed based on the existing location of voice communication stations, required NSE accuracy for RNP 0.3, LDACS range accuracy and the geometry requirements. The constraints for optimization are elevation coverage, distance of coverage and line of sight between the aircraft and the ground station.

Next section gives the theoretical background on some of the concepts related to RNP 0.3, and a brief description of DME and LDACS technologies. Following section explains the placement methodology used to place the LDACS station in order to achieve RNP 0.3. The methodology and results are explained for both LDACS in standalone configuration and when LDACS is combined with DME. Last section discusses the obtained result and further improvements.

THEORY

This section discusses the concepts related to Horizontal Dilution of Precision (HDOP), HPE, total system error and RNP 0.3. It also gives a brief description of DME and LDACS technologies.

RNP 0.3

RNP is a service category of the navigation performance necessary for operation within a defined airspace. RNP has different accuracy requirements depending on the flight phase [8]. The main benefit of implementing RNP is to improve safety hence reducing the risk and efficient use of available airspace. RNP specifications are represented as RNP X, where X specifies the maximum allowed TSE in nmi. RNP specifications only consider the position accuracy in horizontal (East-North) plane. Note that RNP 0.3 also have integrity, availability and continuity requirements which are not discussed here as they are not the scope of this paper, for details refer [8].

Depending on traffic density in target airspace, separation distance between two aircrafts is specified. Terminal area has high aircraft density, hence a $3-$ nmi separation [5] between to aircrafts is maintained to increase the throughput of arrival and departure paths. In order to maintain $3-$ nmi separation RNP 0.3 is required [5].

Total System Error

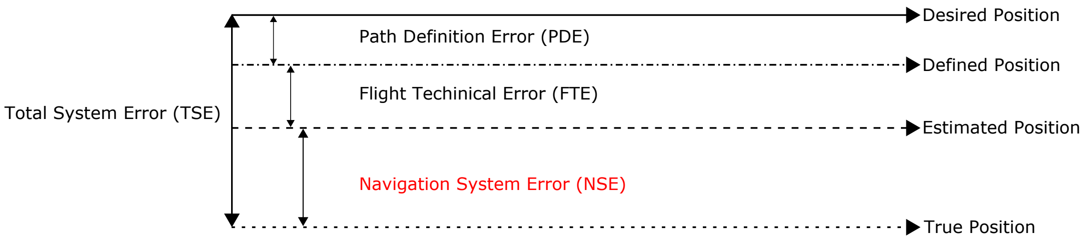


Figure 4: TSE in terms of PDE, FTE and NSE

Based on target environment RNP is specified in terms of TSE as shown in figure (4). TSE is the root sum squared of NSE (Navigation System Error), PDE (Path Definition Error) and FTE (Flight Technical Error) given by the equation (1).

$$TSE = \sqrt{FTE^2 + NSE^2 + PDE^2} \tag{1}$$

PDE is assumed to be zero due to integrity checks performed during way point definition in the Flight Management System (FMS) [9]. FTE is the error between actual track and desired track introduced due to human error in using the Flight Detector (FD), or due to the auto-pilot capability to follow the FMS defined path. FTE assumptions for different phases of flight are shown in table 1.

Table 1: FTE assumptions [10]

Flight Phases	Manual (nmi)	Flight Director (nmi)	Autopilot (nmi)
Oceanic	2.0	0.5	0.25
En Route	1.0	0.5	0.25
Terminal	1.0	0.5	0.25
Approach	0.5	0.25	0.125

NSE is the error between the actual position of the aircraft and the estimated position of the aircraft by the navigation system. Based on the segments of flight different values of TSE are specified.

Table 2: RNP 0.3 TSE [10]

Specification	FTE (FD)	NSE
RNP 0.3	0.25 nmi	307.1 m

To answer the questions poised earlier FTE of 0.25 nmi is selected which results in required NSE of approximately 307.1 m as shown in table 2 to support RNP 0.3 specifications. Hence to provide RNP 0.3, in this paper we focus on achieving 2σ (95%) NSE accuracy of 307.1 m in horizontal plane.

Horizontal Dilution of Precision (HDOP)

The concept of DOP originated with Long Range Navigation (LORAN) navigation system [11]. It relates the uncertainty in range measurement σ_r with the uncertainty in position estimate σ_p, as shown in equation (2).

$$DOP = \sigma_p / \sigma_r \tag{2}$$

Hence, a lower DOP value represents a better position precision. The DOP is calculated using the geometry matrix G [11] and is classified into a number of separate measurements. For aircraft navigation, the DOP is calculated in local coordinate system, as the position accuracy is more meaningful in horizontal and vertical component of the local plane. ECEF to ENU transformation is performed using a rotation matrix R [11]. Considering $\widetilde{G}$ to be the rotated G matrix, the HDOP can be calculated using equation (3), where $\widetilde{H}$ is calculated using equation (4).

$$HDOP = \sqrt{\widetilde{H}_{11} + \widetilde{H}_{22}} \tag{3}$$

$$\widetilde{H} = (\widetilde{G}'\widetilde{G})^{-1} \tag{4}$$

Horizontal Position Error (HPE)

For ease, the assessment of position is done in local reference frame East-North-Up (ENU). Given the geometry matrix $\widetilde{G}$ in local frame, HPE can be computed by equation (5). Where, $\widetilde{H}$ is given by equation (4) and σ is the standard deviation of the user range error.

$$HPE = \sigma \times \sqrt{\widetilde{H}_{11} + \widetilde{H}_{22}} \tag{5}$$

Further if weight W [11] is used for individual range measurement, HPE can be computed using equation (6), which is used for HPE computation in this paper. Where, $\widetilde{H}$ is given by equation (7).

$$HPE = \sqrt{\widetilde{H}_{11} + \widetilde{H}_{22}} \tag{6}$$

$$\widetilde{H} = (\widetilde{G}'W\widetilde{G})^{-1} \tag{7}$$

Distance Measuring Equipment (DME)

DME was invented in 1940s by an Australian engineer James Gerry Gerrand as two-way ranging system for aircraft navigation. DME ground station and on-board equipment operate in UHF radio frequency band between 962 MHz and 1213 MHz. As DME is a two-way ranging system, the slant range from two DME ground stations is sufficient to obtain a horizontal position fix.

The error in the horizontal position fix [4] is given by equation (8). Where, e_p is the horizontal position error, e_1 and e_2 are the range error from the two DME stations in the horizontal plane, while α is the angle between two vectors connecting the two DME stations with the aircraft. For a DME/DME based lateral positioning, the α value shall be between 30^o and 150^o values inclusive.

$$e_p^2 = ((e_1 + e_2)/sin\alpha)^2 \tag{8}$$

Further according to FAA [2] the standard deviation σ_{D_i} of the ranging error from an individual DME station is given by equation (9). Where, $\sigma_{sis} = 0.05$ nmi, $\sigma_{air} = \max\{0.085,\ 0.00125\times D_i\}$.

$$\sigma_{D_i} = \sqrt{\sigma_{sis}^2 + \sigma_{air}^2} \tag{9}$$

From equations (8) and 9 for slant range of 68 nmi the horizontal position error is about 0.1080 nmi. Considering a FTE of 0.25 nmi [12] and assuming negligible PDE, the TSE value becomes 0.358 nmi. Hence, theoretically RNP 0.3 can not be achieved by DME/DME based position solution.

L-band Digital Aeronautical Communications System (LDACS)

The LDACS was originally conceived as a communications system [13], yet it is also being proposed as a navigation system [14]. LDACS uses Orthogonal Frequency-Division Multiplexing (OFDM) for modulation and operates in aeronautical L-band (960 MHz to 1164 MHz) with a bandwidth of 500 kHz [13].

Though the LDACS was originally conceptualized as a communication system, one of the proposal is to extend the functionality of the system to include navigation capability to support APNT. In order to test the ranging capability DLR performed some measurement campaigns in November 2012. The campaign results showed that LDACS-based ranging has standard deviation of 10 m [7]. Further LDACS can be specified to be frequency compatible with the existing Communication Navigation and Surveillance (CNS) infrastructure, most notably DME [15] as shown in figure (5).

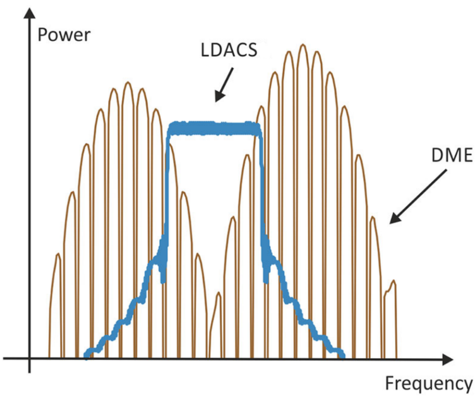


Figure 5: LDACS frequecny allocation [16]

The ranging accuracy of LDACS is so much higher than that of established systems, like DME, that its inclusion in any hybrid position solution will drastically improve error performance. Prior work has shown that the inclusion of LDACS signals in an APNT system has the potential to enable RNP 0.3 services with ground-based transmitters [6]. Note that RNP 0.3 has been cited as one of the long-term goals of APNT development [17].

Among the design decisions that are still open for LDACS is the choice of locations for ground infrastructure. To-date the only specific proposal as to which set of stations could be used for LDACS was computed with the goal of providing communications services, constrained to non-interference with DME signals [15]. In contrast, we use this paper to propose a selection methodology that also takes navigation performance into account.

The navigation protocol for LDACS has not been finalized, but the initial proposal is to develop LDACS as one-way ranging system. In LDACS standalone configuration, at least 4 LDACS stations are required to get a 3D position solution. For a hybrid system (LDACS + DME) minimum of 2 LDACS stations are required, one to compensate for the clock and another to improve the positioning.

DEMAND FUNCTION

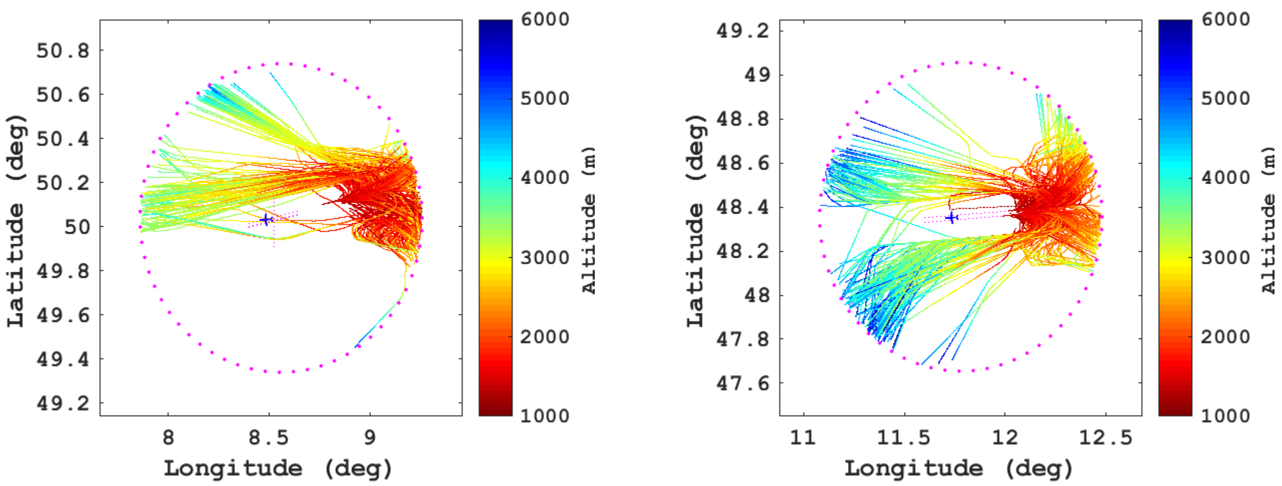
Providing APNT coverage on a large scale, at low altitude and with high accuracy has proven challenging [18]. The introduction of LDACS into the airspace would go part of the way in addressing the issue. It seems intuitive to provide the highest performance where it is most needed.

In this section we propose a demand function that will identify locations at which RNP 0.3 APNT coverage is most desirable for 3− nmi separation. We use the demand function, in combination with a performance metric, to construct an optimization problem that yields a selection criterion for placing LDACS ground stations.

For this reason we construct a demand function that quantifies where there is greatest need for precise navigation in a given terminal area. There are at least two different ways to address this issue: a model-driven approach based on published RNP procedures, and a data-driven approach based on actual traffic information. For this paper we focus on the data-driven approach and leave the idea of model-based placement for future work.

For the assessment of demand for navigation services we resort to surveillance data set provided by Deusche Flugsicherung (DFS), the German Air Navigation Service Provider (ANSP). The data set contains the positions of all flights using German airspace on 30 July 2015, sampled at 30 s intervals, as measured by flight plan information correlated with radar measurements.

From this data set we look at all traffic approaching two of the busiest airports in Germany, Frankfurt and Munich. For each flight we consider the ground track from the moment it enters within 30 nm of the airport (terminal area), until it reaches the final approach segment, at an altitude of 4000 ft at Frankfurt and 5000 ft Munich airport.



(a) (b)

Figure 6: Demand function plot: (a) Frankfurt airport. (b) Munich airport.

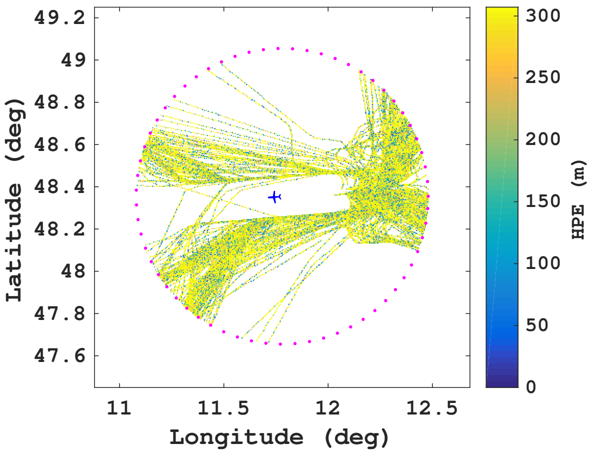
With the information from all ground tracks for the entire day we identify areas of demand. As shown in figure (6) the demand is represented with the color points where RNP 0.3 coverage is required within the terminal area (marked in magenta). As evident from figure (6) the demand function j can be defined as set of points in terms of latitude (λ), longitude (ϕ) and altitude (a) as shown in equation (10). Where f is defined by equation (11) and S is the surveillance data within the terminal area.

$$j = f(\lambda, \phi, a) \times HPE \tag{10}$$

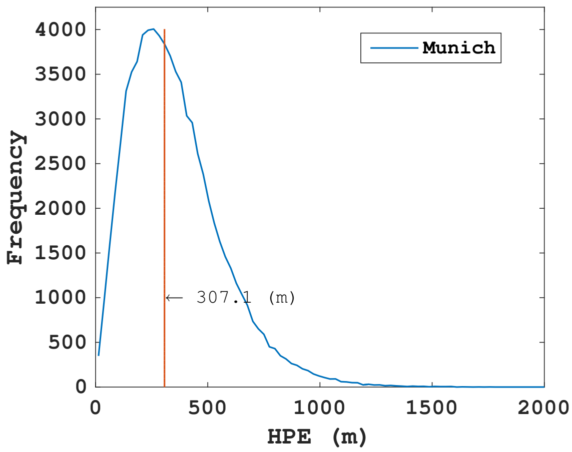
$$f(\lambda, \phi, a) = \begin{cases} 1, & \text{if } (\lambda, \phi, a) \in S \\ 0, & \text{otherwise} \end{cases} \tag{11}$$

It is important to note that we consider this a proof of concept and not a complete assessment of the demand. Given that the available data set spans one day, it cannot be expected to represent demand over longer periods of time. Changing wind conditions and other factors may change takeoff and landing directions, thereby altering the distribution of the approaching traffic.

DME/DME BASED LATERAL POSITIONING ERROR

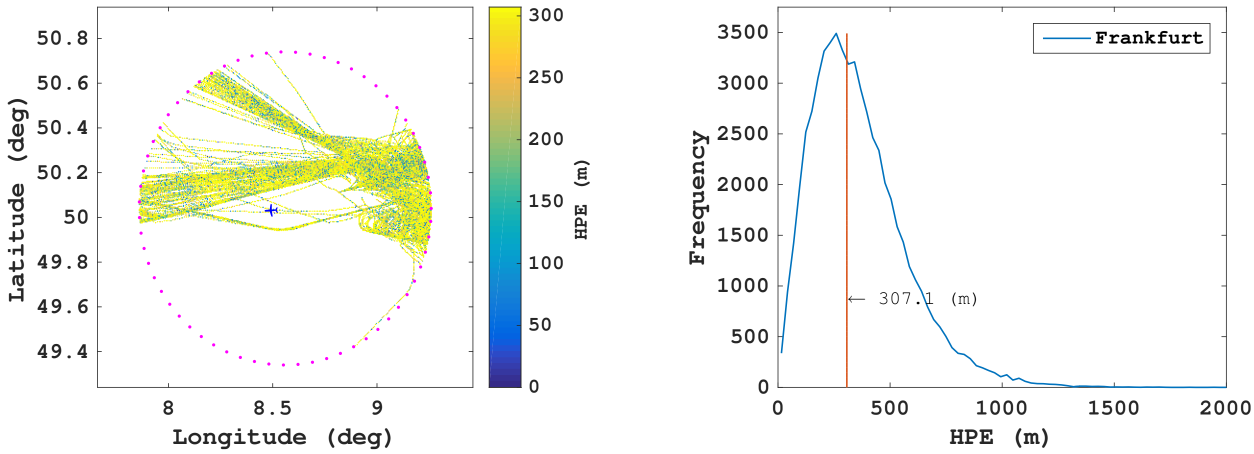


(a)



(b)

Figure 7: Munich airport terminal area: HPE using DME/DME (a) HPE over demand funciton. (b) HPE distribution



(a) (b)

Figure 8: Frankfurt airport terminal area: HPE using DME/DME (a) HPE over demand funciton. (b) HPE distribution

For DME/DME positioning, the horizontal position error is computed using the equation (8) with the angle of inclusion α between 30^o and 150^o [4]. Figure: 7 and 8 show the horizontal position error for Frankfurt and Munich airports respectively for the traffic data of one day.

Performace Compared To RNP 0.3

As shown in figure (7b) and 8b approximately 50% of the HPE over the demand function is higher than the required NSE of 307.1 m to support RNP 0.3. This observation is result of the large ranging error of the DME systems. The obtained result creates the need of an alternate system which can support RNP 0.3. It can be achieved by using an alternate system with low ranging error such as LDACS.

CONSTRAINTS FOR STATION SELECTION

This section explains the constraints in optimization process to obtain the feasible set of LDACS ground stations.

HDOP and HPE considerations

HDOP is used to place the LDACS stations in standalone configuration. Based on the uncertainty σ in ranging error of LDACS as 10 m, the HDOP value is given by equation (12).

$$HDOP = \frac{307.1}{20} = 15.3550 \tag{12}$$

For the hybrid (LDACS and DME combined) system HPE is used instead of HDOP, since the ranging error of both the systems is different. Considering the NSE requirement of RNP 0.3, 95% of the HPE value for the demand funciton should be less than 307.1 m.

Distance of coverage and elevation mask

For LDACS the navigation coverage distance is assumed to be 200 nmi, same as the proposed coverage of the communication system [13]. The minimum elevation e_{min} coverage for LDACS is assumed to be 0.5^o and the maximum elevation e_{max} coverage for LDACS is assumed to be 60^o. For DME the navigation coverage distance is considered to be 200 nmi. The minimum elevation e_{min} coverage for DME is considered to be 1^o and the maximum elevation e_{max}

coverage for DME is considered to be 40^o. The concept of distance of coverage (DOC) and minimum and maximum elevation coverage is illustrated in figure (9).

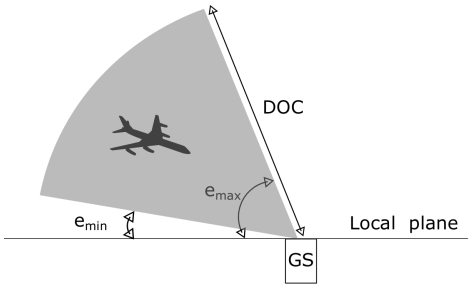


Figure 9: DOC and Elevation coverage

Line of sight

Visibility between ground station and aircraft is important to avoid non-line of sight (NLOS) errors, hence a visibility analysis is performed using the digital elevation models (DEM). DEM is taken from Global Data Explorer website maintained by NASA [19].

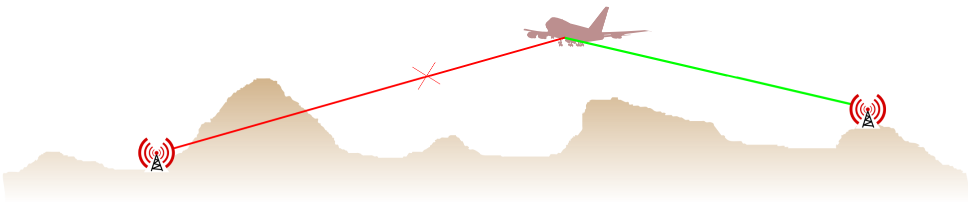


Figure 10: Visibility of ground stations from aircraft

Line of sight analysis is also important to ensure the geometry between the selected set of stations and demand function.

SELECTION OF LDACS STATIONS

Conceptually the simplest way to find the best solution is to select a pre-defined number of candidate ground stations from the set of voice communication stations and assess its HPE. Instead, we propose a methodology by which the number of ground stations is selected using exhaustive process. Selection of stations is a complex problem classified as 'NP-complete' in computational complexity theory [20]. Simply speaking 'NP-complete' means that there are no known efficient algorithms that provides an exact solution(s). Only option to optimize the problem is by performing an exhaustive search.

The assumption that the existing voice communication stations will be used for LDACS is based on multiple arguments. LDACS is fundamentally a communication system, hence it would be only natural to place them at existing communication sites. In additiona is also resuces the load of finding a new site and getting approval. Setting up the infrastructure at a new location is additional operational and financial over-head.

With the number of ground stations becoming a variable, the optimization searches all subsets of the candidate stations with increasing cardinality, from 4 onwards. If no appropriate solution is found, the algorithm increases the cardinality. The termination criterion is based on a histogram as in figure (7b) and (8b). If the histogram of HPE, corresponding to the candidate set of stations at the particular airport, crosses 95% at 307.1 m, we terminate the search. The process is explained using flow chart in following sections. Note that the percentile was chosen for RNP 0.3 and could be set significantly higher (e.g. 99.9%), depending on availability requirements.

The issue of providing RNP 0.3 using LDACS is addressed using two configurations. First we propose LDACS standalone configuration where RNP 0.3 NSE requirement is met using only the LDACS stations. In second part we propose a hybrid configuration, where we combine the pseudo-range measurement from LDACS and two way range measurements from DME. Another important aspect of the hybrid approach is multi-DME selection. Instead of using traditional DME/DME approach where 2 DME stations are used for horizontal positioning, a maximum of 4 DME stations are used for each point in the demand function j.

The optimization process is based on the assumption that in future the alternate navigation will completely switch to LDACS. Hence, the first analysis is to provide RNP 0.3 accuracy using LDACS stations only. As the switch to LDACS only navigation would be gradual, we use the LDACS standalone ground stations to obtain the hybrid solution using LDACS and DME stations.

LDACS standalone configuration

It is assumed that the existing voice communication stations will be upgraded to LDACS station and hence for the analysis existing voice communication stations in Germany are selected. The optimal set of stations were selected using exhaustive search, starting with a cardinality of 4 (since LDACS is assumed to be a one way ranging system) with the condition of distance of coverage, elevation mask and line of sight between each station and flight point. The optimization process is explained using block diagram shown in figure (11) A set of LDACS stations which provides the HDOP value of 10 or less for all the demand point is selected as the optimal solution.

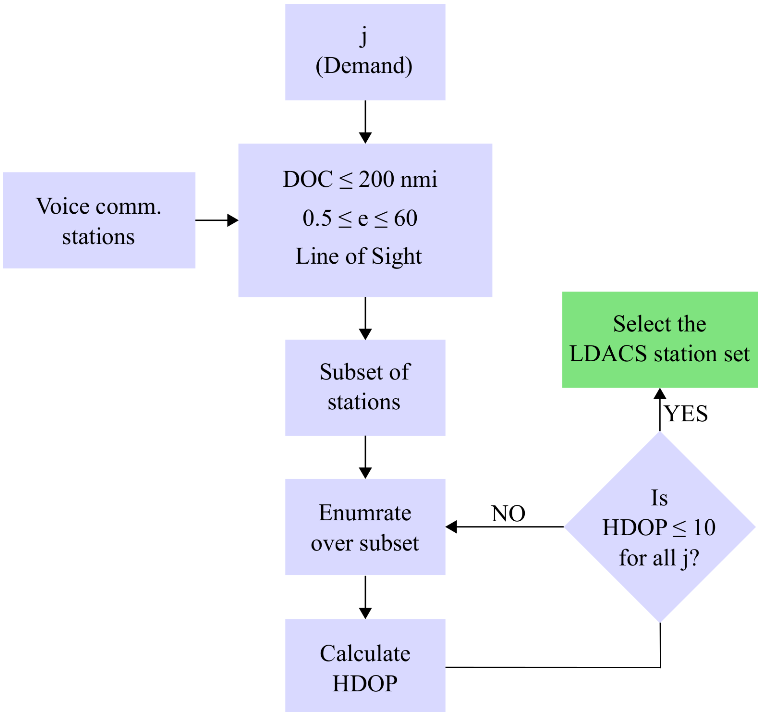


Figure 11: LDACS standalone functional block diagram

As shown in figure (12a) only 6 LDACS stations are sufficient to fulfill RNP 0.3 NSE requirement at Munich airport. Figure (12b) shows the distribution of HPE over the demand function for Munich airport. As evident from the distribution 100% of the HPE is below 307.1 m better than the NSE requirement of RNP 0.3. The result in figure (13a) for Frankfurt airport shows that only 5 LDACS stations are sufficient to fulfill RNP 0.3 NSE requirement. Further the distribution plot in figure (13b) shows that 100% of the HPE is below 307.1 m threshold.

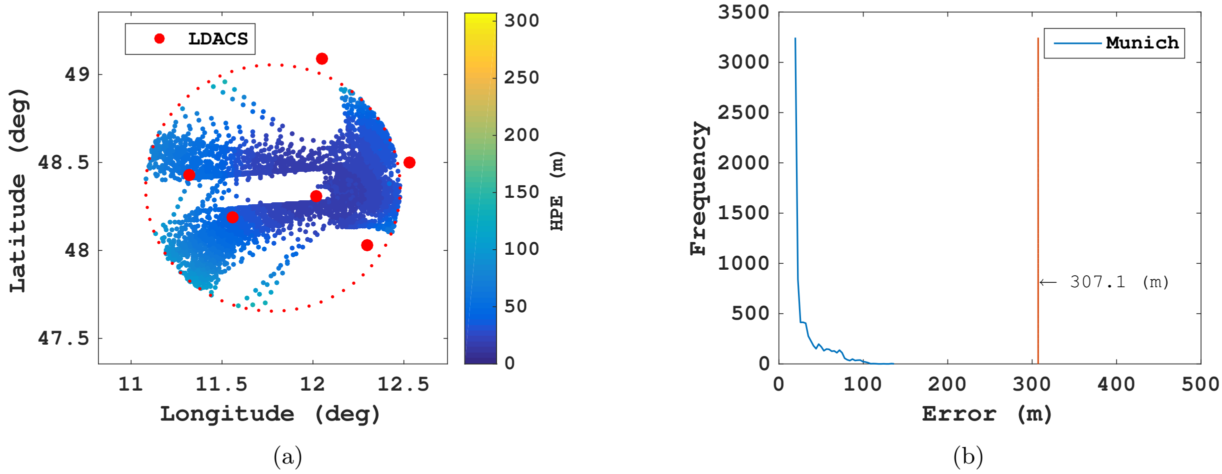


Figure 12: HPE computed after placements of 5 LDACS stations for Frankfurt airport. (a) HPE map plot. (b) HPE distribution

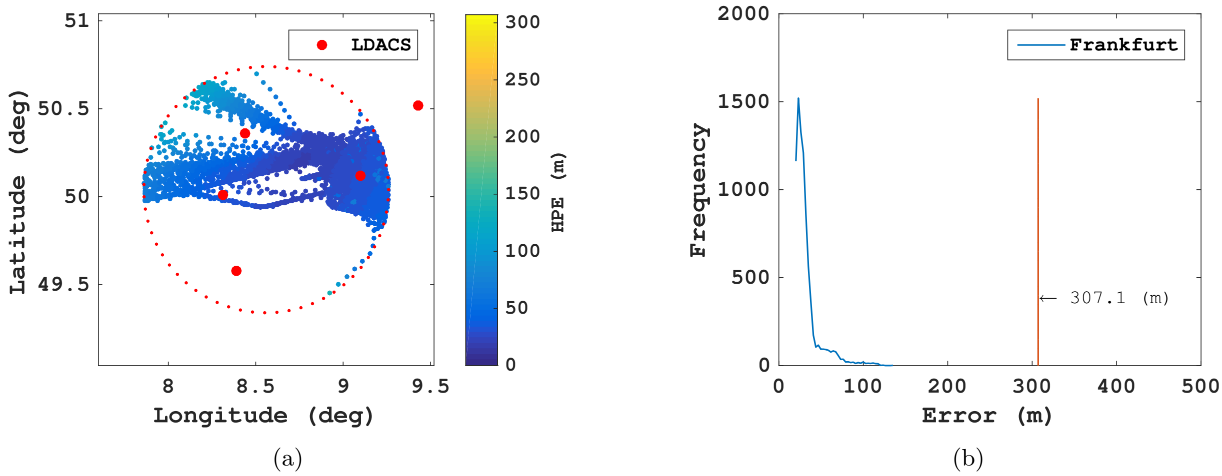


Figure 13: HPE computed after placements of 6 LDACS stations for Munich airport. (a) HPE map plot. (b) HPE distribution

LDACS + DME hybrid configuration

The process of optimization for hybrid configuration is explained in figure (14). As mentioned earlier in hybrid approach, 4 DME stations are used for each point. The minimum and maximum elevation coverage for each DME station is considered to be 1^o and 40^o. The distance of coverage for DME stations us considered as 200 nmi. The optimization process starts with cardinality of 2 LDACS station. If the desired result is not obtained the cardinality is increased by one. A set of LDACS (+ DME) stations which provide HPE value 307.1 m or less for all points in demand function is selected as feasible set.

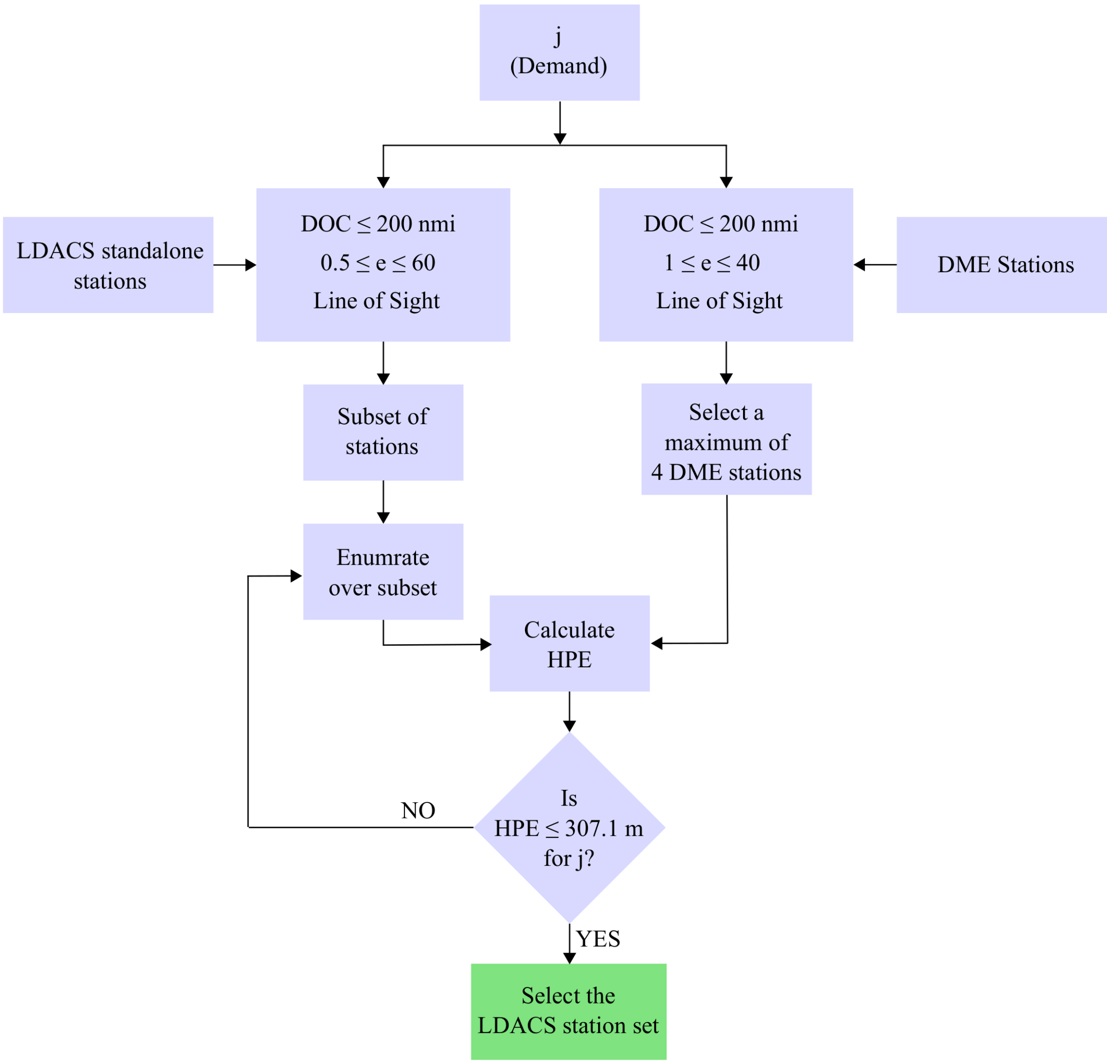
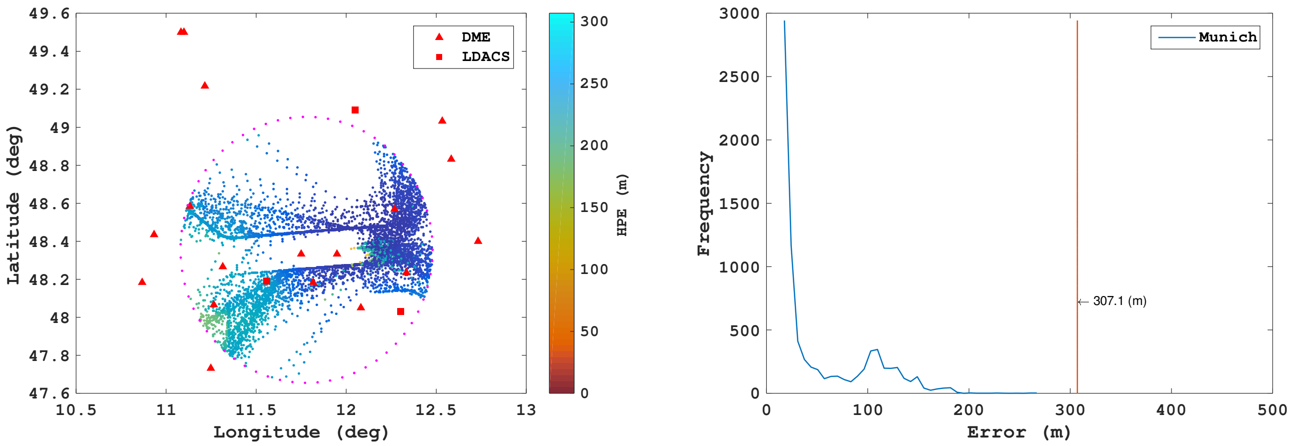


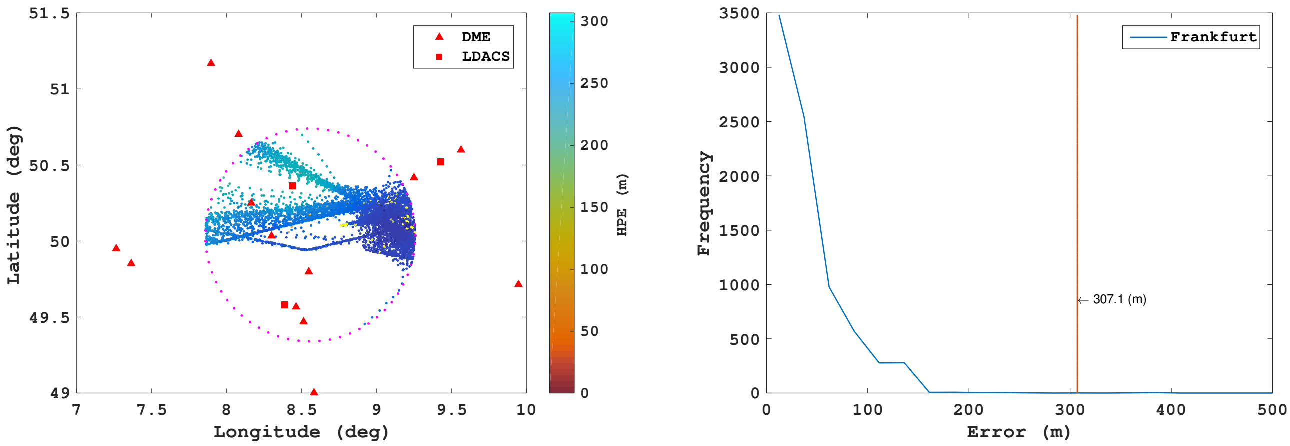
Figure 14: LDACS standalone functional block diagram

Figure (15a) shows the result of LDACS + DME hybrid configuration over the demand function of Munich airport. The result shows that only 3 LDACS stations are sufficient to fulfill NSE requirement for RNP 0.3. As shown by distribution plot in figure (15b), by adding LDACS in existing DME infrastructure 98.7% of the HPE moves to left of the 307.1 m threshold. Similarly for Frankfurt airport the number of LDACS stations required in hybrid configuration is 3 as well. The result for Frankfurt is shown in figure (16a). The histogram shown in figure (16b) has 97.7% of the HPE to the left of 307.1 m threshold.



(a) (b)

Figure 15: HPE computed after placements of 6 LDACS stations for Munich airport.
(a) HPE map plot. (b) HPE distribution



(a) (b)

Figure 16: HPE computed after placements of 5 LDACS stations for Frankfurt airport.
(a) HPE map plot. (b) HPE distribution

RESULT AND DISCUSSION

As shown in figures (12) and (13) , in LDACS standalone configuration more than 95% of the horizontal position error falls below 307.1 m mark, which is the required NSE threshold for RNP 0.3. It is important to note that only 5 stations are required for Frankfurt and 6 stations for Munich airport to provide RNP 0.3 NSE accuracy. In hybrid configuration the number of required LDACS stations reduces to 3 for both Frankfurt and Munich airport.

A very important factor in providing coverage at lower altitudes is the minimum elevation coverage of the LDACS ground stations. If the minimum elevation coverage is increased the number of stations required to provide coverage will increase as well.

Apart from the improvement in positioning accuracy, LDACS has additional advantages. LDACS is one way ranging system, which means there is no performance limitation in terms of number of devices serviced. LDACS can be considered as an upgrade to the existing voice communication system, hence reducing the cost of new ground station installation.

As the current demand function is based on data obtained for only one day, further analysis covering all the runway needs to be performed. It would be a different challenge altogether to provide RNP 0.3 for airports located in or around mountainous region, that needs to be analyzed as well.

For ground based ranging systems quantifying multi-path errors is challenging which makes it difficult to assure the integrity of the system. Nevertheless to provide RNP 0.3 service, integrity assessment needs to be done for LDACS and DME (for hybrid configuration). Additional methods either on-board or on ground will be required to detect any ground station faults.

SUMMARY

Possible alternatives to address the issue of fulfilling RNP 0.3 accuracy requirement was analyzed. Two possible configurations were investigated. LDACS in standalone configuration and LDACS combined with DME - a hybrid configuration. Performance was assessed in terminal area of Frankfurt and Munich airport using surveillance data. Results show that for Frankfurt 5 LDACS stations are sufficient in standalone configuration and 3 LDACS stations are sufficient in hybrid configuration. For Munich number of LDACS stations in standalone congiguration is 6, whereas in hybrid configuration it remains 3, same as Frankfurt.

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