LDACS1 for an Alternate Positioning Navigation and Time Service

B. Belabbas, M. Felux, M. Meurer, N. Schneckenburger, M. Schnell,
German Aerospace Center (DLR), Germany
Email: boubeker.belabbas@dlr.de

BIOGRAPHIES

Boubeker Belabbas is the leader of the Navigation Integrity Group of the Institute of Communications and Navigation at the German Aerospace Center (DLR) in Oberpfaffenhofen near Munich. He obtained an MSc. degree in mechanical engineering from École Nationale Supérieure de l'Electricité de Mécanique in Nancy (France) and a specialized Master in Aerospace Mechanics from École Nationale Supérieure de l'Aéronautique et de l'Espace in Toulouse (France).

Michael Felux is a research associate in the Integrity group of the Insitute of Communications and Navigation at the German Aerospace Center (DLR) in Oberpfaffenhofen. He obtained his diploma in technical Mathematics in 2009 from TU München (Germany) and joined the DLR the same year.

Dr. Michael Meurer is the head of the Department of Navigation of the German Aerospace Center (DLR), Institute for Communications and Navigation, and the coordinating director of the DLR Centre of Excellence for Satellite Navigation. He received the diploma and Ph.D. degrees in Electrical Engineering from the University of Kaiserslautern, Germany. Since 2005 he has been an Associate Professor (PD) at the same university. His current research interests include GNSS signals, GNSS receivers, interference mitigation and navigation for safety-critical applications.

Nicolas Schneckenburger was born in Mainz, Germany in 1985. He received his Dipl-Ing. (M.Sc) degree in electrical engineering from the university of Ulm, Germany, in 2010. Since then he has been working as a research associate with the Institute of Communication and Navigation at the German Aerospace Center (DLR). His main focus in the last year has been the FPGA implementation of the LDACS1 and B-DLR communication system.

Dr. Michael Schnell received his M.Sc. degree in Electrical Engineering from the University of Erlangen-Nuremberg, Germany, in 1987. In 1997, he received his Ph.D. degree from University of Essen, Germany, for his work in the field of spread-spectrum multiple-access communications. Since 1990 he is scientific researcher at the Institute of Communications and Navigation of the German Aerospace Center (DLR) where he is currently group leader and project manager of the Aeronautical Communications Group. He has been involved in several international projects in the area aeronautical communications, including B-VHF, B-AMC, LDACS1, NEWSKY, and SANDRA. Dr. Schnell is Lecturer for multi-carrier communications at the University of Karlsruhe, Germany, and acts as selected Advisor for DFS, the German ANSP, within the Aeronautical Communications Panel of ICAO. He is Senior Member IEEE and member of VDE/ITG.

ABSTRACT

The future L-band Digital Aeronautical Communication System LDACS1 shows a very promising performance as a communication service. The system offers the possibility to also provide a navigation service with minimal adaptation. This paper investigates the level of performance achieved by an LDACS1 based navigation service. The results are outstanding and show that the stringent requirements of RNP0.1 can be reached in a large service volume. Two key parameters have a large impact on the performance of the navigation solution: the density of stations used as ranging sources and the time synchronization accuracy of these stations. The sensitivity of the performance to the second parameter has been investigated in this paper. It is shown that the time synchronization has significant impact on the achievable positioning performance only if the error is larger than 100 ns (one standard deviation). This is a very large synchronization error that can be easily reduced to 20 ns using existing low cost atomic clocks. The simulation results are very promising and open the doors to further investigations including flight experiments (planed in 2012), in particular the investigation of high performance and low cost system architectures that keep or improve the level of safety.

access approach is employed, dynamically allocating certain blocks of subcarriers for a certain time to an AS.

Both transmission modes use frequencies in the L-band and are separated in frequency by a spacing of 63 MHz. For the FL the frequency band from 985.5 to 1008.5 MHz is currently considered while the RL is to use the band from 1048.5 to 1071.5 MHz [4].

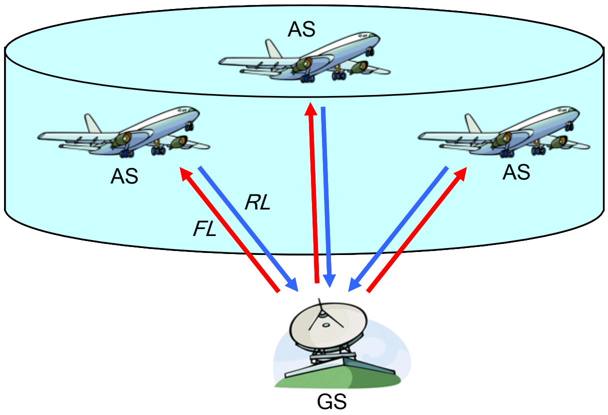

Figure 1 LDACS1 Network Topology

The GS transmit signal is organized in the following structure: The largest entity is a super frame (SF) of length 240 ms. A SF consists of one broadcast (BC) and 4 multi frames (MF). While the MF employs the transmission of user specific data, the BC frame transmits signaling information relevant for all active AS in the cell. However the data transmitted on the BC is neither safety nor time critical. Thus it is fully sufficient to decode the BC of the current GS only every few seconds. Therefore the BC window is a perfect opportunity to tune the frequency to a different GS and perform ranging to that GS if only a single frequency receiver is used. However, if a multi frequency receiver is employed; all frame types within one SF may be used for ranging.

TARGETED NAVIGATION SERVICE

The positioning technique we are investigating in this paper is based on multi-lateration technique using ground ranging sources.
The vertical component is assumed to be covered by a barometric and/or a radio altimeter and only the horizontal components of the position should be determined by the LDACS1 navigation system.
We assume that the ranging sources are identified by their frequency (frequency division among LDACS1 GS) and the time of transmission of a code sequence to be used by the receiver on board.

The navigation service of LDACS1 is based on ground ranging sources. Exactly as for GNSS, a minimum number of stations are necessary to provide a navigation service RNPx (Required Navigation Performance with x nm accuracy limit $x \in [0.1, 10]$ nm). We keep the level of accuracy as a variable.

We assume a minimum service height of 350 ft. This is the decision altitude for navigation using VNAV altimeter. Since the vertical component of the position is assumed to be performed by altimeters LDACS1 position solution is restrained to the horizontal plane and would need at least 3 stations to determine a position.
Only the RNP cross track component is investigated in this paper.

ALGORITHMS TO CALCULATE RNP

The position equation can be written as follow:

$$\mathbf{x} = \left(\mathbf{G}^T \mathbf{W} \mathbf{G}\right)^{-1} \mathbf{G}^T \mathbf{W} \mathbf{y} \qquad (1)$$

We set:

$$\mathbf{S} = \left(\mathbf{G}^T \mathbf{W} \mathbf{G}\right)^{-1} \mathbf{G}^T \mathbf{W} \qquad (2)$$

In this equation, $\mathbf{G}$ is the geometry matrix which is the matrix of horizontal components of the line of sight unit vectors oriented from the ranging source to the aircraft. We consider that the receiver clock is not synchronized with the LDACS1 reference time therefore we add 1 to the unit vector component (user clock drift is considered as an unknown).
Finally $\mathbf{G}$ is as follows:

$$\mathbf{G} = \begin{pmatrix} -\cos E_1 \sin A_1 & -\cos E_1 \cos A_1 & 1 \\ \vdots & \vdots & \vdots \\ -\cos E_N \sin A_N & -\cos E_N \cos A_N & 1 \end{pmatrix} \qquad (3)$$

where E_i is the elevation angle of the *i*th ranging source, A_i the azimuth angle and N, the total number of visible ranging sources.

$\mathbf{W}$ is a weighting matrix defined as follows:

$$\mathbf{W} = \begin{pmatrix} \sigma_1^{-2} & 0 & \cdots & 0 \\ 0 & \sigma_2^{-2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \sigma_N^{-2} \end{pmatrix} \qquad (4)$$

Where σ_i is the standard deviation of the *i*th ranging error. We assume that the ranging sources experience uncorrelated errors. The standard deviation of the *i*th ranging source is obtained using the variance dependency of the Cramer-Rao Lower Bound for an OFDM system as described for example in [5]. The considered standard deviation is inflated by 20% with respect to the CRLB standard deviation. This will be updated using real measurements.

$\mathbf{y}$ is the vector of pseudo-ranges of all visible LDACS1 stations.

$\mathbf{x}$ is the vector comprising two components for the horizontal position, and one for the user clock drift.
The origin of the reference frame for $\mathbf{x}$ is the true position of the user therefore this equation is not appropriate for navigation. The choice of this reference frame is practical for error analysis as we will show below.

$\mathbf{S}$ can be written as follows:

$$\mathbf{S} = \begin{pmatrix} s_{east,1} & s_{east,2} & \cdots & s_{east,N} \\ s_{north,1} & s_{north,2} & \cdots & s_{north,N} \\ s_{t,1} & s_{t,2} & \cdots & s_{t,N} \end{pmatrix} \qquad (5)$$

The error equation is equivalent to equation (1)

$$\delta\mathbf{x} = \begin{pmatrix} \delta x_{east} \\ \delta x_{north} \\ \delta t \end{pmatrix} = \mathbf{S}\delta\mathbf{y} \qquad (6)$$

Where δx represent the error in the scalar x or $\delta\mathbf{x}$ the error in the vector **x**.

The covariance matrix is calculated as follows:

$$\operatorname{var}(\delta\mathbf{x}) = E\left[\delta\mathbf{x}\delta\mathbf{x}^T\right] = E\left[\mathbf{S}\delta\mathbf{y}\delta\mathbf{y}^T\mathbf{S}^T\right] \qquad (7)$$

$\mathbf{S}$ is non random and can be moved out of the expectation operator:

$$\operatorname{var}(\delta\mathbf{x}) = \mathbf{S}E\left[\delta\mathbf{y}\delta\mathbf{y}^T\right]\mathbf{S}^T = \mathbf{S}\operatorname{var}(\delta\mathbf{y})\mathbf{S}^T \qquad (8)$$

We consider that the pseudo ranges are independent therefore the covariance matrix of the pseudo range vector is diagonal:

$$\operatorname{var}(\delta\mathbf{y}) = diag\left(\sigma_i^2\right) \qquad (9)$$

Equation (8) can be rewritten as follows:

$$\mathrm{var}(\delta\mathbf{x}) = \begin{pmatrix} \sum_{i=1}^{N} s_{east,i}^2\sigma_i^2 & \sum_{i=1}^{N} s_{east,i}s_{north,i}\sigma_i^2 & \sum_{i=1}^{N} s_{east,i}s_{t,i}\sigma_i^2 \\ \sum_{i=1}^{N} s_{east,i}s_{north,i}\sigma_i^2 & \sum_{i=1}^{N} s_{north,i}^2\sigma_i^2 & \sum_{i=1}^{N} s_{north,i}s_{t,i}\sigma_i^2 \\ \sum_{i=1}^{N} s_{east,i}s_{t,i}\sigma_i^2 & \sum_{i=1}^{N} s_{north,i}s_{t,i}\sigma_i^2 & \sum_{i=1}^{N} s_{t,i}^2\sigma_i^2 \end{pmatrix} \quad (10)$$

This can be written in a simplified way:

$$\mathrm{var}(\delta\mathbf{x}) = \begin{pmatrix} d_{east}^2 & d_{EN} & d_{ET} \\ d_{EN} & d_{north}^2 & d_{NT} \\ d_{ET} & d_{NT} & d_t^2 \end{pmatrix} \quad (11)$$

We define the variance of the horizontal navigation error as being the largest Eigen value of the covariance matrix of the position error reduced to a 2 by 2 matrix, dropping all the terms depending on the time delay (Third line and third column of the covariance matrix).

$$\sigma_{horiz}^2 = \frac{1}{2}\left(d_{east}^2 + d_{north}^2 + \sqrt{\left(d_{east}^2 + d_{north}^2\right)^2 - 4\left(d_{east}^2 d_{north}^2 - d_{EN}^2\right)}\right) \quad (12)$$

This gives after simplification:

$$\sigma_{horiz}^2 = \frac{d_{east}^2 + d_{north}^2}{2} + \sqrt{\left(\frac{d_{east}^2 - d_{north}^2}{2}\right)^2 + d_{EN}^2} \quad (13)$$

The performance we are interested in is the level of RNP cross track achievable by such a system.
This is a function of the Total System Error (TSE).

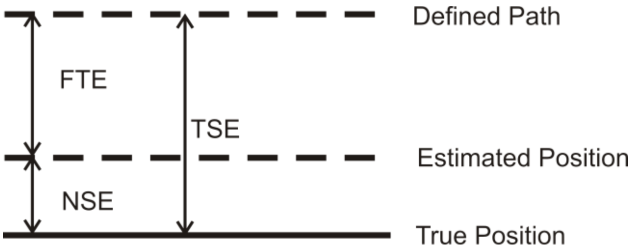

Figure 2 Total System Error

Figure 2 shows the relation between TSE, the Flight Technical Error (FTE) in the cross track direction and the Navigation Sensor Error (NSE) also in the cross track direction. We assume the path definition error negligible.

$$\sigma_{TSE}^2 = \sigma_{FTE}^2 + \sigma_{NSE}^2 \quad (14)$$

We set $\sigma_{NSE}^2 = \sigma_{horiz}^2$ with σ_{horiz}^2 as defined by Equation (13)

RNPx is achieved if:

$$\sigma_{TSE} \le \frac{x}{2} \quad (15)$$

The accuracy is defined as the 95% TSE [6].

The integrity limit or containment limit is defined as being 2 times the accuracy limit which corresponds to 4 times the standard deviation of the TSE. This value corresponds to an integrity risk (TSE larger than the containment limit) of 10^{-5} per Flight Hour (FH) [6].

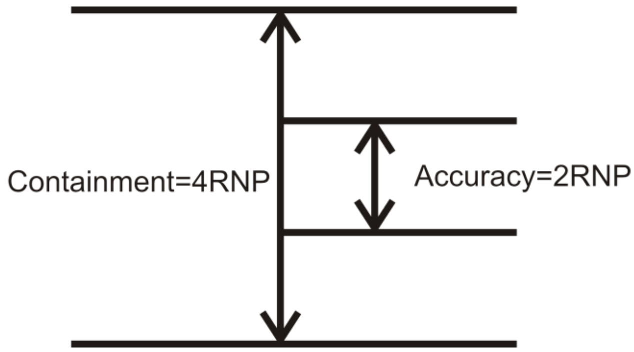

Figure 3 Containment and Accuracy of RNP

SCENARIO DEFINITION

For the analysis, we assume all DME/VOR station all over Germany to be the locations of LDACS1 ranging sources (159 stations). This might not be representative of what will be installed in a future architecture but will give a clear insight into the potential of the studied navigation system.

Only stations visible from an aircraft and being at a distance less than 120 nm are considered in the navigation solution.

A minimum of 3 stations is necessary to determine a position solution.

We consider an aircraft having an FTE of 0.07 nm (2σ) (see [6]).
The time synchronization error of the stations to a reference time is considered as a sensitivity parameter that can take the values 20, 100 or 1000 ns one standard deviation.

RESULTS AND ANALYSIS

Taking into consideration the scenario defined before, we plot in the following graphics the level of RNP cross track performances achieved at 3 different altitudes (350 ft, 1200 ft and 8000 m). The processing of data was made using a latitude-longitude grid of 200 by 200 points from 45.1 to 57°N and from 3.8 to 17°E (area around Germany).

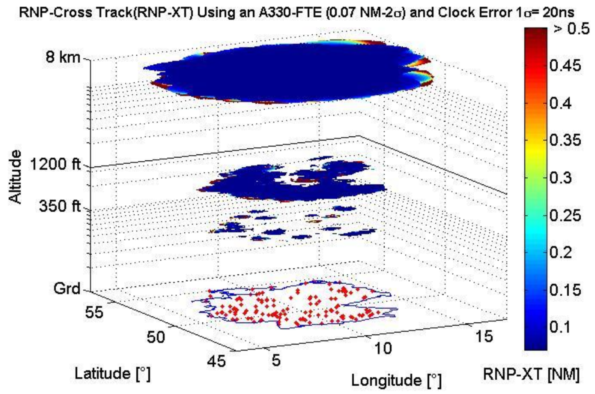

Figure 4 RNP layers using a time synchronization error of 20 ns (one standard deviation)

The red dots in Figure 4 represent the location of the LDACS ranging sources corresponding to the location of DME and VOR stations for a time synchronization error of 20 ns. The colored surfaces at 350 ft, 1200 ft and 8 km represent the level of performance reached. The color bar in the right side of the plot is scaled from 0.08 to 0.5 nm. We can observe that for low altitude (350 ft for example), the area of navigation service are limited to the areas around airports where the density of stations is the highest. The reason for that is simply due to the earth curvature. We considered a mask angle of 0 degree which is a very optimistic scenario and still the area of service is very limited. The higher the aircraft is, the larger the number of stations visible from the airplane. At 8 km altitude, a very good performance can be achieved in an area larger than the area of network location.

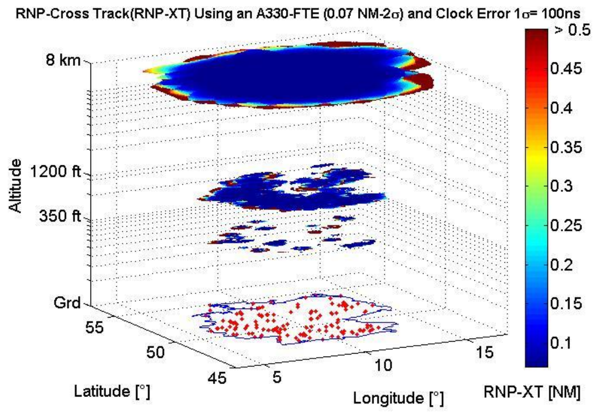

Figure 5 RNP layers using a time synchronization error of 100 ns (one standard deviation)

In Figure 5 the same color scale is used, but the area of RNP0.1 is reduced. This can be seen for the 8 km surface. The level of the synchronization error is 5 times worse than in the previous figure. Even in this scenario only the poor geometries are significantly impacted by this time synchronization error.

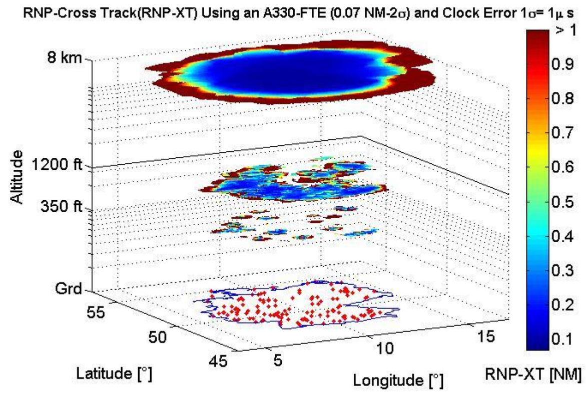

Figure 6 RNP layers using a time synchronization error of 1 μs (one standard deviation)

With another increase in the synchronization error of 10 times to 1 micro second

Figure 6 shows a large degradation of the performance especially in the border of the navigation service (where the geometry is poor). The color scale is limited to 1 nm and not anymore 0.5 as in both precedent figures. One micro second error (1 standard deviation) is very large. To give an idea, using a quartz oscillator with an Allan variance as proposed in [7] and a clock calibration once per day, we would end up with 0.1 micro second deviations (RMS); it is practically unlikely to reach or exceed such level of errors for all stations. What could happen is that 1 or 2 stations are experiencing clock drifts; in this case it is necessary to investigate autonomous fault detection techniques which are beyond the scope of this paper.

CONCLUSION

The results obtained are very promising. The use of all DME/VOR stations over Germany, an aircraft having a flight technical error cross track of 0.07 nm and assuming a realistic time synchronization error of 20 ns (which can be achieved with existing non GNSS systems) show that the stringent RNP0.1 is achieved almost everywhere where a position can be calculated.

As expected the sensitivity of the navigation performance to the time synchronization error of the stations is very high, especially when approaching 1 micro second error. All locations are not equally impacted by time synchronization degradation. The locations with poor geometries are first impacted by this error source.

These simulation results need to be validated using real measurements, which is planned to be done in 2012 using one of the DLR aircraft.

The future work consists of investigating a low cost network (minimal number of stations and using existing infrastructure). Based on a targeted level of service, synchronization performance requirements will be derived. Another aspect to be investigated is the probability of ranging source failure impact on the performance of the navigation service.

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