NEW TIME OF ARRIVAL ESTIMATION METHOD FOR MULTILATERATION TARGET LOCATION

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ABSTRACT

The "Multilateration" (MLAT) system is a Surveillance and Identification element of the A-SMGCS that uses the SSR transponder (Mode S or even A/C) Reply/Squitter as received by a number (e.g. 15 or 20) of fixed stations where the time of arrival , TOA, is estimated. In a central processing unit, the target position is estimated by the TDOA technique (Time Difference Of Arrival), which exploits the TOA in one station taken as the reference station. Due to the (possibly large) Dilution of Precision, the final accuracy as specified by the international recommendations can be obtained only if the TOA accuracy is very good (i.e. sub - metric).
In this work a new, patented [7] TOA (Time Of Arrival) estimation method, derived from the maximum likelihood estimation (MLE) method, is described and compared with the standard method (based on pulses edges and threshold crossing). The accuracy, by analysis and simulation, is one order of magnitude better than standard methods. Moreover a set of measurements and pre-operational trials with real signals in an airport environment (Tassignano, Tuscany) are reported and compared with analysis and simulations to verify the performances of this new TOA estimation method as embedded in a complete system.

INTRODUCTION

Multilateration of Mode S squitters/replies (MLAT) is becoming an important surveillance and identification system for large airports [1], [2].

A typical MLAT system as shown in Figure 1, is made up by a number (e.g. 12-15) of Measurement Stations capable of receiving, time-tagging and transmitting oven a redundant Local Area Network (LAN) the replies and the squitters to a Central Processing Station (CPS) in the airport. Moreover, one or more Reference Transponders permit synchronization and monitoring of the whole system; the Times of Arrival (TOA's) of replies/squitters due to the SSR equipped aircraft and vehicles and to the reference Transponder(s) are processed in the Central Processing Station where multilateration algorithms locate the aircrafts and mobiles. Because of the increasing airport traffic, in particular on the 1090 MHz channel, both the MLAT accuracy/resolution and the robustness to interference have to be improved without increasing the number of MLAT stations too much (limitations are due to cost and installation problems). Different technical solutions have been implemented to locate the SSR transponder of an aircraft on the airport surface or of the "non-transponder device" of equipped vehicles. The "non transponder device" has the same functionalities as the SSR Mode S transponder without the "flyability" characteristics. The MLAT location error is affected by a significant Dilution of Precision (DOP), therefore in order to maintain the overall location r.m.s. error within 3.75 metres (in [2] it is specified an error below 7.5 m for 95% of time) the r.m.s. error of each station has to be of the order of 1 metre, i.e. the various contributions (whose root sum squares is to be below 1 metre) must be kept in the order of 0.3 metres, corresponding to about one ns of equivalent time error.

The limitations of the state of the art in this context (TOA estimation) can be referred to the limited precision of the time measurements that allow localization of the transponder and therefore of the vehicle that carries it on board. In fact in the existing MLAT systems the measurements of the time of arrival of SSR signals in each Station are obtained getting the instant of time correspondent to the overcoming of an assigned threshold of amplitude by the leading edge (or trailing edge) of the first pulse of the signal, with a quantization error due to the fact that such time is found by reading, in correspondence to this event, a clock with which the Station is equipped. This procedure involves, for the measurement, a quantization step equal to the period of the clock (for example 33 nanoseconds - corresponding to 10 meters - for clock at frequency of 30 MHz) with a correspondent peak to peak error of the same order of magnitude.

Another problem of existing MLAT systems is the synchronization between the clocks of the various Stations and the temporal reference of the central processing unit where the multilateration algorithm is implemented. In the absence of the synchronization it shall not be possible to reconstruct the position of the transponder because the measurements of the various Stations that contribute to location of the transponder would be affected with deviations (i.e. bias) that in turn would affect in an uncontrollable way the location itself. In the existing state of the art, synchronization is often realized controlling the clock of the Stations with atomic clocks or using the precise time supplied by GPS receivers. Both these solutions have some drawbacks, in fact the atomic clocks are well more expensive than the quartz clocks and the use of the GPS renders the system vulnerable to eventual electromagnetic disturbances in the range of frequency of GPS and to eventual interruptions or intentional degradations of the GPS service by the manager of the GPS system.

Moreover, existing Multilateration systems are not capable to discriminate superimposed SSR signals ; in the case of superimposition, the measurement of the time of arrival is often limited to the first arrived signal and the decoding is incomplete or missing as superimposition corrupts the codes; therefore, the location and identification function is severely affected. This is an increasingly important problem as the future wider and wider use of Multilateration and other SSR – based systems will render the superimposition condition more and more probable. A proposed solution is described in [6].

Finally, a critical aspect of existing MLAT systems is the Multilateration algorithm: iterative algorithms (recursive) introduce problems of initialization and convergence, not-iterative algorithms can offer an insufficient precision.

This work attempt to exceeds the limitations of MLAT systems and to considerably improve the operation both in terms of performance and in terms of reliability and continuity of the service.

In particular the limitations of the state of the art are exceeded through: (a) a new measurement technique for the TOA (time of arrival) that allows to obtain much greater precision than the existing state of the art and is not limited from the frequency of the clocks of the measurement Stations, (b) the use, in each Station, of a simple clock, at low cost and free to deviate from the temporal reference of the central processing unit, in which the temporal data of the Station is estimated without the necessity of synchronizing it and without neither expensive (and complex) atomic clocks nor GPS receivers and (c) the use on both non-recursive and recursive algorithms for the Multilateration function. The problem of discriminating of superimposed replies is also very relevant but it is not a topic of this paper.

The basic concept of the new measurement technique, (a), is the optimal estimation of the time of arrival of signals through a filter matched to the signal itself followed by a differentiator, and finally followed by an interpolation processor that allows to obtain a measure TOA with resolution that does not depend on the granularity of the clock.

The basic concept that permits the use of simple clocks, previous point (b), is to reconstruct the precise and common temporal reference of the events of each Station through filtering and prediction, according to the classic Kalman methodology.

The use on both non-recursive and recursive algorithms for the Multilateration function, (c), is useful as the non-linearity of the localization equations requires iterative procedures for the search of the optimal solutions. It is therefore important to choose algorithms able to guarantee the convergence, beyond the precision, and whose computational load is not excessive. This work propose to use two algorithms: the first algorithm, non-recursive, initialises the estimation of the position while the second, recursive and based on the minimization of the quadratic error, improves the estimation until the required level of precision is reached.

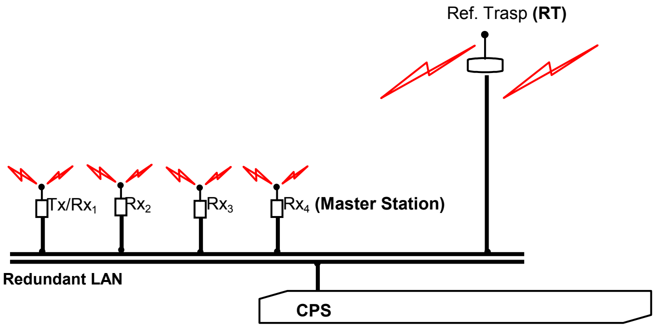


Fig. 1. A typical MLAT System

TOA ESTIMATION

In the present work the classical leading-edge measurement, which is commonly used in the SSR context for TOA estimation, is compared to a novel [7], more effective one, derived from the maximum likelihood estimation (MLE). The classical measurements methods for TOA are based on the estimation of leading (and trailing) edges of the pulses by a simple threshold crossing. The novel approach utilizes a digital filter matched to the waveform of pulses that are the elements of the SSR signals. The centroid of each pulse is estimated by the maximum of the matched filter output. To find the maximum of the output a differentiator is needed. The new algorithm requires a wide band before the A/D conversion and implements pulse detection and optimal measurement in parallel, using a FIR filter, whose coefficients may be set to three values, i.e. 1, 0 and –1, without significant losses with respect to "full dynamic range coefficients" and with a very easy implementation. The large bandwidth implies a large (40 to 60 Msamples/s) sampling and A/D conversion rate. The received signals have a high SNR due to the short ranges found in airport applications, therefore thermal noise is not the main limiting factor for system performance. The TOA range estimation is affected by errors caused by: interferences, propagation phenomena (multipath, reflections), sampling (lack of synchronisation between the sampler and the reply) and A/D converter dynamic range (finite number of bits). In this paper we assume that the A/D converter has a large enough number of bits (e.g. more than 12) to neglect the quantization effect, therefore an ideal sampled signal will be considered in the following , with samples vi, i=1,2,...received at istants Ti, i=1,2,... .

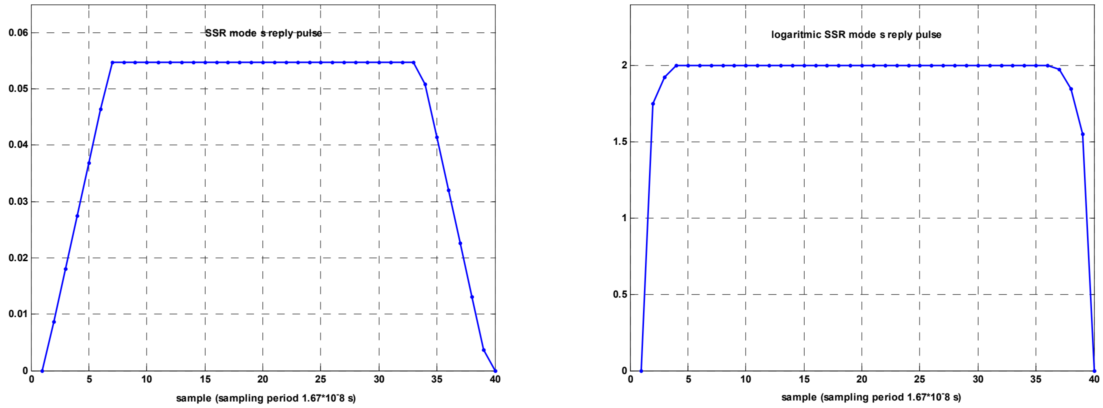


Fig. 2. Pulse of a SSR mode S reply, left, and logarithmic version (log-detector dynamic range: 74 dB), right.

In order to explain how the TOA estimator architecture was obtained, we suppose that the only noise contribution is thermal noise (zero mean white Gaussian noise) and that the samples are statistically independent (notice that the A/D converter could, in some cases, make the samples highly correlated). Let's define *g(t)* as the transmitted signal according to ICAO recommendation, [3] (see Figure 2), *Ts* the sampling period, *A* the normalized amplituded referred to the RMS noise voltage and *To* the TOA, then the signal to noise ratio as a function of time is:

$$R(t) = \frac{1}{2} A^2 g^2 (t - T_o) \qquad (1)$$

with SNR for the i-th sample being

$$R_i = \frac{1}{2} A^2 g^2 (T_i - T_o) \qquad (2)$$

Due to the statistical independence of the samples, the joint probability density function state *To* and *A* is:

$$L(\underline{v} | T_o, A) = \prod_{i=1}^{N} f_{v_i} (v_i | T_o, A) \qquad (3)$$

where f_{vi} is a Rice function:

$$f_{vi}(v\,|\,A,T_o)dv = v\,exp\left\{-\frac{v^2+A^2g_i^2}{2}\right\}I_o(Avg_i)dv \tag{4}$$

with $g_i = g(T_i - T_o)$ and $I_0()$ is the modified Bessel function of zero order. Let's define $\lambda = \log(L)$ and $g_i^{'} = {d[g(T_i - T_0)]}\big/{dT_0}$. The Maximum Likelihood estimator is:

$$\frac{\partial\lambda}{\partial T_o} = -A^2\sum_{i=1}^{N} g_i g_i^{'} + \sum_{i=1}^{N} v_i g_i^{'} A\frac{I_1(v_i g_i A)}{I_0(v_i g_i A)} = 0 \tag{5}$$

Remember that g_i has even simmetry, so that

$$\sum_i g_i g_i^{'} \cong 0$$

and SNR is large enough to assume

$$\frac{I_1(v_i g_i A)}{I_0(v_i g_i A)} \cong 1 \tag{6}$$

the ML estimator for TOA, T_0, can be approximated by the solution of the equation, indipendent from A:

$$\sum_{i=1}^{N} v_i g'(T_i - T_o) = 0 \tag{7}$$

This corresponds to (a) sending the received signal to a filter whose impulse response is equal to the derivative of the expected signal in the absence of disturbance (according to ICAO standards) and (b) finding the time instant in which the filter output crosses the zero value.

In the digital implementation, see Figure 3, assuming a sampling frequency of 60 MSamples/s, the MLE estimator can be approximated by 18 sums (more precisely 9+9 sums and a difference) and therefore with a simple FIR filter. The interval where the impulse response is zero must be smaller than the minimum pulse width allowed by the ICAO recommendations and the total length has to be larger than the maximum pulse width. In these conditions, the r.m.s. error of TOA estimation can be evaluated analytically, as shown in [4] even if for another application. However, since, signal samples are correlated and pulse integration is not so favourable, the real performance has been evaluated through simulation techniques in this paper.

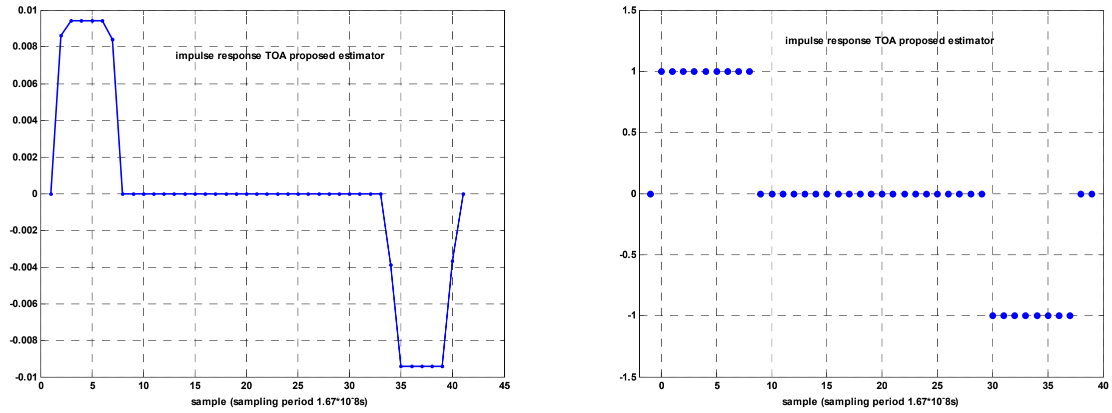


Fig. 3. TOA optimal estimator impulse response,left, and its approximated version (with coefficients set to +1, -1, and 0), right.

Moreover, due to the lack of synchronism (i.e due to the jitter) between the sampler and the reply receiving time, the estimation error, using only the zero-crossing (which evaluates the TOA as the time of the first sample after zero crossing) is:

$$\sigma_T = \left(\frac{T_s^2}{12} \right)^{1/2}$$

where T_s is the sampling interval (e.g. 16.67 ns). This quantization error can be significantly reduced [4] by interpolation of the two samples adjacent the null at the output of the filter, providing a measurement with an accuracy of a fraction of T_s. The novel estimation is made up by the series of (a) a matched filter to the pulse, (b) a differentiator, (c) a zero-crossing detector and (d) an interpolator whose output is the estimated TOA. Figure 4 shows the output of the filter (i.e. matched filter plus differentiator).

The dynamic range of the receiver before the A/D converter is an important issue when there are transponders between 15 *m* and 8000 *m* from the closest receiving multilateration station. Such a wide dynamic range can be managed by the use of a logarithmic detector followed by an A/D converter with 8 bits or by a high dynamic range linear receiver followed by an A/D converter with 12 or more bits (or by a combination of both). In both cases the r.m.s. error due to the noise can be kept below 0.3 or 0.4 m. The fact that logarithmic detection modifies the shape (see Figure 2) of the pulses when their maximum amplitude varies, i.e. with a variation of the distance of the transponder suggest us the use of the linear receiver. A sample result from the many simulations performed is shown in Figure 5 where the conventional measurement without interpolator is compared to the MLE with linear detector and a 16 bit A/D converter.A sampling frequency of 60 Msamples/s is used throughout this paper.

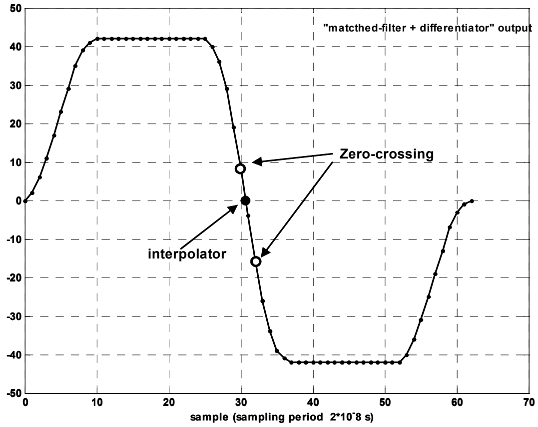


Fig. 4. Matched Filter+differentiator, interpolation and zero-crossing.

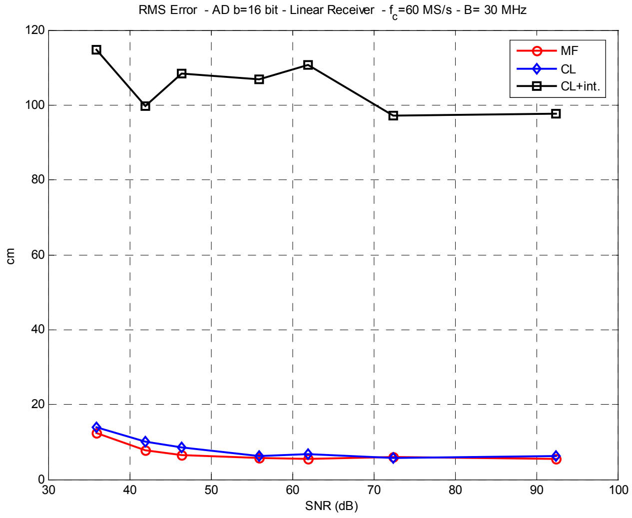


Fig. 5. RMS TOA error (cm, with 16 bit A/D converter and linear receiver) of the MLE estimator (○) and of the conventional estimator - with (◊) and without (□) interpolator - versus SNR, MLE done by Matched Filter plus differentiation followed by interpolation and zero-crossing.

SYNCHRONISATION OF RECEIVING STATIONS

The MLAT system uses one or more Reference Transponders whose position is exactly known and permits the transmission in "line of sight" with all receiving stations. The time tagging of reference transponder signals (squitters) as resulting from TOA estimates from MLAT stations is only affected (neglecting the noise contribution) by synchronization errors due to clock drift of various stations with respect to reference clock.

The clock erros can be modeled as

$$x(t) = x(0) + y(0)t + \frac{1}{2}Dt^2 + \varepsilon(t) \tag{8}$$

where *x(t)* is the normalized time error (i.e. the phase of the clock divided by 2 times the nominal frequency), *y(t)* is the frequency deviation w.r.t the nominal frequency (i.e. the frequencies offset) and D is the frequency drift. It is assumed that the clock is synchronized at *t=0*.

From this model, a simple Kalman filter can be built [5], [7] to track and correct in the Central Processing Unit the clock error; however, when high accuracy (e.g. better than 1 ns) is requested, as in the present case, the correction has to be performed many times per second, with significant computation burden.

POSITION ESTIMATION

The localization of a source using the Time Difference of Arrival (TDOA) has several applications in the navigation systems, in surveillance and geophysics. The TOA measurement allows the TDOA computation and the definition of a set of equations which provide the target's position without the knowledge of the time of emission. The solution of these equations represents the intersection of *M-1* hyperboloids, if the number of receiving stations is *M.*

There are different approaches to the localization problem. A possible solution is shown in [8], [9]. It is an iterative scheme to solve the algebraic non-linear equations. The method starts with an rough initial guess that is improved by minimizing the local linear least squared error. The most important drawbacks are the need of the initial guess, the convergence (not assured) and that the process is computationally burdensome.

To overcome the problem of an initial guess several closed form algorithm has been fully investigated ([10],[11],[12]). These methods are cheaper but the solutions are non optimal in the MLE sense, as shown in [13]. Moreover, the final solutions are ambiguous, making the operational implementation unacceptable since the position of the target at the first acquisition is obviously unknown. The ambiguities must be solved in a systematic way but not always this is easy to deal with. Therefore the adoption of one of these algorithms as a sole-means does not seem to be the directly applicable.

An alternative close form method is presented in [13]. This approach approximates the ML estimator when the TDOA errors are reasonably small. The TDOA equations are transformed into another set of linear equations. The Least Squares Method gives the first solution that improves providing the final position estimate using the relationship between an extra variable and the co-ordinates [13]. Only the final solution is ambiguous, like all the closed form procedures, whilst the initial and the intermediate ones are not. The idea is to use the initial closed-form solution of the algorithm presented in [13] as the initial guess for the iterative algorithm. In fact, the method in [13] has the initial solution which is not ambiguous and it can provide a quite accurate starting point for the common MLAT signal-to-noise ratio level. This can overcome the traditional limitations of the iterative method without the need for an initial guess.

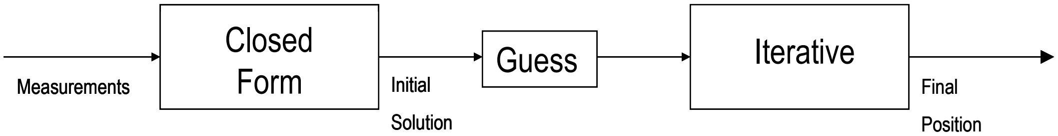


Fig. 6. Scheme of the position estimation process. The first solution derived from the closed-form algorithm is sent to iterative method as initial guess.

In this section the results of the position estimation by MLAT are presented. The algorithm described before is applied to the Marco Polo airport in Venice. The positions of the 14 stations in the airport layout is sketched in figure 7. The requirements the installation should take care are the highest number of stations visible from all the permitted target position, the minimum number of total stations to be installed to reach the previous goal and the compliance – in height and extension - with the mask of the structures can be built (buildings, walls, trellis, etc.). In particular, the choice of the installation shown below is mostly concerned with the Diluition of Precision (DOP) and the visibility problems.

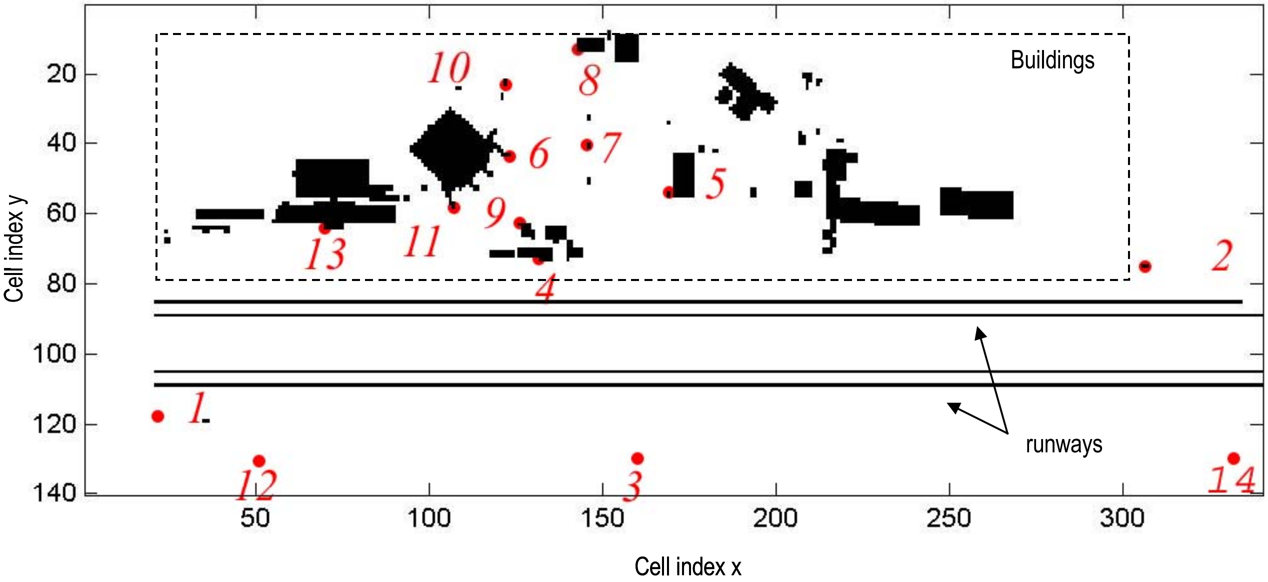
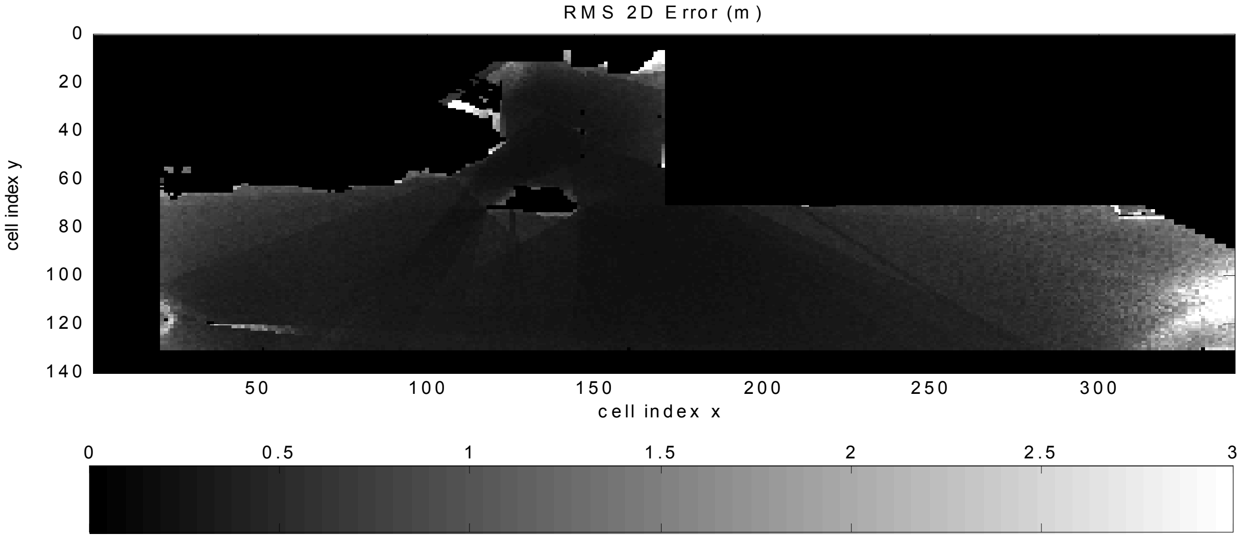


Fig. 7. Marco Polo airport. The airport surface is divided into a number of discrete cells (10 m x 10 m). Each cell is approximately 10 m width. 14 stations with heights (in meters) z=[2 5 2 13 5 17 5 13 13 5 17 2 40 3].

The simulation is related to a 3D algorithm. The vertical error is strongly affected by the bad VDOP (Vertical-DOP) values. The presented scenario has most station close to an horizontal plane so the vertical accuracy is poor. The behaviour of the rms 2D error is shown in figure 8. The maximum value in figure is equal to 3 m. The 2D error is in a range from 0.3 m to 0.7 m in the most part of the considered area (especially in the apron and along the runways), i.e. much lower than the EUROCAE minimum performances [2].



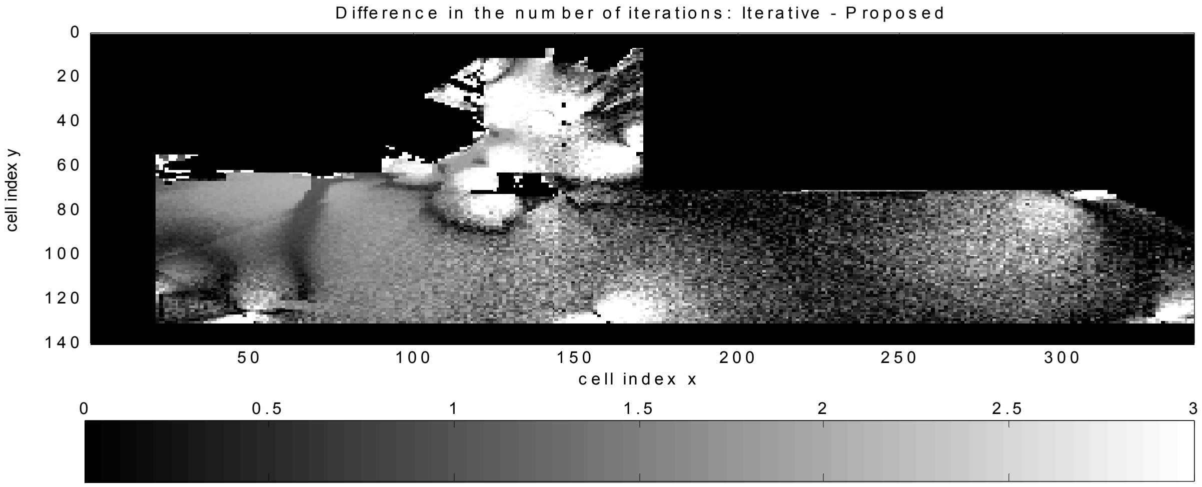


Fig. 8 (up) . Grey-level map (metres) of the RMS horizontal position error for the configuration shown in figure 7. The σ_{TOA} error measurement is set equal to 0.3 m.

Fig. 9 (down) . Difference in the number of operations (Iterative minus the Proposed cascade approach).

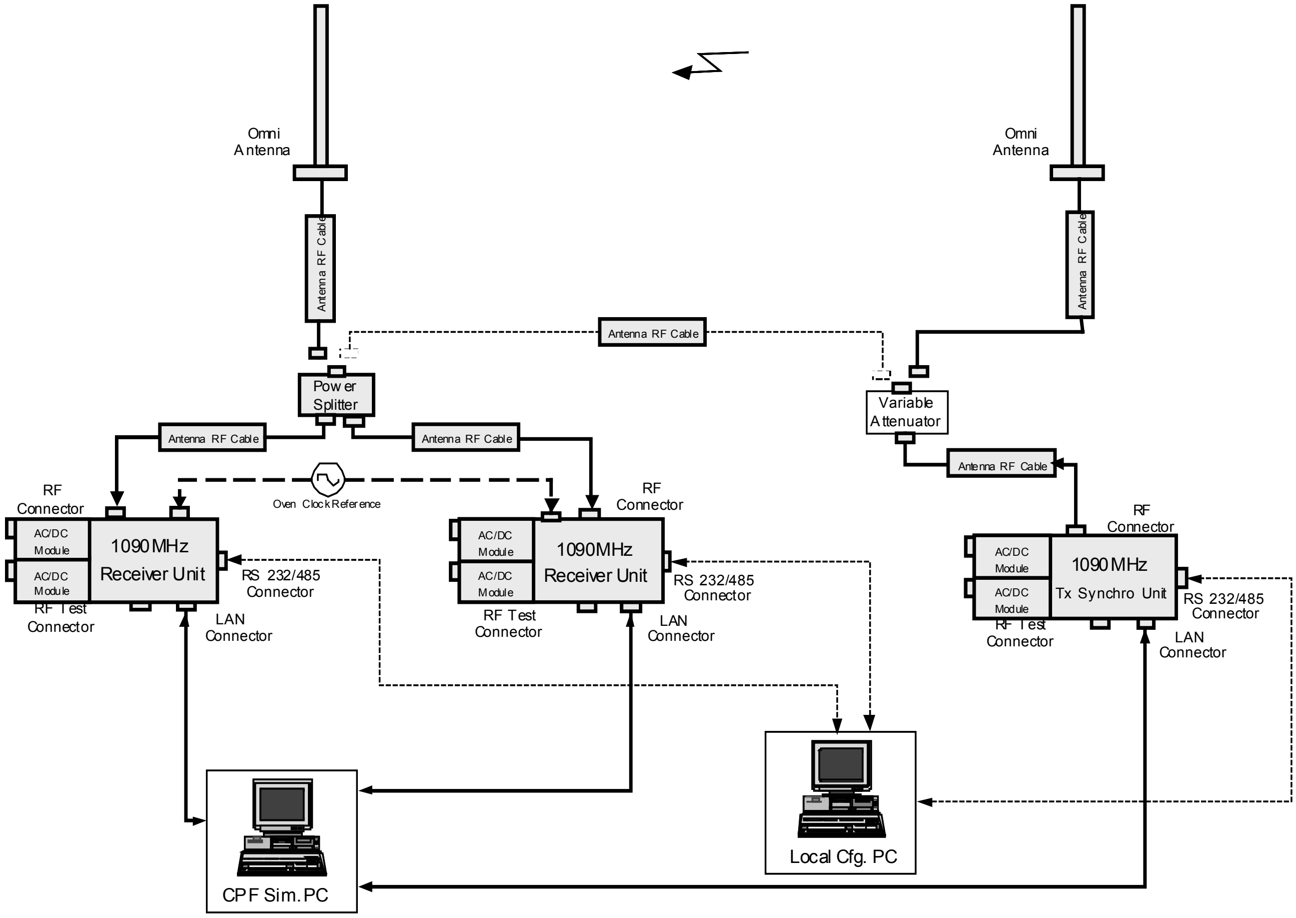


Fig. 10. Measurement Test Bed

EXPERIMENTAL MEASURAMENT ON MLAT SENSOR

This paragraph describes two experiments for the evaluation of the MLAT sensor accuracy in TOA measurement. In the first one only the TOA estimator accuracy is evaluated, while in the second also the contribution of the clock drift is considered.

The first measurement test bed is reported in Figure 10 and consists of the following elements:

- A 1090 MHz transmitter, sending a SSR Mode S reply every 2 s
- Two 1090 MHz identical receivers with a preselector bandwidth of 30 MHz, a linear receiver and a A/D converter with 16 bits and a sampling frequency of 60 MHz
- A power splitter
- A Personal Computer simulating the Central Processing Facility
- A configuration PC
- An oven-controlled oscillator (thereafter, OVEN)
- Two antennas, one in transmission and one in reception (optionally an RF connection between the transmitter and the power splitter, not used in this test)

The second measurement test bed, differs from the previous one only for the use of two independent OVENs as pilot clock for the two receivers.

For both experiments, as the receivers and the RF cable downstream the power splitter are identical, the TDOA should be equal to zero. Deriving a statistics for TDOA errors, allows as to obtain a statistics for TOA measurement simply scaling by a factor $\sqrt{2}$, as the two measurements are independent.

The aim of the two measurements is to evaluate the accuracy of the MLAT sensors TDOA (and of the TOA) estimation.

In the first set of measurements only one OVEN has been used as pilot clock for the two receivers. In this way it was possible to have the same drift in the two systems. The TOA accuracy is 1σ=3.4181e-10 sec (i.e. as small as 10 cm) and the TDOA values are shown in Figure 11.

In the second set of measurements two different OVENs are used and also the system accuracy suffers the effect of the two different clock drifts. The TDOA trend is shown in Figure 12. TOA accuracy is improved using a Kalman filter to track and correct the difference in clock drifts, see Figure 13. The Kalman algorithm is performed for every pulse received (so with clock drift difference estimation filtered in real time for every TOA estimation) with a process noise standard deviation equal to $10^{-13.}$

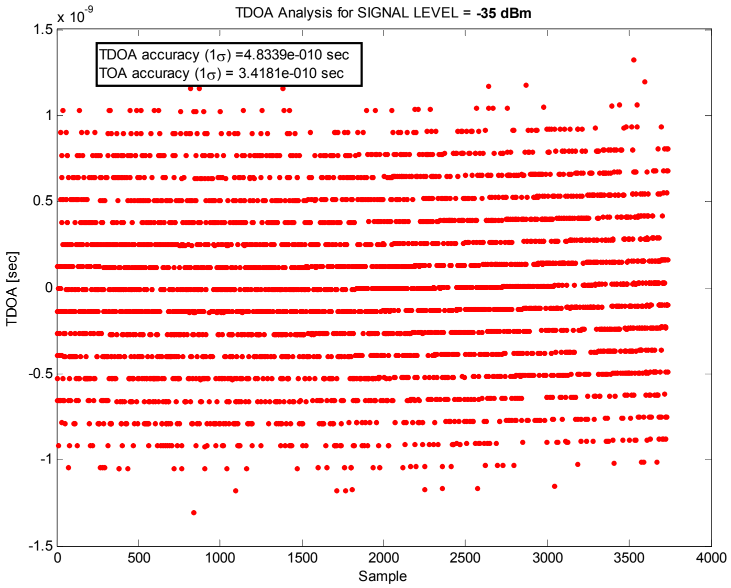


Fig. 11. Accuracy Estimation, test bench with single OVEN as pilot clock for two receivers

IV. CONCLUSIONS

This paper analyzes accuracy of a last-generation Multilateration System [7] to be used for A-SMGCS and , more generally, Airport and APRON Traffic Management. The main errors arise from the TOA estimates, and paper deals with a novel method of TOA estimation which can provide a measurement with an error well below the sampling period. The method, based on MLE estimation, can be implemented using a FIR filter whose coefficients can be set to +1, -1 and 0 without significant losses and with an easy implementation. Other error sources are described and an overall error map for a typical application (Venice) is shown.

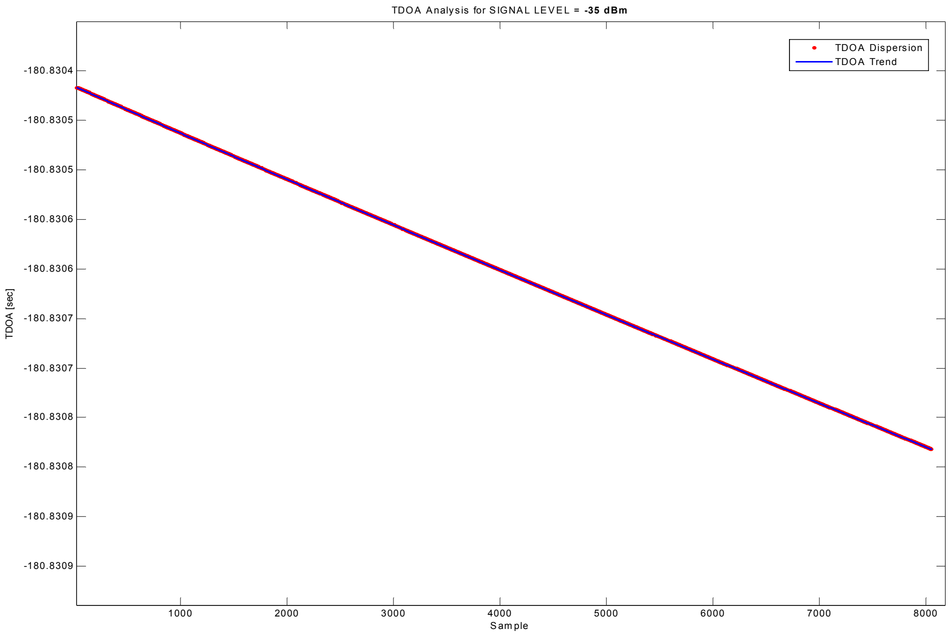


Fig. 12. TDOA measurements with free oven, second experiment

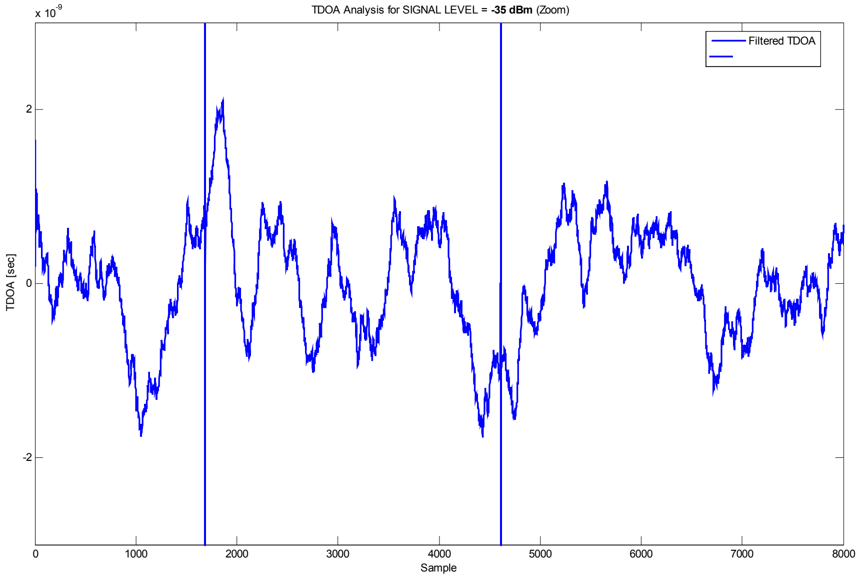


Fig. 13. TDOA measured with tracker clock driift.

REFERENCES

[1] EUROCAE, “Minimum Aviation System Performance specification for advanced surface movement Guidance and Control System (A-SMCGS)”, ED-87A, January 2001.

[2] EUROCAE, “Minimum Operational Performance Specification for Mode S Multilateration System for use in advanced surface movement guidance and control system (A-SMCGS)”, ED-117, April 2003

[3] ICAO Annex 10, *Aeronautical Communications*, volume 1.

[4] Galati G., Studer F.A., “Maximum likelihood azimuth estimation applied to SSR/IFF systems”, *IEEE Trans. 1990*, AES-26 (1), pp 28-43.

[5] Galati, Gasbarra, Leonardi, Magarò, “New signal processing techniques in SSR-Mode S replies multilateration for A-SMGCS”, IRS2004, VARSAW 19-21 May 2004.

[6] Galati, Leonardi Italian Patent n° RM2001A00176 , 3 aprile 2001 “Apparato ricevente ed elaborativo per segnali ‘replica’ del radar secondario di sorveglianza con capacità di super risoluzione“; USA Patent US 6,819,282 B1 , nov 16, 2004, EU Patent 02728019-7-2220-IT 0200206.

[7] G. Galati "Sistema di sorveglianza ad alta precisione mediante multilaterazione di segnali SSR", Italian patent RM 2004 A000249, Tor Vergata University, 17.05.2004 ; " High Precision Surveillance System by means of Multilateration of SSR Signals", Patent Cooperation Treaty Application PCT/IB 2005/51519 , subm. No. 4622 , 10 May 2005, Applicant : Università degli Studi di Roma Tor Vergata .

[8] W. H. Foy, “Position Location Solutions by Taylor Series Estimation”, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES 12, pp 187-194, March 1976.

[9] D. J. Torrieri, “Statistical Theory of Passive Location Systems”, IEEE Transactions on Aerospace and Electronic Systems, Vol. AES 20, pp 183-198, March 1984.

[10] B. Friedlander, “A Passive Localization Algorithm and its Accuracy Analysis”, IEEE J. Ocean. Eng., vol. OE-12, pp 234-245, January 1987.

[11] H. C. Schau, A. Z. Robinson, “Passive Source Localization Employing Intersecting Spherical Surfaces from Time of Arrival Differences”, IEEE Transactions Acoustic, Speech, Signal Processing, vol. ASSP-35, pp 1223-1225, August 1987.

[12] J. O. Smith, J. S. Abel, “Closed Form Least Squares Source Location Estimation from Range Difference Measurements”, IEEE Transactions Acoustic, Speech, Signal Processing, vol. ASSP-35, pp 1661-1669, December 1987.

[13] Y.T. Chan, K.C. Ho, "A Simple and Efficient Estimator for Hyperbolic Location", *IEEE Trans. 1990 on Signal Processing*, vol. 42, no. 8 August 1994, pp 1905-19