ADS-B/MLAT surveillance system from High Altitude Platform Systems

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***Abstract*—In this work the potential usage of ADS-B and Wide Area Multilateration (WAM) Surveillance with High Altitude Platform Systems (HAPS) is considered. The paper investigates the possible configuration of the system, the link budget, the geometry and the limitation due to the random access to the channel by the Mode S Signals (capacity). The surveillance performance of the proposed architecture in a Wide Area Multilateration context is evaluated by both simulation and statistical analysis (Cramer Rao Lower Bound).**

***Index Terms*—location, air traffic control, multilateration, HAP**

I. INTRODUCTION

Automatic Dependent Surveillance -Broadcast (ADS-B) or Wide Area Multilateration (WAM) independent surveillance are becoming of widespread use in modern Air Traffic Management system. These systems use the SSR Mode S channel and the messages emitted from the airplanes to localize and identify the cooperating targets in their coverage area [1]. In the first case (ADS-B) the positions of the airplanes (targets), obtained from the on-board navigation subsystem (usually GPS based), are included in the message, in the second one the target positions are obtained by the system, receiving the same message at different receiving stations, in different locations, and then computing an hyperbolic localization algorithm. These kind of systems have various advantages compared with the classical radar surveillance but they have also some disadvantages related to, for example, the correct positioning of the various receivers or the coverage of each station that could be reduced by blockage from obstacles. Another problem is due to the use a non directional antenna in the receiving station. This means that SSR signals from different directions may overlap in time resulting in reduced detection and/or decoding performance.

In ESAVS 2010 the DLR-Institute of Space System proposed the ADS-B surveillance from satellites and one feasibility trial was done using a very low cost stratospheric balloon [2]. That paper clearly shows that there is the basis to a possible deployment of a ”‘flying”’ Mode S surveillance systems. In this paper we propose an alternative to the satellite implementation that is the use of HAPS.

HAPS is proposed because the use of a satellite for low cost ADS-B payload may be not recommended, due to: (a) unfavorable link budget due to very large distances between the ADS-B receivers and the aircraft, order of one thousand kilometers; (b) presence of a large numbers of targets in the main beam of the receiving antenna, exacerbating the problem of overlapping replies/squitters.

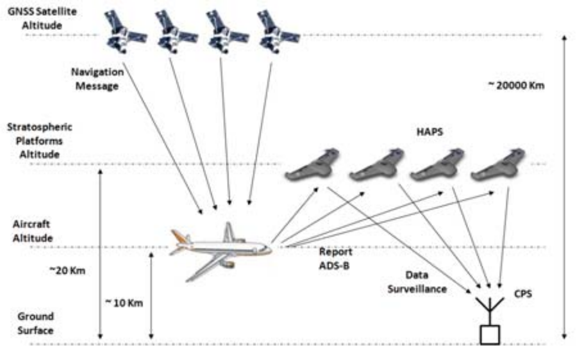

Figure 1. System architecture. The Mode S signal is received from HAPS and then transmitted to the Central Processing Facility and delivered to the ATC Surveillance System.

Besides, HAPS are becoming more and more attractive, as shown by the number of scientific researches about this type of platform for telecommunication applications [3] [4] [5] and HAPS Mode S surveillance solution has clear advantages with respect to the ground deployment of the classical system, namely:

- opportunity to ensure the surveillance in regions where stations can’t be installed (Oceans, deserts, etc..);
- opportunity to ensure the surveillance in the valleys of mountain regions, where coverage by ground stations is difficult;
- lower sensitivity of the station to natural disasters (earthquakes, hurricanes, etc..)
- better robustness with respect to intentional interferences and Jamming;

and also some advantages with respect to the satellite solution:

- possibility to guarantee the surveillance of small region of the world;
- short time to deploy the system;
- lower costs.

The disadvantages introduced HAPS Mode S surveillance are:

- lower life cycle;
- higher cost of implementation.

In Figure 1 the proposed architecture for a generic ADS-B/MLAT stratospheric deployment is shown. This architecture allows, depending on the number of HAPS, the deployment of mixed systems with different possibilities, i.e.: the possibility to improve an already existing MLAT/WAM system with one or more HAPS, the possibility to create an "'HAPS only"' WAM system or, finally, to create a simple flying-net of ADS-B receivers. This architecture concerns 4 levels of service: the aircraft is equipped with an ADS-B transponder that computes the aircraft position using the GNSS system and then transmits this information in broadcast; the HAP stations (between 17 and 22 km of altitude), receive these information and after adding the time stamp, the identification number of the station and the position of the station send the message to the ground *Central processing Station* (CPS). In this station the message can be decoded and the surveillance of the traffic is performed. If at least four receiving stations (HAP or terrestrial) are deployed, the Multilateration algorithm can also be performed on Mode S replies and Squitters.

The feasibility aspects, i.e.: weight and dimension of the payload, geometry (related to signal reception and blockage), link budget and region of coverage of these solution will be analyzed in the following sections. Finally the channel capacity, related to the number of fruits in the coverage area will be considered.

The performance of possible HAPS Mode S systems is reported in the last section with some simulations and trials.

II. Geometry and Coverage for Satellite ADS-B

Before considering the HAP system a brief analysis of ADS-B receiver on satellite as secondary application (i.e. *"'piggy-back"'* payload that must have reduced power consumption, weight and volume to be carried on a satellite designed for another application) will be done.

Considering the study proposed in [2] the Iridium NEXT Satellites can be used as test bed for satellite ADS-B receiver. This constellation is composed of 66 satellites on 11 orbital planes (with an inclination of 86.4°). The satellite altitude is *780 km*. To assure a global coverage each satellite must have an adequate footprint that call for an antenna beam width $2\beta_m$ of about 124°. Considering Figure 2 is possible to calculate all the parameters to describe the coverage of the system, and the parameter useful to manage the datalink (i.e. the elevation of the satellite and the distance).

Calling the coverage area S, the minimum elevation angle α_m, the maximum distance D_M and imposing β_m equal to 62° is possible find all the other parameters (considering also the Earth radius $R_E = 6378\ km$ and Satellite altitude of $H = 780\ km$). In particular, defining $L = R_E + H$, the following equations can be written:

$$L = D_M cos(\beta_m) + R_E cos(\gamma_m) \quad (1)$$

$$D_M^2 = L^2 + R_E^2 - 2R_E L cos(\gamma_m) \quad (2)$$

and is possible to compute γ_m and α_m:

$$\gamma_m = arcos\left(\frac{L - D_M cos(\beta_m)}{R_E}\right) \quad (3)$$

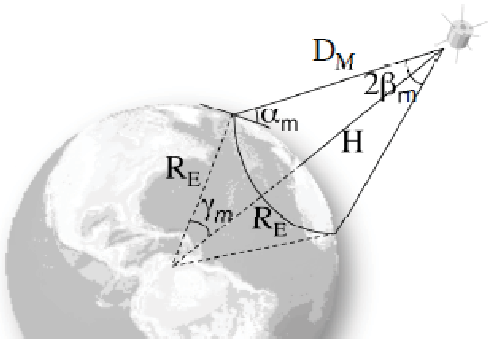

Figure 2. System geometry for a Satellite ADS-B receiver.

$$\alpha_m = \frac{\pi}{2} - \beta_m - \gamma_m \quad (4)$$

The coverage area S and the coverage radius for each satellite can be calculated by the following equations:

$$S = 2\pi R_E^2 (1 - cos(\gamma_m)) \quad (5)$$

$$D = 2R_E\gamma_m \quad (6)$$

All the resulting geometry information are summarized in Table I .

$H[km]$	$D_M[km]$	α_m	γ_m	**S** $[km^2]$	**D** $[km]$
780	2503.31	7.72°	20.27°	**15838703.965**	**4514.2283**

Table I
Coverage parameters for an Iridium satellite with an antenna beamwidth of 124°.

For this coverage it is necessary to verify if the transmitted signal from the airplanes arrive at the satellite receiver with enough power to be decoded (i.e. greater then the receiver sensibility) and also optimize the radiation pattern of the antenna. It is possible to calculate the satellite antenna pattern from the Friis equation[6]:

$$P_{rx} = P_{tx} + G_{tx} - L_{tx} - L_{at} - A_{fs}(\beta_m) + G_{rx}(\beta_m) - L_{rx}\ \text{[dB]} \quad (7)$$

where P_{rx} is the receiver sensitivity, P_{tx} is the transmitted power of the transponder (Class A3 transponder, i.e. 21 dBW), L_{tx} e L_{rx}, are the transmitting and receiving losses, L_{at} is the propagation loss and A_{fs} is the free-space attenuation.

P_{tx}	P_{rx}	L_{tx}	G_{tx}	L_{at}	L_{rx}
21 dBW	-120 dBW	3 dB	0 dBi	3 dB	3 dB

Table II
Parameters for link-budget computation.

Given the parameters in Table II, considering a target at the maximum distance $D_M(\beta_m)$ is possible to compute the free-space attenuation:

$$A_{fs} = 10log\left(\frac{4\pi D_M(\beta_m)}{\lambda}\right)^2 \text{ [dB]} \quad (8)$$

and the the Antenna gain directly from the equation 7.

In Figure 3 a vertical (azimuth) cut of the pattern is represented.

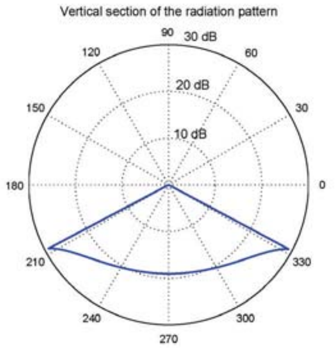

Figure 3. Ideal vertical section of the radiation pattern of a full coverage Iridium ADS-B antenna.

This kind of radiation pattern cannot be generated with a small and simple antenna. This means that the ADS-B payload must be more complex (multichannel receiver and multibeam antenna), at least as complex as in the primary application of the satellite (for example, the antenna should be very near, in dimensions, to the Iridium antenna, i.e. composed by 3 panels of about *180 cm X 90 cm*). It may be concluded that global coverage by ADS-B on satellites may bring to too large and too complicated systems, with an unfavorable cost effectiveness.

III. HAP Payload Description

Considering the architectures of the system given in Figure 1 is possible to define the HAP's payload for the 1090ES channel as described in Figure 4. The payload receives the Mode S signals and ADS-B report, decodes it and sends the information decoded to the CPS. The payload must add information to every Mode S reply received about Time Of Arrival (TOA) of the message and the platform precise position. So, the platform has a GPS/GNSS receiver. It is important to verify if this payload respects the requirements to fly on an HAP (in term of weight, volume and power consumption). Therefore a brief analysis of the needed hardware with COTS components was done; the results are reported in Table III.

Considering that a typical Unmanned Aircraft System (UAS) or a typical airship for stratospheric fly can carry a payload of 50 kg and can supply a power of kW, the ADS-B/Multilateration receiver, with its weight of less than 5 Kg and a power consummation smaller then 3 W can be a secondary payload for an HAP mission (i.e. Telecommunication or Satellite Navigation augmentation [7]).

Component	**Weigh** [kg]	**Size** $[cm^3]$	**Power** [W]
Antenna 1090 MHz	0.1086	$8.20 \times 10 \times 3 = 246$	0
Mode S Receiver	0.7	$3.8 \times 17.4 \times 12.4 = 841.46$	2.8
Process and Control unit	0.13	$9 \times 9.6 \times 2 = 172.8$	6
GPS antenna	0.111	$8.73 \times 5.59 \times 3.2 = 156.16$	1
GPS Receiver	0.54	$9.5 \times 4.2 \times 16.8 = 670.32$	1.7
Estimate Weight, size and power	**1.59**	**2087**	**11.5**

Table III
Power consumption, weight and volume of a COTS ADS-B receiving system.

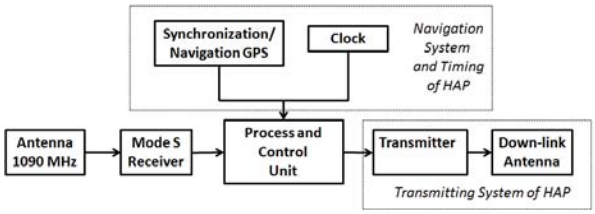

Figure 4. HAP ADS-B Payload diagram

IV. Coverege of the HAP

The real coverage of the HAP system must be also evaluated. This is essentially limited from: (a) geometry; (b) capacity of the channel and (c) the power, i.e the link budget.

Concerning the geometry and the coverage, it is possible to use the formulas for the satellite application, section II, while considering an altitude of 20 km for the HAP. The results are reported in Table IV.

H $[km]$	D_M $[km]$	α_m $[°]$	γ_m $[°]$	β_m $[°]$	**S** $[km^2]$	**D** $[km]$
20	505.48	0	4.53	85.8203	**798038**	**1008.02**
20	195.54	5	1.74	83.3	**118494**	**388.43**

Table IV
Parameters for the maximum geometrical coverage achievable with the use of an HAP ($\alpha_m = 0°$ and $\alpha_m = 5°$.

Considering that the airplane can be at 10 km of altitude the real coverage of an HAP can be also larger: for an airplane flying at 10 km of altitude the maximum distance from the HAP in line of sight is *862.25 km*, this means that only one HAP can cover the European core.

The capacity of the channel depends essentially on the traffic scenario and on the ability of the receiver to decode superimposed replies. Here, the traffic scenarios proposed in the CASCADE Program from EUROCONTROL [8] is considered to exploit the problem of system capacity. The CASCADE program considers the following scenario: a Mode S receiver in Bruxelles at an altitude of 3300 feet and a coverage area with a radius of $R_{max} = 300NM$ with three scenarios for the fruit densities:

1) high interference ($\lambda_{max,1} = 105000$ fruits per second)
2) reduced Radar infrastructures ($\lambda_{max,2} = 55000$ fruits per second)
3) medium interference ($\lambda_{max,3} = 50000$ fruits per second)
4) low interference ($\lambda_{max,4} = 27500$ fruits per second).

If an uniformly distributed traffic in the coverage area and an arrival process of the fruits Poisson distributed are considered [9], it is possible to write:

$$p(n) = \frac{(\lambda T)^n}{n!} e^{-\lambda T} \tag{9}$$

in which $p(n)$ is the probability of receiving n replies in the time interval T (length of the Mode S reply), for a fixed number of fruits per second λ. When n is larger than one it means that one or more fruits arrive before the end of the reply, i. e. interference condition. Not all the tranponders in the coverage area will interfere with a reply but only the reply that have enough power to produce a Signal to Interference Ratio (SIR) smaller then a given value. For this reason only the message coming from airplanes which have a distance from the receiver between 0 and $R+\Delta r$ are considered, where R is the distance of the interfered airplane and the receiver and Δr is such that the received power of the interfering reply is no less than $3dB$ below the received power of the interfered reply. This means that it is assumed that a signal to interference ratio greater than 3 dB can be managed. In Figure 5 the probability of receiving a non interfered signal from a transponder at a given distance R using a standard receiver is reported; we have assumed the previous hypothesis and that the number of fruits (λ) is computed by using the effective radius of the interfering area:

$$\lambda_i = \frac{\pi(R+\Delta r)^2}{\pi(R_{max})^2} \cdot \lambda_{max,i} \tag{10}$$

It is possible also to consider an enhanced receiver that has the capability to decode the message also in the case of interference conditions, as described in [9]. In particular, calling t_p the Mode S preamble duration and t_{ES} the Mode S reply duration the following events can be considered:

- A:(0 interfering signals in $[0 - t_{ES}]$);
- B:(0 interfering signals in $[t_p - t_{ES}]$);
- C:(1 interfering signals in $[t_p - t_{ES}]$);
- F:(0 interfering signals in $[0 - t_p]$);

and for this enhanced receiver we can say that we do not have interference if:

$$P_{free} = P(B \cup C|F) = \frac{P((B \cup C)F)}{P(F)} = \frac{P(BF) + P(CF)}{P(F)} = \frac{P(A) + P(C)P(F)}{P(F)} = \frac{P(A)}{P(F)} + P(C) \tag{11}$$

FRUIT level					105000	55000	50000	27500
Probability to receive an interference-free reply	A long squitter	Not less	90%	Coverage range [NM]	~19 (*) ~45 (') ~64 (") ~82 (^)	~27 (*) ~62 (') ~89 (") ~112 (^)	~28 (*) ~65 (') ~94 (") ~118 (^)	~37 (*) ~88 (') ~126 (") ~159 (^)
			95%		~13 (*) ~36 (') ~55 (") ~72 (^)	~18 (*) ~50 (') ~77 (") ~99 (^)	~19 (*) ~53 (') ~81 (") ~104 (^)	~25 (*) ~72 (') ~109 (") ~141 (^)
	At least one squitter in four seconds	Not less	90%	Coverage range [NM]	~47 (*) ~77 (') ~98 (") ~115 (^)	~65 (*) ~106 (') ~135 (") ~159 (^)	~68 (*) ~142 (') ~112 (") ~167 (^)	~92 (*) ~150 (') ~192 (") ~226 (^)
			95%		~40 (*) ~70 (') ~91 (") ~108 (^)	~55 (*) ~96 (') ~125 (") ~149 (^)	~58 (*) ~101 (') ~131 (") ~157 (^)	~79 (*) ~137 (') ~177 (") ~211 (^)
	At least one squitter in ten seconds	Not less	90%	Coverage range [NM]	~73 (*) ~104 (') ~125 (") ~142 (^)	~100 (*) ~144 (') ~172 (") ~196 (^)	~105 (*) ~151 (') ~181 (") ~206 (^)	~142 (*) ~203 (') ~244 (") ~278 (^)
			95%		~67 (*) ~98 (') ~119 (") ~136 (^)	~92 (*) ~135 (') ~164 (") ~197 (^)	~97 (*) ~142 (') ~172 (") ~197 (^)	~131 (*) ~191 (') ~232 (") ~266 (^)

Table V
COVERAGE LIMIT DUE TO THE DIFFERENT RECEIVER CAPABILITY (STANDARD (*), ENHANCED RECEIVER FOR ONE ('), TWO ("), THREE (^), INTERFERING SIGNALS).

this means that if only the preamble is free of interference and the data-block has zero or one superimposed signals, the message can be considered free of interference because the interference can be managed and solved [9]. In the same manner also the interference with 2 or 3 replies can be modeled. Table V shows the resulting coverage area (due to the capacity of the channel) for different scenarios.

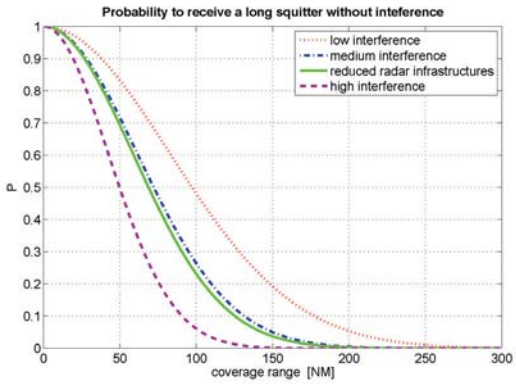

Figure 5. Probability of receiving one long squitter without interference.

In the Table V it is possible to see that the capacity of the channel (i.e. the number of aircraft in the coverage of the sensor) is the most important factor that limits the system's performance, only using enhanced receiver is possible to achieve a coverage area range of 136 NM for a single reply ($P_D = 0.9$) or 232 NM for 9 replies (at least 1 reply every 10 seconds).

The last system parameter to be investigated is the link budget. Staring from the Friis equation, it is possible to change the coverage area choosing the appropriate antenna for the receiving station.

In figure 6 the ideal vertical section of the radiation pattern of an HAP ADS-B antenna (from 20 Km of altitude) is shown, it is computed with the same formulas used for computing the satellite ideal radiation pattern.

Different types of antenna have been analyzed from a 20 Km high HAPS, in particular:

- Dipole antenna;
- Vertical array of 4 dipoles with about 8 dBi of maximum gain that allows 60 NM of coverage;
- Vertical array of 6 dipoles with about 9 dBi of maximum gain that allows about 120 NM of coverage.

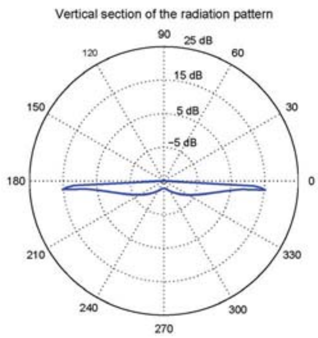

Figure 6. Ideal vertical section of the radiation pattern of a ideal HAP ADS-B antenna.

In table VI the coverage due to the antenna configuration are reported and the considered capacity scenario are also compared with the antenna coverage. It is possible to see that existing configurations for HAP application in high traffic or low traffic condition match also with the proposed antennas.

V. Innsbruck WAM - Simulation Trials

To understand the capability of an HAP ADS-B receiver some simulations were done. In particular the real Innsbruck WAM system was supposed to be enhanced with an HAP platform. The actual Innsbruck WAM system consists of 9 stations (Figure 7): 3 transmitting and receiving station, 5 receiving -only, and one reference transponder (Patscherkofel station) [10]. Considering the position of all the sensors (Table VII) we add an HAP (204 km of altitude) at coordinates: (47°16'N, 11°23'E).

It is possible to understand the performance of these systems (with or without the HAP receiver) using the Cramer Rao

FRUIT level			105000	55000	50000	27500
Probability to receive a interference-free reply	A long squitter	Antenna	A	A	A	A
		Coverage permitted by the antenna	50/60 4NM	50/60 NM	50/60 NM	50/60 NM
		Coverage permitted by the receiver	~19 NM	~27 NM	~28 NM	~37 NM
	At least one squitter in four seconds	Antenna	A	B	B	B
		Coverage permitted by the antenna	50/60 NM	110/120 NM	110/120 NM	110/120 NM
		Coverage permitted by the receiver	~47 NM	~65 NM	~68 NM	~92 NM
	At least squitter in ten seconds	Antenna	B	B	B	B
		Coverage permitted by the antenna	110/120 NM	110/120 NM	110/120 NM	110/120 NM
		Coverage permitted by the receiver	~73 NM	~100 NM	~105 NM	~142 NM

Table VI
PROPOSED ANTENNA FOR THE CONSIDERED TRAFFIC SCENARIOS. A:{DIPOLE, AVIONIC ANTENNA}, B:{4 OR 6 ARRAY OF DIPOLES)}.

Position	Latitude	Longitude	Altitude [m]
Patscherkofel	47°12′31.4″	11°27′36.7″	2245
Flughafen	47°15′28.2″	11°21′9.8″	616
Hafelekar	47°18′46.4″	11°23′10.3″	2336
Rangger Köpfl	47°14′37.4″	11°10′51.9″	1910
Tulferer Berg	47°15′11.6″	11°33′20.9″	1360
Hecher	47°19′15.7″	11°44′30.8″	1895
Kanzelkehre	47°24′34.6″	11°47′15.1″	1006
Telfs	47°18′11.9″	11°04′23.1″	605
Gschwandtkopf	47°18′49.3″	11°10′39.5″	1459

Table VII
WAM INNSBRUCK- STATIONS COORDINATES [10].

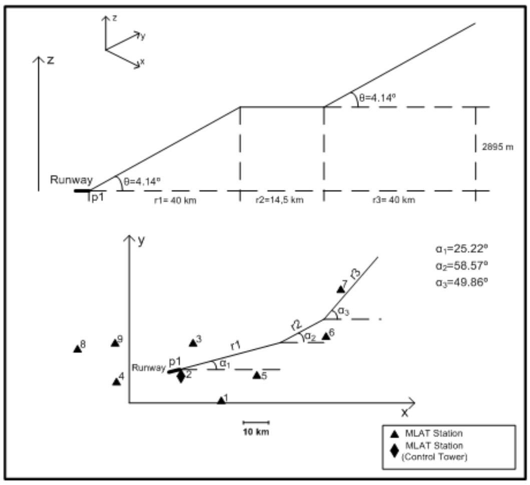

Figure 7. Innsbruck WAM real layout and taking off path.

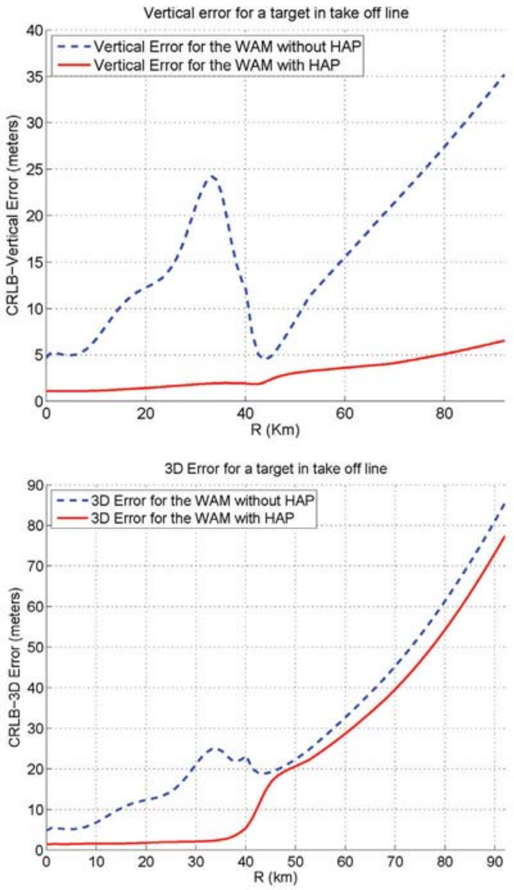

Figure 8. Comparison of CRLB for a taking off airplane in the Innsbruck scenario with or without one HAP over the airport.

Lower Bound (CRLB) method described in [11], considering a TOA accuracy of:

$$\sigma_{TDOA,i}(\theta) = max\left\{\frac{1}{B\sqrt{2SNR}}, 1\right\} [meters] \quad (12)$$

Where B is the receiver bandwidth supposed equal to 20 MHz and SNR the signal-to-noise ratio.

The CRLB was computed along the taking off path reported in Figure 7 and the lower bound for Vertical ($\sqrt{\sigma_z^2}$) and 3D error ($\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$) are reported in Figure 8.

Figure 8 clearly shows the benefits introduced by using the HAP over the airport. The height of the HAP allows improvement of the Dilution Of Precision (DOP) and therefore of the system accuracy (e.g. 3D position error below 5 meters until 40 Km of coverage). This kind improvement cannot be obtained with any type of ground stations.

VI. Conclusion

The paper shows that it is possible to develop a low cost ADS-B Mode S receiver to be installed in a HAP with a very simple antenna and receiver. The problem of the coverage of this kind of station was discussed and different solution have been proposed for high density and medium density traffic. A coverage radius greater than 140 NM (limited by the capacity of the channel) can be achieved with all the advantages due to the fact that we have a flying receiver station. The advantages of having a flying station is very clear when the station is a part of Multilateration system (Local or Wide area), in this case the performance increases a lot with respect to the classical deployment due to the high decrease in the value of the vertical DOP, as shown with simulation for the Innsbruck WAM system. The aim of the paper was to study the possibility to develop a small, not heavy and cheap system to be used as a *piggy-back* system over the primary application of the HAP (telecommunication or satellite navigation applications) but the results call for a study for the development of a more complex system with a multibeam antenna that can manage more than one independent coverage area (this is possible because the maximum geometrical coverage is about 500 NM) with an ad hoc designed platform with a big array antenna and a multichannel receiver.

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