INSTALLATION AND FLIGHT INSPECTION OF HEIGHT MONITORING STATIONS (HMU) IN EUROPE

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1 - BACKGROUND

The inaccuracy of traditional altitude measuring chains for aircraft increases with the altitude. Up until the 1960s, the performance of commercial airliners in service did not allow them to reach very high altitudes in flight, and a conventional vertical separation of 1000ft minimum was fixed. It was entirely compatible with the altimetry errors observed. All this was put into question with the appearance of the first high-performance jets and/or turboprop aircraft. It is for this reason that, as from 1966, ICAO adopted the following rule :

- From the transition altitude up to flight level FL 290: the vertical separation minimum remains at 1000 ft. Above level FL 290 and up to FL 410: the vertical separation minimum is fixed at 2000 ft.
- This allows levels FL 310, 330, 350, 370, 390 and 410 to be used. These six levels are reduced to three available levels with application of the quadrant rule. Flight levels above FL 410, which are only accessible to Concorde flights and a few other rare high-performance aircraft, also have a vertical separation minimum of 2000 ft.

The idea of reducing the vertical separation minimum to 1000 ft (RVSM: Reduced Vertical Separation Minimum) instead of 2000 ft between FL 290 and FL 410 appeared towards the late 80s. The reasons were both to optimise aircraft fuel consumption of course, and also to improve the capacity of the airspace. Allied to this factor is an improvement in the accuracy of altimetry measurements on the new generations of aircraft.

The vertical separation minimum in effect since 1966 generally only provides three possible levels between FL 290 and FL 410 for a given route. It appears that doubling the levels available provides the possibility of giving the aircraft a choice of flight levels to allow them to choose the best option in terms of altitude and route followed, which varies according to the influence of the wind.

At certain peak periods the flight levels are saturated in the European upper airspace. The implementation of RVSM will certainly not absorb the currently increasing traffic on its own, (approximately 6% per year before 11 september 2001), however it will contribute to a marked improvement.

There should be a resulting improvement in the capacity of the airspace: a total of six additional flight levels will be available (300, 320, 340, 360, 380 and 400). However, this does not mean that the quantity of air traffic could double in the volume under consideration!

On 27 March 1997, ICAO authorised limited implementation of RVSM between FL 330 and FL 370 in the area of the North Atlantic Minimum Navigation Performance Specifications (NAT MNPS). This authorisation was extended between FL 310 and FL 340 as from 8 October 1998.

Further to this implementation, the following improvements were observed:

1. 50% of the fuel penalties attributed to the NAT system itself were eliminated (these penalties are based on the routes, weather forecasts, flight levels and congestion of the system).
2. It was possible to publish 25% fewer compulsory routes, which means more flexibility for airlines in the choice of other routes.
3. There was a 5% increase in flights authorised to use both the altitude and route desired
4. In view of these benefits, as from 24 February 2000 ICAO authorised RVSM to be used in the Ocean Pacific area. Extension of RVSM to the West Atlantic area of the New York FIR portion (WATRS) was planned as from 1 November 2001, and finally to the Continental European area as from 24 January 2002.

In the oceanic areas these applications were fairly limited, firstly in view of the small volume of traffic, and secondly because of the specialised nature of the type of aircraft (long-haul flights only) and airlines. On the other hand, in the Continental European area this operation affects a large population and is decisive for future applications (North America, the Far East, etc.) moving towards a possible world-wide generalisation.

The operational implementation of RVSM in Europe, as done previously in the oceanic areas, has required a large number of conditions to be met. Among the most important ones, two major ones can be identified:

- operational approval of aircraft,
- setting up an altitude hold monitoring system.

2 - OPERATIONAL APPROVAL OF AIRCRAFT

On this point, which is not the main subject of this article, we would recall that operational approval, which is subject to the sovereignty of the States of registration, requires the aircraft to be certified, and for the operators to set up a training programm for crews, as well as a system for updating the various manuals concerned (Operation Manual, Maintenance Manual, etc). Certification is not a difficulty for recent generation aircraft such as the A320, A330, A340, B777, etc. On the other hand, it can require major technical modifications to be carried out for certain types of aircraft, even as far as installing an Air Data Computer system (ADC) on some of the older generations. However, the North Atlantic experience has shown that the average operational gains allowed a rapid return on investment for the operators (not more than one year).

For groups of aircraft, of which the design and manufacture are nominally the same in all aspects that may affect the accuracy of altitude hold performances, ICAO recommends that the Minimum Aviation System Performance Standards (MASPS), verified during the certification process be as follows :

- the Total Vertical Error (TVE) does not exceed an average of 80 ft (25 m) ;
- the standard deviation is less than (92-0.004z2) for $0<z<80$, z being the average TVE, in feet, or (28-0.013z2) for $0<z<25$, when z is expressed in metres ;
- and the components of the Total Vertical Error have very specific characteristics.

For aircraft not belonging to a group, i.e. those with unique altimetry system characteristics, the values are slightly different, particularly the aircraft ASE, which must not exceed 200 ft (61 m) in all flight conditions.

These ICAO technical recommendations have been transcribed in Europe in the airworthiness regulations (document JAA TGL 6), which is the applicable document for certification.

Normally, aircraft that do not satisfy these requirements are not authorised to fly in an airspace where a reduced vertical separation minimum is applied.

3 - SETTING UP OF MONITORING SYSTEMS

One of the difficulties of RVSM is the level of confidence that can be given to the aircraft certification by the States of registration, as well as maintaining the certified characteristics over time.

For this reason, ICAO recommended setting up a monitoring system in order to determine to what degree aircraft measure up permanently to the altitude hold performances.

This monitoring system has two purposes:

1. In the period preceding the effective implementation of RVSM, i.e. as long as flights have a vertical separation of 2000 ft, the monitoring systems check the altitude hold accuracy of aircraft that are already certified. These inspections contribute to the safety case. It had to be shown that spacing at 1000 ft in the upper airspace does not deteriorate the current safety level of flights in Europe. The final decision to implement RVSM on 24 January 2002, or to postpone it was dependant on the results of this study.
2. In the period following implementation of RVSM, the monitoring systems have to ensure that there is no degradation in performances of altitude hold accuracy for aircraft authorised to fly in the European Continental RVSM airspace, through a lack of maintenance or for any other reason. It was felt that this monitoring phase should last for seven years, meaning until January 2009. At the end of this period, the monitoring systems should, in principle, be withdrawn from service.

For the European Continental RVSM, Eurocontrol was requested by the European Civil Aviation Conference (ECAC), an emanation of ICAO, to set up this system.

The monitoring system is composed of stations fixed to the ground, named HMU (Height Monitoring Unit). However, as it is illusory to think one can succeed in monitoring 100% of the fleet, the HMU is completed by an individualised monitoring system named GPU (GPS Based Monitoring Unit). This is installed on board certain carefully selected aircraft, which are representative of the categories not well monitored by the ground monitoring system. This system was developed by ARINC for the NAT RVSM. The principle of a GMU is simple. It consists of a digital recording of the GPS altitude of the equipped aircraft, expressed of course in the WGS84 reference system. From these recordings, an analysis is carried out a posteriori on the ground to determine the altitude hold deviations.

4 - PRINCIPLES OF MEASUREMENT BY TRANSPONDER MULTILATERATION

The principle of the HMU is to measure the geometric height of each aircraft and to provide this height, together with the aircraft identification and its assigned flight level, to a computer named TMU (Total Vertical Error Monitoring Unit), which sends the data it has to a unit located in Brétigny/Orge (Eurocontrol Monitoring Cell).

An HMU station is therefore a unit comprising :

- a sub-assembly composed of a central HME computer which determines the x, y, z position of the aircraft, the TMU computer, and systems for communication with the Monitoring Cell;
- several sub-assemblies (at least four) which are the measurement stations sited in such a way as to satisfy the above requirements.

The measurement station is a transponder multilateration sensor that detects mode A, mode C and mode S replies from the aircraft situated in its detection area. The arrival times of each reply are dated, and using an algorithm, the HME computer calculates a 3D position without any co-operation required from the aircraft or its crew (the transponder works anyway).

When an aircraft enters the coverage area of an HMU, the closest ground receiver (measurement station) starts to detect and extract the reply codes from the transponder (mode A, mode C and short squitter messages giving the mode S address if it is equipped). Normally this occurs at a distance of 70 NM, well beyond the limits of the radioelectric horizon at the flight levels concerned.

The same thing happens for the other measurement stations when the aircraft enters their coverage area.

At the measurement station, the transponder replies received go through a complex process including, in particular, rejection of the effects due to multipaths or to garbling, and extraction by statistical methods (not all replies are needed to elaborate a position).

Time stamping of the pulses deemed to be correct is carried out by each measurement station, using the GPS signal. Since this includes inaccuracies as the time information can have a difference of a few nanoseconds on a cycle of one second on average, a Cesium atomic clock is used which will provide the required accuracy in the short term.

After that, this information is sent to the central computing station. The TMU computer needs valid data from at least four stations in order to elaborate an x, y, z position.

It is to be noted that there is a difference in design between the Nattenheim-Geneva system, built by the British firm Roke Manor Research, and the one at Linz built by the Czech firm ERA. At Linz the pulses are not time stamped on the measurement site, but sent directly to the central computing site, which does the time stamping.

The code values statistically retained are sent to the central computer at the rate of 1 Hz and this is what decides which transponder replies are received by at least 4 measurement stations and can be used to calculate a position from the algorithm elaborated by the manufacturer.

In order to measure the Total Vertical Error, the altimetry system error and the assigned altitude deviation, the ground computer needs to know the true geometric altitude, the geometric height of its assigned altitude, the altitude sent by the transponder and the altitude indicated in the cockpit.

In the case of the HMU, the hypothesis is made that the correspondence error is null, consequently the technical flight error is equal to the assigned altitude deviation. In other words, the altitude sent by the transponder is equal to the altitude indicated in the cockpit.

The geometric height of the assigned altitude is a parameter that the computer in the central station elaborates from meteorological data supplied by the World Met Office located in the United Kingdom. From a network of observations made over the whole of Europe, they transmit the geometric heights that have been forecasted according to a previously defined grid, which includes the HMU coverage areas. These are valid for 24 hours and updated every 4 hours. In actual fact, they are sent, after automatic analysis, to the HMU stations by the Eurocontrol Centre in Brétigny every 6 hours.

The processing chain of the HMU central station functions in the following way :

- the HME computer supplies the true altitude of the aircraft from data received from the measurement stations ;
- the TMU computer (Total vertical error Monitoring Unit) evaluates the errors (Total Vertical Error and deviation from the assigned altitude), using the previous data, the flight plan data and meteorological data.

The monitoring cell in Brétigny studies these results to prepare the safety case requested by ICAO (International Civil Aviation Organization). They carry out the necessary investigations with the users of aircraft that pose a problem.

The aim of the altitude hold monitoring system is, of course, to cover the largest possible number of aircraft using the airspace situated between FL 290 and FL 410.
For the NAT airspace, two HMU measurement stations have been installed at the entrance points of the airspace concerned (Strumble in Wales and Gander in Newfoundland). Taking into account the specific character of the airspace and the existence of a transition area, which is unavoidable, it was not difficult to determine the location of these sites.
For the Europe area, the choice was rather more complicated. Studies started in 1996.
The number and position of the HMU stations to be installed depends directly on the proportion of traffic to be monitored.
A study was carried out on the air traffic density established from the flight plan information available at the CFMU.
It has to be noticed a correct correlation between the density of air traffic areas and the European 'economic banana'.
The Frankfurt region shows the highest density (30840 flights). The calculations show that if one single HMU were installed in this region, it would monitor practically half of the total fleet. The addition of a second station in the Geneva region would reach 60%. A third station further East, in Austria, would take this figure to 65% by introducing a wider diversity in the types of aircraft and operators (flights towards the Middle East and Far East).
On the other hand, the siting of additional stations would not increase the percentage affected to any large extent, and to cover all of the fleet a very large number of stations would be needed (approximately a hundred), which is economically unrealistic.
The number of three stations installed in the regions mentioned above therefore seemed to be a good compromise. However instead of Frankfurt, which is a congested region from a radioelectric point of view, it was the Nattenheim region, located about a hundred kilometres to the West which was finally chosen.
The specifications for each of the stations were fixed as follows :

- Coverage area: circle with a radius of 45 NM.
- Availability: 24 hours a day.
- The sections of air routes monitored by the station must have a minimum length of 25 NM.

5 - DESCRIPTION OF THE HMU STATIONS ARCHITECTURE IN GENEVA

Once the number and location of the HMU stations had been decided (i.e. the sites of Linz, Nattenheim and Geneva), the next decision was to establish the optimum architecture and particularly the geographical layout, of each of the measurement stations. Here we will only examine the Geneva station on which STNA worked directly.

The Lémanique basin surrounding the city of Geneva is a plain which extends towards the North-East and which is edged by a chain of mountains to the North (Jura), to the South (Chablais) and to the West (Revermont and Bugey).

The area allows very easy installation of a central system (HME and TMU computers) in the Sky Guide ' NAG ' building at Geneva Cointrin airport. However, the measurement stations necessarily have to be installed in the neighbouring terrain, which is mountainous.

Several criteria need to be taken into account in the choice of sites for the measurement stations:

a) High points, which meet the required coverage specifications, but are nevertheless easily accessible for installation and maintenance.

b) Sites already having appropriate installations if possible with, in particular, an electric power supply and adequate security.

c) Sites with no radio disturbance, particularly in the ATC transponder and GPS receiver radio-frequency ranges.

d) Possibility of transmitting data from the measurement station to the central station. The dedicated telephone line solution was quickly abandoned in favour of the solution of microwave transmission. This decision heavily influenced the choice of sites since it requires either line-of-site ranges between the stations and the NAG, or the installation of relays.

After much long and difficult preliminary work, five sites were chosen for the measurement stations. Other sites initially considered were eliminated since they did not comply with the above requirements. The sites selected are described below and are shown on the map :

1. Le Cunay (Switzerland) altitude 1609m: this is a site on which there had previously been a Sky Guide remote VHF transmission centre. This site already had a microwave data-link with NAG. It is accessible in winter after removal of snow.
2. Septmoncel (Jura department, France) altitude 1157 m: this is a power transmission pole operated by TDF. This site corresponds well to the specifications. It was however necessary to take down a neighbouring power transmission pole which interfered with the microwave data-link. The site is accessible practically all year round.
3. Chevreaux (Ain department, France) altitude 637 m: this is a communications tower operated by TDF. This site corresponds well to the specifications and there was only one difficulty: that was the question of heating the HME cabinet installed in very large, rather cold, premises at the bottom of the tower. The problem has now been solved by installing appropriate partitions.

4. Le Grand Colombier (Ain department, France) altitude 1443 m: this is the site where the DGAC's CBY VOR is already located. This site, which is interesting from a geographical point of view, required quite a lot of civil engineering work to set up the HMU measurement station (installation of a shelter, electric power supply to the shelter, installation of two power transmission poles – one for the HMU and one for the microwave data-link). There are several drawbacks to this site: access is difficult in winter (in the worst case the only solution is by helicopter); risk of disturbance of aircraft transponder replies due to the DME station sharing the site with the VOR; and the low temperatures which could be reached in winter if there is a power cut, which may affect the atomic clock.
5. La Pointe des Brasses (Haute Savoie department, France) altitude 1502 m: this is at the top of a medium mountain ski resort. On the site there was previously a private telecommunications relay belonging to a private local area network (ambulance service). The site needed repair of the underground electric power supply, replacement of the old power transmission pole with a larger one, a great deal of thermal insulation of the existing premises by exterior siding, and particularly meticulous lightning protection. The problem of access in winter was solved by using snow scooters rented from a local firm.

The microwave data-link between the Pointe des Brasses, Chambéry and the NAG building was made by using a relay located in a TDF Communications Tower in Mont Salève.

The link between Septmoncel, Chevreaux and the NAG building was made by using a relay site on the Dole radar site in Switzerland. In fact, the parabolic data-link antennae were installed in an old faired direction finder antenna tower.

6 - FEATURES OF EQUIPMENT AND FACILITIES

a) Measurement stations

The measurement stations include a rack installed in premises which have a heat setting and a 220V electrical power supply, including

- the transponder receiver
- the Ethernet link system
- the frequency reference system
- the atomic clock
- the GPS receiver
- the telecommunication equipment (microwave data-link transceiver)

Regarding the antennae, the system has a DME type antenna for reception of transponder replies, a GPS antenna and a lightning grounding dissipator.

b) Microwave data-links

The microwave data-links use transceivers made by Ericsson with Andrew antennae.

The data-link has a capacity of 2 Mbps, it operates on a frequency of 7 GHZ, with a power of 2W. The transborder link required special negotiations between the French and Swiss authorities. On the French side, the negotiation was carried out by the BMNF (the French military frequency office) because of the transborder aspect.

7 - RESULTS

At the end of the year 2000, all the work was finished on the three HMU sites and flight inspections could be carried out in order to validate the measurements.
These tests provided evidence of the fact that the system had the required level of accuracy within the coverage volume.
A few areas show less accuracy, either because of the geometrical configuration of the measurement stations or because of antenna problems that were revealed and are presently being resolved. In particular, in the case of the Geneva HMU, the altitude differences in the measurement stations can explain certain areas with less accurate results (more abundant multipaths).
The Geneva, Linz and Nattenheim stations respectively were monitoring approximately 600, 450 and 650 aircraft per day at mid 2001.
Note : It can be noted that the TMU provides Radar type information, which is therefore not so rich in detail. Furthermore ERA, the firm that developed the Linz system, is considering supplying the same sort of system to be used for radar to one of the countries in the Mediterranean area.
There is an unquestionable economic advantage, the cost of this type of system being approximately one tenth of that of a radar. It does, however, require overflying aircraft to be 100% equipped with mode S.

8 - FLIGHT INSPECTIONS OF THE HME STATIONS

8 - 1. The Challenge

After deployment of the HME stations at the three sites of Nattenheim, Linz and Geneva, Eurocontrol wished to check that the performances of these stations met the requirements of the specifications given to the manufacturers. This was also necessary to certify the system.
A European call for tender was put out.
STNA made a bid, calling upon its partner, SEFA, for the 'aircraft operation' aspect.

The specifications can be summed up as follows:

- The HME system measures the height of the entering aircraft overflying the coverage area, using the WGS 84 reference system,
- The measurement error is to be evaluated with sub-metric accuracy in the service area: a circle of 45 NM centred on each station for flight levels between FL 290 and FL 350,
- The analyses of the results and conclusions are to be carried out by Eurocontrol.

The Aircraft used for the flight inspection is capable of flying at FL 350 with an autonomy of 5 h 30 min, while delivering a trajectory reference based on the VP-DGPS system, which is more than sufficiently accurate. The system is integrated in the CARNAC 21 calibration bench, developed by the company SAGEM.
STNA, having made a bid using this aircraft at a competitive cost, won the contract.

8 - 2. Mission

Eurocontrol defined the flight profiles, as the measurements had to be made at night (after midnight local time) in order to minimize ATC constraints.

Three flights were planned over the Nattenheim and Linz stations at FL 290, 330, and 350. After the first flight the lower levels, which were not of great interest, were abandoned in favour of the higher levels. In addition, it was decided also to inspect the Linz station, which had been already calibrated by another competitor.

Finally, further to some tuning and operations problems at the Nattenheim and Geneva stations, some additional flights were carried out.

The calendar was scheduled as follows: (for a total of 56 h 38min of flight):

Nattenheim	21/22 September 2000	2000 FL 290 and FL 350
Genève	12/13 October 2000	FL 350
Linz	16/17 October 2000	FL 350
Nattenheim	25/26 October 2000	FL 350
Genève	30/31 October 2000	FL 350
Genève	04/05 January 2001	FL 350

The aircrew was composed of two pilots, the STNA mission leader and an observer from Eurocontrol.

There was also an engineer from STNA on the ground taking care of the implementation and monitoring of the VP-DGPS beacon.

The trajectory reference system (GPS accuracy differential) was obtained in the WGS 84 reference system both in real time and also in deferred time by using a 'backward and forward' post-processing system. The average accuracy readings obtained were respectively 30/40 cm and 8/12 cm.

This measurement campaign demonstrated the capabilities of the VP-DGPS trajectory reference system in terms of range.

8-3. Results

The results were presented in the form of files and graphs using 'Excel'. Reports and CD-ROMs assembling the raw data, processing information and tabulation were provided.

The aim was to calculate and show the errors at each station for each flight segment.

As the HME system is based on a multi-distance calculation of the aircraft position, an accuracy degradation factor according to the distance from the centre of the system had to be taken into consideration. A graph of error according to distance was therefore added.

The interpretation of the results and conclusions was left in the care of Eurocontrol.

GLOSSARY

ADC	Air Data Computer
CFMU	Central Flow Management Unit
HMU	Height Monitoring Unit
HME	Height Measurement Equipment
NAT	North Atlantic region
ICAO	International Civil Aviation Organization
RVSM	Reduced Vertical Separation Minimum
TMU	Total vertical error Monitoring Unit
VP-DGPS	Very Precise -Differential Global Positioning System
WGS-84	World Geodetic System 84