Chapter 6 – DGPS PERFORMANCE ANALYSIS

6.1 INTRODUCTION

During flight test activities performed with DGPS, data was analysed with the aim of assessing the performance of the system in flight. A preliminary assessment was carried out on the MB339-CD aircraft. In this phase, only a qualitative evaluation was made in order to verify the performance of both the ASHTECH and the TRIMBLE GPS receivers during high dynamic manoeuvres (mainly in terms of data quality and continuity). Once the dynamic performance of the systems was verified, one of them was selected (i.e., ASHTECH Z-12) and used for the final in-flight evaluation carried out mainly on the TORNADO-IDS aircraft. During these activities the in-flight manoeuvring limitations of the system were investigated and additional instrumentation/analysis was used in order to determine the accuracy provided by the ASHTECH system in flight.

6.2 MB-339CD DGPS IN-FLIGHT INVESTIGATIONS

During the MB-339CD avionics flight trials, performed by AERMACCHI S.p.A. and the Italian Air Force Flight Test Centre, an in-flight evaluation of DGPS was carried out. The aim of this assessment was to compare the performance of the TANS and the ASHTECH receivers (both installed in the prototype aircraft) in a dynamic environment, in order to select the system with the best performance for employment in future activities. Particularly, the assessment focused on the data quality and continuity provided by the two GPS receivers during execution of low, medium, and high dynamics manoeuvres and re-acquisition times after GPS data losses. Therefore, no dedicated accuracy tests were performed in this phase, except an initial evaluation of DGPS altitude data. The results of the MB-339CD in-flight investigation are reported in Annex C.

6.3 TORNADO-IDS DGPS IN-FLIGHT INVESTIGATIONS

Analysing several data from the MB-339CD DGPS test campaign and other flight test activities performed with DGPS instrumented aircraft (i.e., F104 ASA-M, AM-X, EF-2000, MB-339A, TORNADO-IDS, etc.), it was clear that the main disadvantage of the GPS is its vulnerability to signal losses caused by satellites masking and low SNR. Therefore, during some TORNADO-IDS flight trials these problems were thoroughly investigated, to test the capability of the on-board GPS receiver to reacquire satellite signals and to provide TSPI even with degraded satellite constellations. In order to assist in the investigation a simulation tool was used to evaluate the global masking effect due to antenna and aircraft body masking. A preliminary assessment was also carried out of Doppler effects influence on data quality. Moreover, appropriate procedures were defined for the optimal use of DGPS (continuous positioning data gathering with reduced satellite signal losses) in flight test activities with high performance aircraft. Finally, an assessment of DGPS data accuracy was carried out, by comparing the positioning data provided by DGPS with other known references (i.e., radar altimeter, laser range finder and optical tracking system).

6.3.1 Masking and SNR Investigation

The main reasons of interruption of the satellite signals in flight tests activities with DGPS are the shielding of the GPS antenna by the aircraft body (especially the wings and the tails) during turns, and the reduction of Signal-to-Noise Ratios (SNR) during high dynamics manoeuvres. In order to investigate GPS antenna masking and the effects of SNR reduction, a dedicated analysis as carried out on TORNADO-IDS. The detailed results of the investigation are reported in Annex D.

6.3.2 Flight Test Mission Planning and Optimisation

As a result of the Masking/SNR analysis some recommendations were formulated in order to optimise the use of DGPS as a datum in flight test missions (i.e., in order to reduce signal loses). In particular, the following criteria's should be taken into account:

- It should be always assured the visibility of at least four satellites with an elevation near 50°;
- The maximum bank angle allowed is 50°;
- A stabilisation of at least 20 seconds should precede and follow the significant flight phases;
- The heading variations should be as gradual as possible;
- It should be minimised the number of left turns performed with an initial heading ranging from 45° to 135°, and the number of right turns performed with an initial heading between 225° and 315°; and
- The distance between the aircraft and the ground receiver should be always less than 200 NM.

These restrictions, of course, imply operational limitations that reduce the spread of possible DGPS applications in the flight test environment. Further details are given in Annex D.

6.3.3 Doppler Effect

During the initial phase of GPS evaluation it was noted that the reacquisition time after loss of one or more satellites signals could be up to 40 seconds, depending on flight conditions and satellite constellations. We wondered whether and how the Doppler effect could affect the receiver capability to track the carrier phase and rapidly reacquire the signal after a loss.

The typical equation used to express the Doppler shift associated to a certain instantaneous velocity along the line of propagation of the signal, is the following:

$$\Delta f = \frac{v}{c} \cdot f \tag{6.1}$$

where:

Δf = frequency shift;

v = velocity of the receiver;

c = speed of light $\left(3 \cdot 10^8 m \cdot s^{-1}\right)$; and

f = transmitted frequency (in our case 1575.42 MHz).

The Doppler shift directly affects the signal acquisition time of the receiver, both in terms of frequency of the code and frequency of the carrier. In general, the acquisition time increases in presence of Doppler shift as shown in Figure 6-1.

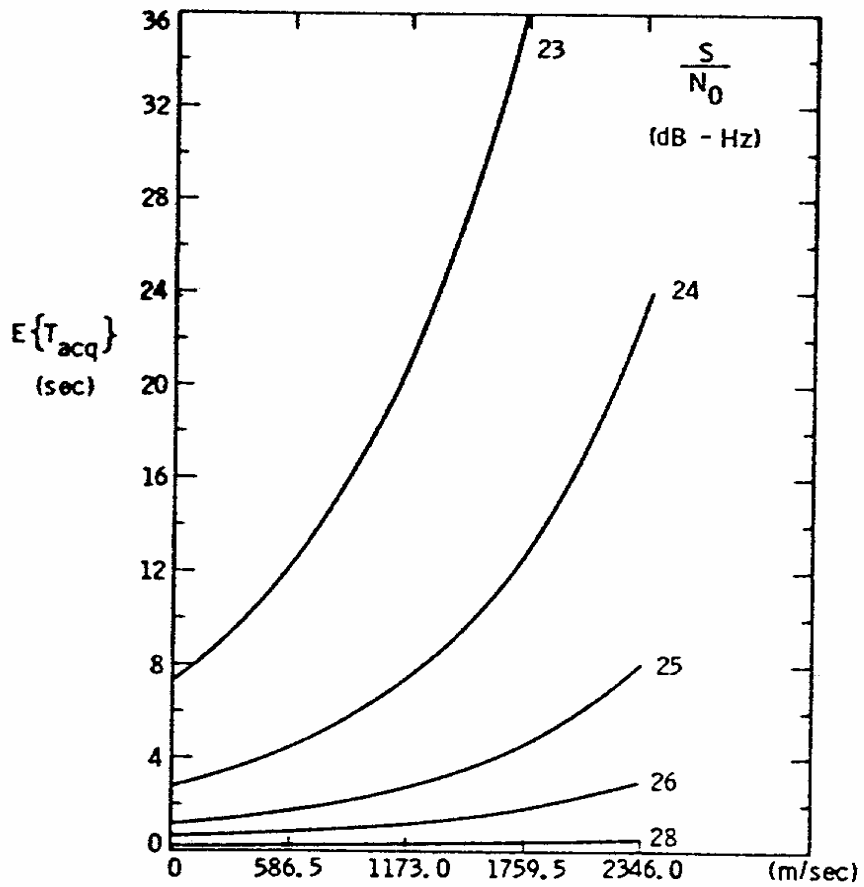


Figure 6-1: Mean Acquisition Time as a Function of Relative Velocity and SNR.

Considering the case of one satellite tracked, the Doppler shift is due to the relative velocity of the satellite and the receiver (i.e., the difference between the projections of the velocity vectors along the satellite-receiver direction). The worst case is, therefore, that of an aircraft flying along the line of sight (LOS) to the satellite, in which the full velocity vector of the aircraft must be used to determine the relative velocity (e.g., with an aircraft flying along the LOS to the satellite at a velocity of 350 kts, the Doppler shift for L1 is in the order of 10 KHz).

The analysis of receiver data recorded during several flights and up to speed of 500 kts highlighted that the Doppler effect causes a frequency shift, with respect to the carrier phase L1, which reaches a maximum value of about 15 KHz. This value can be considered risible with respect to the GPS frequency bandwidth (i.e., about 30 MHz), and the high dynamic characteristics of the PLL (Phase Locked Loop) circuit internal to the receiver guarantee that neither the data accuracy is degraded nor the carrier phase can be lost because of the Doppler shift. Nevertheless, it is hypothesised that the coupling between such frequency shift and the signal reacquisition strategy of the receiver significantly affects the time necessary to get data after a signal loss, even when a good satellite configuration is available.

6.3.4 DGPS Data Accuracy

A comparison of positioning data provided by the GPS receiver and by other airborne sensors or ground tracking systems allowed the evaluation of DGPS data quality and accuracy.

It must be underlined that a proper determination of the errors associated with an airborne navigation system would require a reference datum with an accuracy of a list a factor of 8 to 10 times better. This kind of

reference is obviously very difficult (if not impossible) to be identified in the case of DGPS accuracy testing. The best options available is to use high-accuracy cinetheodolites or laser tracking systems of proven pointing stability, whose quoted accuracy are typically in the order of 0.2 ÷ 0.5 metres. For the TORNADO-IDS DGPS accuracy flight trials, the following position reference systems were used:

- The TORNADO-IDS aircraft Radar Altimeter (R/A);
- Laser range from the Convertible Laser Designation Pod (CLDP) installed on the aircraft; and
- Ground-based optical systems (cinetheodolites).

6.3.4.1 DGPS-Radar Altimeter

A comparison was made between the DGPS-TSPI altitude data and the measurements provided by the on-board radar altimeter, in order to preliminarily assess the DGPS data quality. For this purpose a number of over-sea flight legs were included in the trials.

The ASHTECH DGPS altitude data output was both in the form of geodetic altitude or ellipsoidal height. The height above terrain measured by a Radar Altimeter (R/A) is obviously different from the geodetic height provided by the GPS. Moreover, there is not a fixed relationship between the height above Mean Sea Level (MSL) and the geodetic height. This is due to irregularities of the Geoid (i.e., the equipotential surface defined in the Earth's gravity field which can be approximated, for some practical applications, to MSL).

Flying over the sea, the R/A height approximated the MSL altitude. As the Geoid-MSL separation was unknown, a certain degree of uniformity was obtained flying round tracks over limited sea areas (i.e., there was an unknown bias in the comparison).

Various tests were carried out with different satellite numbers and PDOP ranging from 2.4 to 5. The differences between DGPS and R/A altitudes were measured in the range 3 ÷ 13 metres. Figure 6-2 shows the GPS and R/A data recorded in one of the flights.

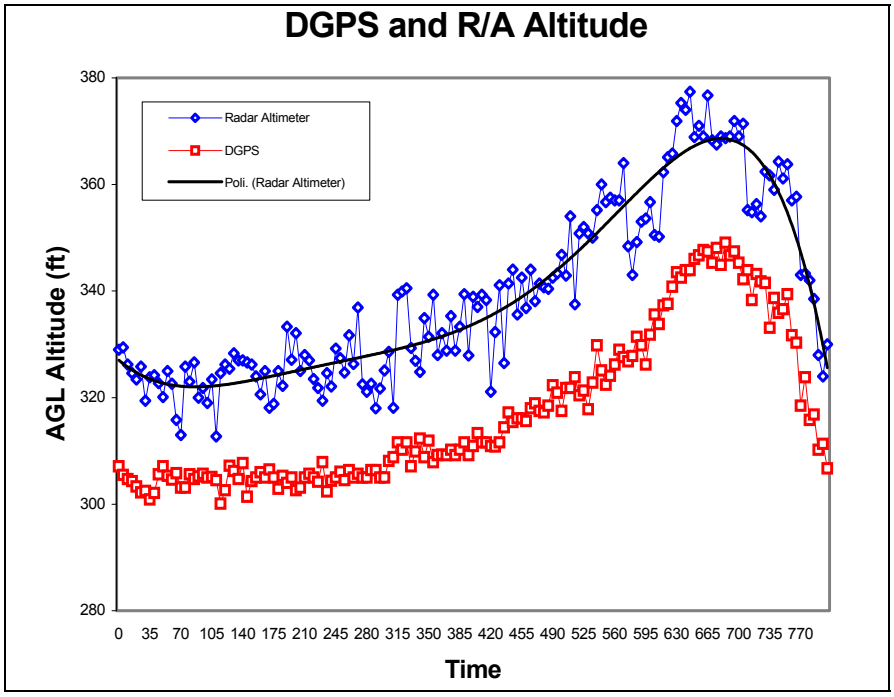


Figure 6-2: Comparison between DGPS and R/A Data.

The R/A data 6th order polynomial fit, shown in the graph, follows quite well the DGPS data trend. The estimated measurement bias was in the order of 7.5 metres. Considering the R/A quoted error of ± 3% (of the height displayed), the results of this preliminary and purely qualitative comparison of DGPS and R/A data were considered satisfactory.

6.3.4.2 DGPS-Laser Range

This evaluation was performed during the TORNADO-IDS flight test activities for integration of the Thomson CLDP (Convertible Laser Designation Pod). These activities were conducted at the Cazaux test range (France).

The CLDP system is designed to provide the aircraft with day and night laser designation/ranging capability, for both cooperative and self-designation attacks performed using laser-guided weapons. The pod is equipped with an internal designation laser operating at 1.064 µm (non-eyesafe region of the spectrum) and may be configured for day-time operation by using a television camera (TV) or for day/night operation by using an IR sensor (IR). The TV configuration may also provide daytime advantages in high humidity conditions. In its subsidiary role, the CLDP can also act as a sensor for navigation fixing including altitude fixing.

As shown in Figure 6-3, both CLDP configurations consist primarily of two sections: an interchangeable front section containing a TV sensor head or IR sensor head, and a common body containing a central section and a rear cooling unit.

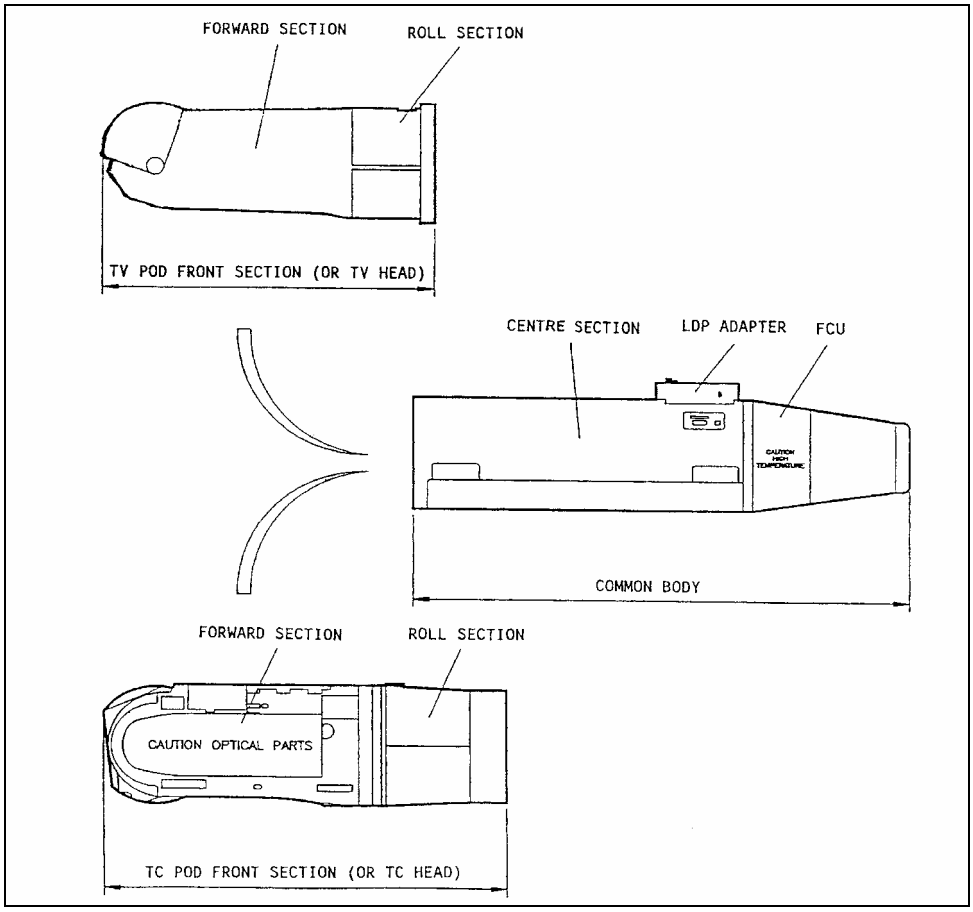


Figure 6-3: CLDP TV and IR Configurations.

In the TORNADO-IDS integration scheme, the CLDP is a non-jettisonable store and is carried on the forward section of the aircraft left shoulder pylon (Figure 6-4).

Figure 6-4: TORNADO-IDS CLDP Installation.

An electrical adaptor installed on the back of the CLDP centre section provides the electrical interface between the pod and the aircraft. The adaptor interfaces with the aircraft computers via a MIL-STD-1553B data bus.

The slant ranges between the aircraft and a fix point obtained by using GPS latitude, longitude and altitude data have been compared with the laser range provided by the CLDP for the same two test points. The satellite constellation for both tests included 5 satellites with a PDOP value of 4. The calculated differences between DGPS and CLDP ranges for distances from the fix point up to 8 km, are shown in Figure 6-5.

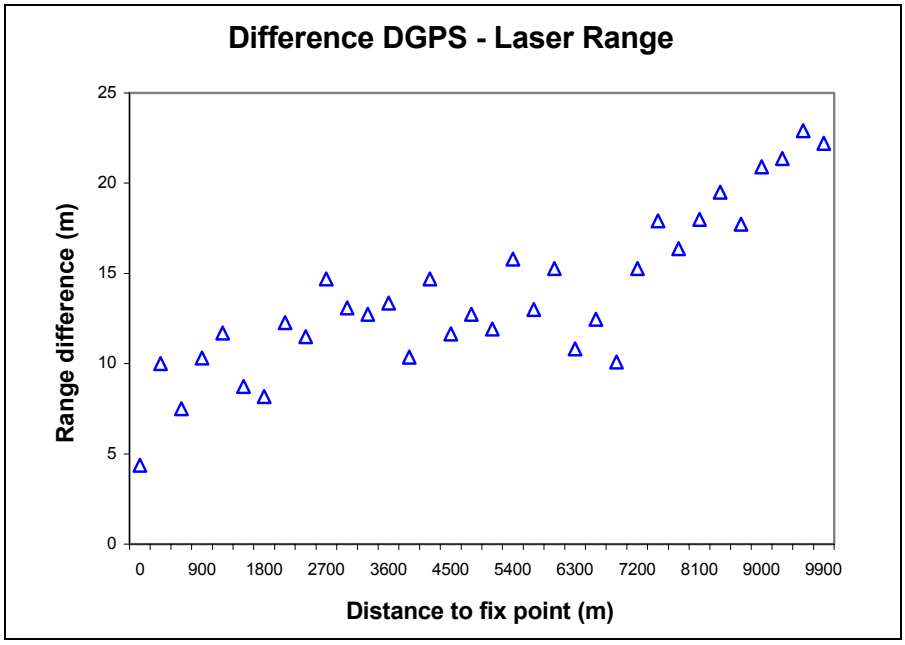


Figure 6-5: Differences between DGPS and CLDP Laser Range.

As shown in the graph, the differences between calculated DGPS range and laser range were below 25 m up to a distance of about 10 km from the fix point. The error increased with distance mainly due to worsening of the range measurements provided by the CLDP (caused by laser line-of-sight instability).

6.3.5 DGPS-Optical Tracking Systems

Some flight trials were carried out in the Sardinia test range (Poligono Militare Interforze del Salto di Quirra) in which cinetheodolites (CITE) were available to provide the required datum accuracy (the nominal accuracy provided by the optical trackers was 0.5 metres).

One of the difficulties encountered in the data analysis of these trials was the difference of the geodetic reference adopted by the two systems (Gauss-Boaga for CITE and WGS-84 for GPS), and the time de-correlation of data (CITE provided higher data rate than GPS). The first problem was solved by using a co-ordinates transformation software, while for the second problem an interpolation was required of the various measurements provided by the CITE in one second (1 Hz was the GPS data-rate).

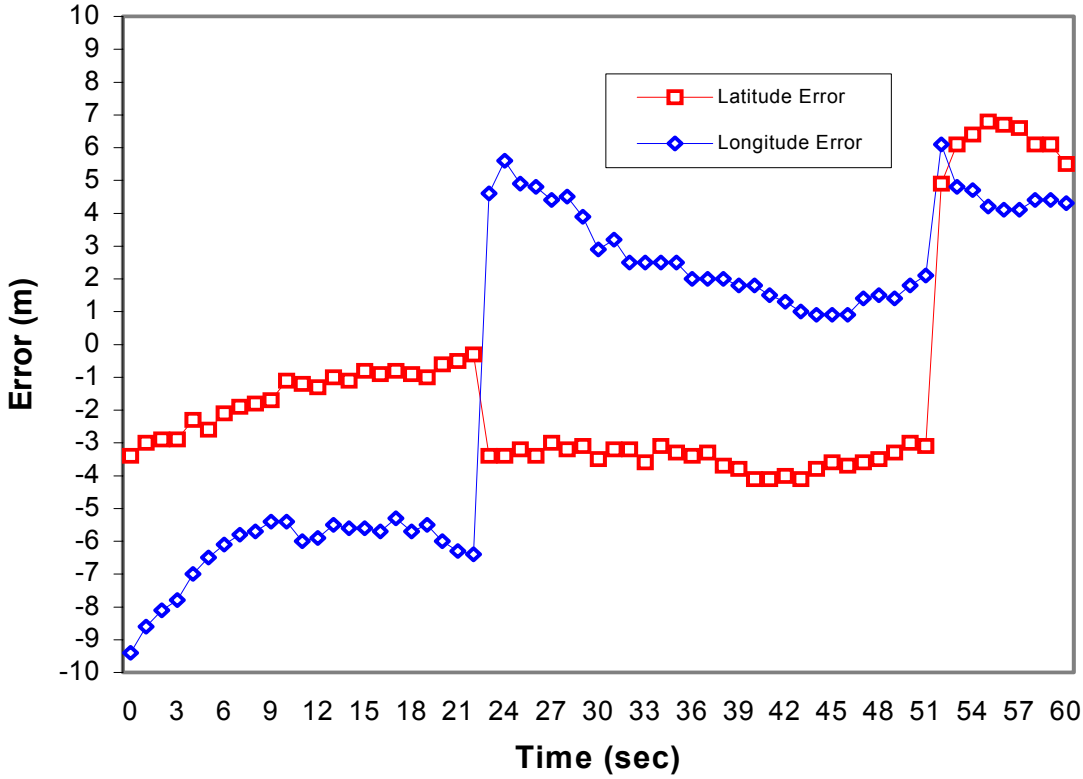
An initial analysis was carried out with data samples collected in five different flights. The accuracy figures so determined were 23.3 m SEP stand-alone C/A code and 6.3 m SEP C/A code differential. These accuracies were comparable to the values quoted by ASHTECH (i.e., 100 m SEP stand-alone C/A code and 3 m SEP C/A code differential), and well inside the limits stated in the DGPS technical specification documents (i.e., 100 m SEP stand-alone C/A code and 10 m SEP C/A code differential).

Another DGPS accuracy evaluation with optical trackers was carried out during the Cazaux activity already mentioned in the previous paragraph. On this occasion, special care was taken to monitoring all factors that could possibly affect the synchronisation between the different sources of data (ground reference station, airborne FTI and cinetheodolites). The calculated spherical errors were in this case 21.7 m SEP for the stand-alone C/A code solution and 5.8 m SEP for the C/A code DGPS solution (Table 6-1).

Table 6-1: DGPS-TSPI Data Accuracy

Errors	Mean (m)	Standard dev. (m)
Longitude	2.772	3.549
Latitude	2.679	2.283
Altitude	3.563	3.979
SEP	5.799	

Figure 6-6 shows two sudden variations of the DGPS errors (latitude, longitude and altitude errors). They both correspond to changes in the configuration of the tracked satellites. However, in the first case (small PDOP increase), the change did not cause a worsening of the overall spherical error, which remained in the order of 6.5 metres. In the second case (greater increase of PDOP), the constellation change caused an evident degradation especially in the altitude and latitude accuracies, giving an overall spherical error of about 14.3 metres.



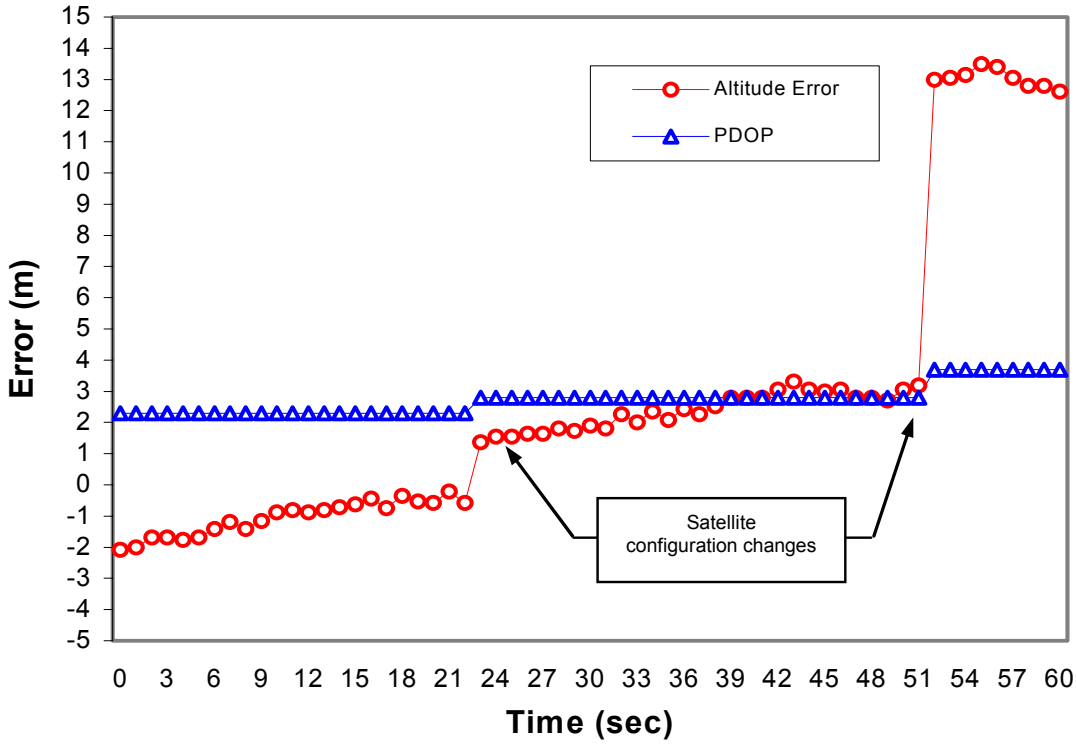


Figure 6-6: Differences between Optical Tracker and DGPS Data.