

# Use of GPS for Precise and Operational Orbit Determination at ESOC

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## ABSTRACT

A GPS Tracking and Data Analysis Facility (GPS-TDAF) has been operating now for three years at the European Space Operations Centre (ESOC). This facility was developed in order to support future ESA projects that involve GPS.

The GPS-TDAF has been used for our participation in the International GPS Service for Geodynamics, as both Operational Data Centre and Analysis Centre, from the start of the IGS. ESOC is currently providing GPS tracking data from 5 ESA ground stations, precise orbits, precise clocks, earth orientation parameters (eop's) and station coordinate solutions.

ESOC is especially interested in the use of GPS for satellite orbit determination. In this context we have analyzed GPS data from two very different satellites,

Topex/Poseidon and Astropas. With the Topex/Poseidon data we have obtained orbits that could be used to support applications that require a very precise orbit (e.g. altimeter). The Astropas data do not have the same quality, but is of high interest because it is closer to the kind of data that will have to be processed in some missions that will use GPS for automated navigation and rendezvous.

The ESOC approach to GPS data analysis is presented, together with the last results obtained for the different applications.

## INTRODUCTION

The Near Earth Navigation and Geodesy Section of ESOC was established to perform the orbit determination and other navigation tasks needed for a series of Near Earth satellites of the European Space Agency. It was foreseen that some of these satellites would have very demanding orbit determination accuracy requirements. Navigation software was developed to include all the measurement types needed for precise and operational orbit determination. The software has been used to its full capabilities with the ERS-1 and ERS-2 satellites, that had stringent orbit determination accuracy requirements to allow for the full utilization of the altimetry data (Ref. 1).

When the software was first developed it was required that it be able to process the most important tracking measurements at that time: microwave ranging, laser ranging, and altimetry. As time passed new tracking methods for Near Earth satellites have been developed: GPS, DORIS and PRARE. These tracking types have also been incorporated into the software. PRARE data from Meteor-3 was successfully processed at our section (Ref. 2) and we are now ready to process ERS-2 data as soon as it is available. DORIS will be used by Envisat and we have already processed data from the Topex/Poseidon satellite (Ref. 3). GPS is foreseen for In Orbit Infrastructure applications like ARP and ATV and for use in small Earth Observation satellites.

We started our GPS activities with the processing of GIG-91 data (Ref. 4). The orbit and geometric parameter estimation software had to be adapted to accommodate the measurement types and processing techniques needed for GPS. This started the development of the ESA GPS Tracking and Data Analysis Facility (GPS-TDAF), that includes not only the data analysis system but also a number of GPS receivers at ESA ground stations and the associated communications and control software and hardware. This paper describes the ESA GPS TDAF and the orbit determination activities that have been performed using the facility.

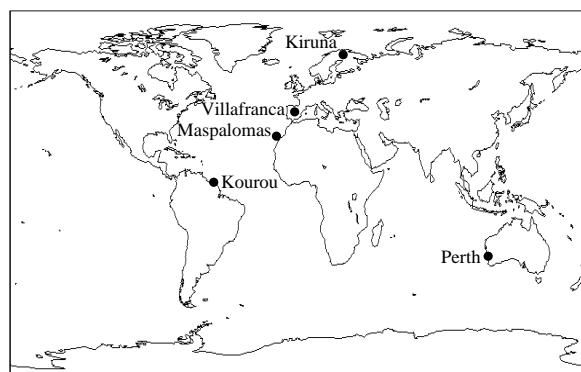
### The ESA GPS-TDAF

The ESA GPS Tracking and Data Analysis Facility started as an extension of our Precise Orbit Determination Facility (Ref. 5) to incorporate GPS measurement types. The first opportunity to analyze GPS data came with the GIG-91 campaign and it was clear that an extensive effort was needed in order to preprocess the data before it could be fed into our existing orbit determination software.

Our orbit determination software is optimized for its most important use, that is operational orbit determination and prediction. A typical case of this is the routine orbit determination for the ERS-1 and ERS-2 satellites. These satellites are routinely tracked by only one ground station, Kiruna, with about 10 passes per day of some minutes. The need to obtain a precise orbit with sparse tracking data and the need to be able to accurately propagate it so that it can be used for the scheduling of instruments and ground station operations were important for the selection of the estimation algorithm and force modelling. A batch least-squares was selected, with acceleration modelling based on state of the art dynamic models.

When GPS observables had to be incorporated in the software, those suited for batch estimators were used. Our best results have been obtained using double differences of ionospheric free carrier phase and we have also implemented double difference pseudo-ranges. These measurement types have been implemented for pairs of ground stations, in order to improve the GPS satellite orbits or for geodesy, and for orbiting receiver/ground station pairs, in order to obtain precise orbits of the satellite carrying the GPS receiver.

GPS preprocessing software was needed to convert the basic GPS observables to double difference observables. A cycle slip algorithm based on integer almost ionospheric free combinations was implemented and also an algorithm to select a set of independent double difference combinations. Antenna phase center and center of mass corrections were also



**Figure1. ESA Ground Stations equipped with high precision GPS receivers**

included in the preprocessing software.

Post-processing software had also to be adapted for the GPS measurements. The most important part is the multi-arc orbit and geodetic parameter estimation software that has been used to obtain station coordinates solutions (Ref. 6). A completely new development was needed in order to obtain precise clock bias values (Ref. 7). These were estimated in post-processing using the estimated orbits and correction parameters obtained processing double differences.

A simultaneous development to that of the analysis software was the deployment of high precision geodetic GPS receivers at the ESA ground stations. Receivers have been installed and are operating in Maspalomas (Canary Islands, Spain), Kourou (French Guyana), Kiruna (Sweden), Perth (Australia) and Villafranca (Spain) (Fig. 1). The reasons for installing this GPS network were:

- To be able to obtain near-real-time GPS data to support operational and precise orbit determination of satellites equipped with GPS receivers.
- To be able to compute local ionospheric models using dual frequency GPS data to correct one frequency microwave ranging data.
- To be able to accurately determine the positions of the stations in a global reference frame.

These GPS receivers are remotely controlled from ESOC. Highly automated controlling and communications software had to be developed to minimize both on-site support and operator intervention.

### Participation in the International GPS Service for Geodynamics

Having participated in some of the early discussions concerning the establishment of an operational service for generation of high precision GPS orbit parameters, a proposal was submitted by ESOC in May 1991 in response to the call for participation issued by the

International Association of Geodesy/International Union of Geodesy and Geodynamics (IAG/IUGG). Our proposal was based on two starting points which could provide a significant contribution to the development of such a service:

- the existence of a network of globally distributed ESA ground stations, already equipped with communications, atomic standard timing systems and other relevant infrastructure.
- a state-of-the-art orbit and geodetic determination software that allowed for consistent processing of different types of geodetic satellite data (in particular SLR and GPS).

Our first solutions for orbital and polar motion parameters were transmitted to the IGS about one month after the start of the IGS-92 campaign. ESOC continued to process IGS data after the decision to continue the IGS activity in the form of an "IGS Pilot Service" and from 1 January 1994 as an operational service (Ref. 8).

We are now operating our five GPS receivers as IGS stations. ESOC acts as the Operational Data Centre for these receivers, retrieving the data and delivering them to the designated IGS Data Centres. We are also contributing as Analysis Centre, processing data from about 50 IGS stations to obtain high accuracy GPS daily products, with a delay of less than 10 days.

The data and products that we provide are the following:

- RINEX observation files, containing dual frequency phase and pseudo-range data at 30 seconds intervals from our five ground stations.
- Improved GPS satellite orbits, with an accuracy estimated to be of about 15 cm per axis.
- Improved earth orientation parameters (eop), with accuracy at the level of 0.3-0.4 milliarcsec.
- Precise GPS satellite clock biases, with accuracies in the nanosecond range.
- Station coordinate solutions with accuracies in the cm range, with the last submission in the form of a full covariance matrix for position and velocity estimates.

The orbit and clock solutions provided by the different IGS Analysis Centers are used to compute a combined IGS solution (Ref. 9) that is being widely used for applications (geodetic and other) for which accurate GPS orbits are needed.

Our clock bias estimates have also been used for time transfer experiments such as the one described by Tor Melgaard in these proceedings.

### Topex/Poseidon GPS data analysis

Topex/Poseidon has been a satellite of unique

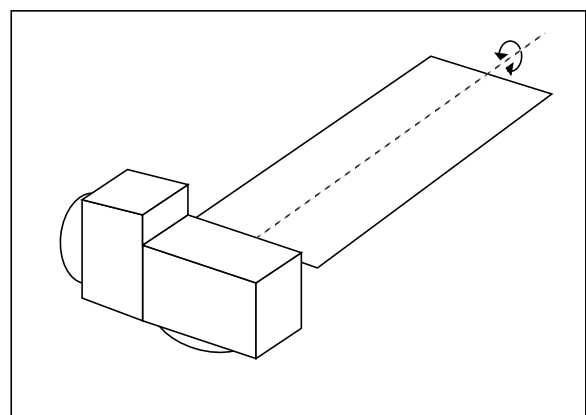
importance for the evaluation of on-board GPS. It carries a high precision dual-frequency receiver producing long cycle-slip free carrier phase passes as well as P-code pseudo-range measurements. It was launched when the GPS constellation was almost complete and when the IGS network of high precision receivers had started to provide globally distributed tracking data.

As a high precision altimetry mission, very accurate orbit determination was vital to its success. The satellite was equipped with several tracking systems: laser ranging retroreflectors (SLR), a doppler receiver (DORIS), and an experimental GPS receiver. This has made Topex/Poseidon a veritable precise orbit determination laboratory that allows the inter-comparison of the three tracking techniques.

As the ESOC precise orbit determination system adopts a fully dynamic approach, the high accuracy expected for Topex/Poseidon required the best possible force models and an accurate reconstitution of the attitude of the satellite, in order to compute surface forces and to correct measurements for centre of mass offset.

The force models used in the processing of the data were (Ref. 3):

- The JGM-2 (70x70) gravity model, that was specially developed to support this mission (Ref. 10).
- MSIS air density model combined with a variable area model based on a geometric description of the spacecraft as a composite of simple geometric bodies (Fig. 2), with surface properties provided by the Topex/Poseidon Macro-Model (Ref. 11).
- Lunisolar perturbations.
- Solid Earth tides (Wahr's model).
- Extended Schwiderski ocean tides.
- Solar radiation pressure using the spacecraft model already described.
- One cycle per revolution empirical forces (transverse



**Figure 2. Topex/Poseidon spacecraft model used to compute surface forces**

		DORIS	SLR+ DORIS	GPS	
				(1)	(2)
SLR	R	1.8	1.0	3.1	1.9
	T	6.2	2.6	16.1	9.4
	N	12.6	1.0	7.5	2.1
DORIS	R		1.2	1.7	1.1
	T		4.7	13.5	5.8
	N		12.4	12.3	3.0
SLR + DORIS	R			2.0	1.3
	T			14.2	6.9
	N			7.5	2.2

**Table 1: Average comparison statistics for ESOC orbits. Shown is difference rms in cm for the radial, transverse and normal components (R,T,N). For GPS orbits (1) before and (2) after Helmert transformations**

and normal).

The reconstitution of the attitude of the satellite was needed in order to calculate surface forces and centre of mass corrections. Topex/Poseidon is a three axis stabilized satellite with the radar altimeter constantly pointing downwards normal to a reference ellipsoid. In order to maintain the solar panel facing the sun, a sophisticated attitude law consisting of a combination of yaw steering about the local vertical and solar array pitching about its axis has been devised (Ref. 11). The different regimes of the attitude law and the transition modes were implemented in the software.

Other orbit determination modelling, including the definition of the reference frames, was done in consistency with the IERS Standards of 1992 (Ref. 12).

A 10-day period (repeat cycle 21) was selected for the analysis of the orbit restitution capability of the three techniques: SLR, DORIS, and GPS, although longer intervals were processed for SLR and DORIS data.

The SLR tracking for the period was about 20 passes per day, with a total of 22 stations performing some tracking in the 10-day period. The geographical distribution of the data shows that 76% of the tracking was performed from Europe and the US. The orbits were computed using three-day arcs and the average value of the residuals for all stations was at the level of 5 cm.

The DORIS tracking scenario is very different from that of SLR, as 43 DORIS beacons were active during the period. An almost complete geographical coverage without significant data gaps was achieved. The number of passes per day was about 130 with very

		JPL Reduced Dynamics		DUT Reduced Dynamics		DUT Full Dynamics	
		(1)	(2)	(1)	(2)	(1)	(2)
ESOC	R	3.2	2.8	3.2	2.9	2.1	1.5
Full Dynamics	T	16.4	8.2	10.6	8.1	8.7	5.3
	N	24.8	4.5	10.8	4.1	10.3	2.7

**Table 2: Average comparison statistics for GPS orbits. Shown is difference rms in cm for the radial, transverse and normal components (R,T,N) (1) before and (2) after Helmert transformations**

marginal day to day variations. Range-rate and tropospheric (zenith delay) biases were estimated for each pass. Average DORIS residuals so obtained were of 0.50 mm/s.

An improved station coordinate solution had been calculated for the processing of DORIS and SLR data. This solution was based in the processing of 3.5 months of Lageos SLR together with 18 days of Topex/Poseidon DORIS and SLR data. With this solution we could achieve a reduction from 0.54 mm/s to 0.50 mm/s in our DORIS residuals.

Topex/Poseidon orbits computed using a combination of SLR and DORIS were also generated with the combined station coordinate solution. The level of residuals obtained was about the same as that obtained in the individual solutions.

For the GPS processing (Ref. 13), Topex/Poseidon observations were used together with data from 17 to 20 ground receivers from the IGS network. The four eclipsing satellites during the period were not used, due to the erratic attitude behavior during and shortly after eclipse. From the rest, a total of 15 GPS SV's were used. Ionospheric free carrier phase double differences involving Topex and a ground receiver were the data type chosen for analysis. Additionally, and in order to solve for the orbits of the GPS SV's, ground based double differences were used. Measurements were generated every 2 minutes when involving the orbiting receiver and every 4 minutes when involving only ground stations. A Kalman filter was used to estimate receiver clock biases and drifts, but no appreciable drift was ever detected in the Topex/Poseidon clock.

The coordinates used for GPS were those from the IGS (ITRF), following a similar approach to that of the IGS Analysis by fixing the coordinates of a core set of stations and estimating the others. Drag scaling factors for Topex/Poseidon were estimated every 12 hours. The double difference phase measurements were fit to a level of 17 mm for those involving Topex/Poseidon.

In order to assess the performance of the different tracking data types, the ephemerides generated by each method were compared with each other and with ephemerides obtained by JPL (for GPS only) and by the Delft University of Technology (DUT) (Ref. 14). The results of these comparisons are shown on Table 1 for internal comparisons and in Table 2 for inter-centre comparisons.

Internal comparison with respect to our GPS orbits display relatively high values in the transverse and normal directions which are associated with large mean components and very small standard deviations. This occurrence can be interpreted as due to reference frame incompatibilities, mainly the inclusion or not of small empirical celestial pole corrections. In order to get rid of reference frame differences a Helmert transformation was applied individually to each arc to get the GPS orbit in the reference of the other orbit. The agreement between the different orbits is very good, even without Helmert transformations.

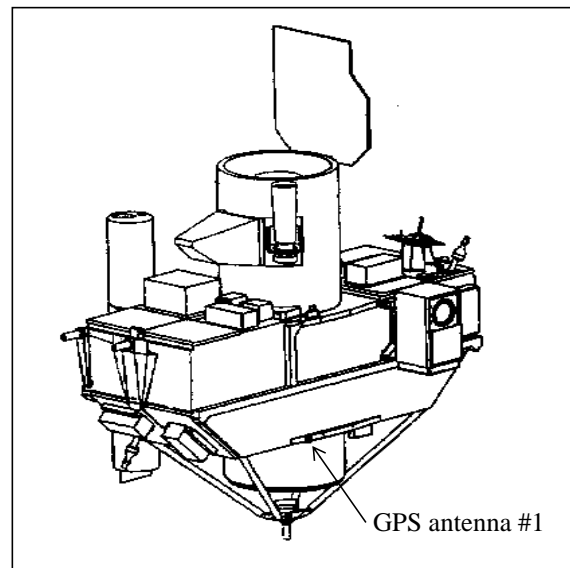
The Table 2 shows the comparisons between the ESOC GPS orbit and external GPS orbits. Our GPS orbit agrees best with the DUT dynamical solution, but the agreement between our solution and the reduced dynamics solutions is also very good, especially in the radial component.

These results indicate that GPS can be used for precise orbit determination and that the orbits so obtained are very close to the orbits obtained using other precise tracking methods. They also validate our software with respect to the use of GPS observables for precise orbit determination.

### Astrospas GPS data analysis

A second aspect of GPS orbit determination is its use for operational navigation of satellites. There have been a number of satellites that use a GPS receiver to calculate on-board the position and even the orbit of the spacecraft. It is foreseen that some elements of support to the International Space Station will be equipped with GPS receivers for this purpose. These receivers used for operational navigation may not be dual-frequency P code receivers. The receiver that is being planned for ARP (ATV Rendezvous Pre-development and Verification) is a C/A code one-frequency receiver. The GPS SPS Signal Specification (Ref. 15) only specifies the characteristics of the L1 C/A code. The use of other kinds of measurements (P code, L2) has to be based on empirical and unguaranteed sources.

One of our goals is to obtain absolute positioning of user spacecraft. These absolute positions can then be used as a yardstick for absolute on-board navigation



**Figure 3. The Orfeus-Spas in flight configuration**

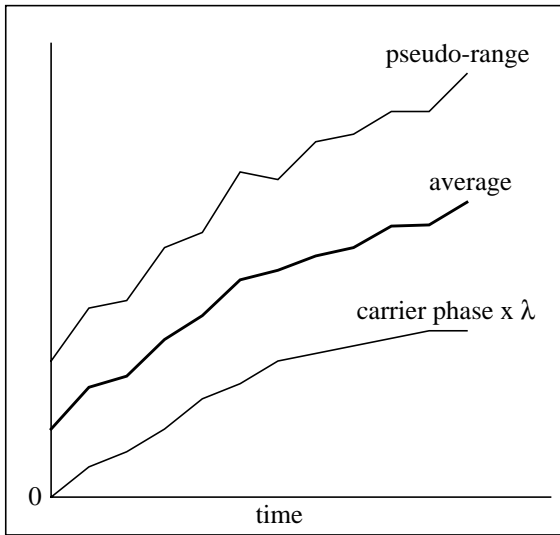
and relative rendezvous experiments.

In operational orbit determination, an important role of on-ground orbit determination with GPS is to obtain predicted orbits to be used in operations scheduling.

ESOC had the opportunity to obtain GPS data from the September 1993 flight of the Astrospas spacecraft (Orfeus-Spas mission). Astrospas is a reusable Shuttle dedicated satellite that carries a telescope as prime payload instrument (Fig. 3). The spacecraft is deployed from the Shuttle by the Orbiter RMS, it operates for some days in Shuttle's vicinity and is then retrieved and brought back to ground by the Shuttle. It has a one-frequency receiver recording C/A pseudo-range and L1 carrier phase from up to 6 GPS SV's at any time. The operating environment and GPS receiver of this spacecraft are similar to those of future Space Station missions.

The most important differences between the GPS data analysis performed for Topex/Poseidon and that needed for Astrospas are:

- Data quality: Topex/Poseidon carries a high precision GPS receiver that is optimized to obtain long cycle slip free carrier phase passes. The receiver in Astrospas is optimized for best GDOP, even if this means changing the set of tracked satellites.
- The Topex/Poseidon clock is steered to minimize its clock bias, while the Astrospas clock is in free drift, of about 0.04 ms/s, with clock resets every 8 minutes
- Topex/Poseidon has a GPS antenna on top of a mast with a choke-ring to minimize multipath, while Astrospas has two antennas to maximize visibility of the GPS constellation.
- Topex/Poseidon is kept in a very well known attitude, controlled by reaction wheels. Astrospas is oriented to



**Figure 4. Average measurement**

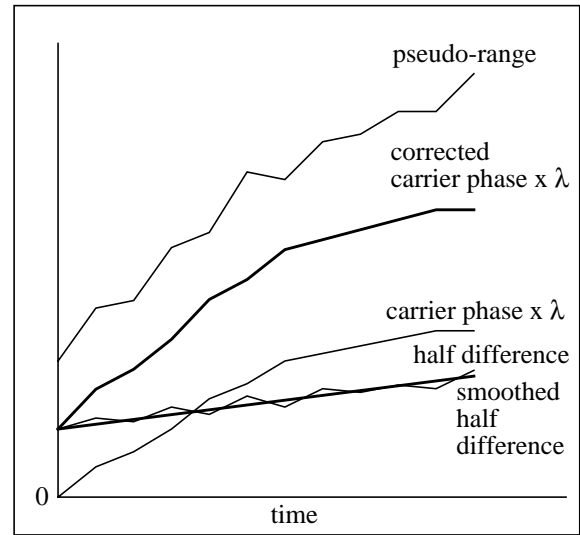
different astronomical sources with periods of observation of 20-40 minutes and it changes its attitude using cold gas thrusters. This may cause dynamic modelling problems.

- The ionospheric correction for Topex/Poseidon can be obtained using the dual-frequency data, but for Astrospas this is not possible. Ground based ionospheric corrections may not be applicable for an orbiting receiver, because the spacecraft is inside the ionosphere and not below it.

There are two possible ways of obtaining ionospheric free measurements for a single frequency receiver. One is to obtain an average of the carrier phase and the pseudo-range measurement. This new measurement will be free of ionospheric effect, but it will have a noise at the level of that of the pseudo-range and an ambiguity as the carrier phase. Figure 4 shows an example of this technique.

The second way is to obtain a smoothed approximation of the half difference between pseudo-range and carrier phase for a pass and to use this smoothed function to correct the phase measurements. Figure 5 shows an example of this technique and Figure 6 shows the smoothing of the half difference using real Astrospas data. The value of the smooth function at the measurement time is added to the carrier phase value to correct it for the ionospheric effect. The post-fit residuals of the smoothing are an indicator of the pseudo-range noise and for Astrospas they are typically in the 2 meter rms range.

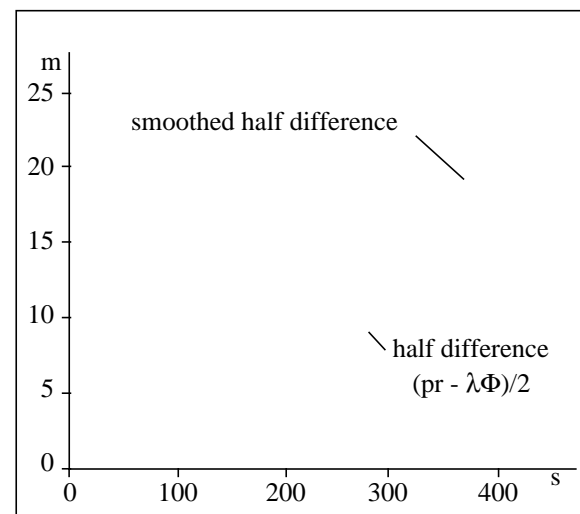
Both ionospheric correction techniques rely on the use of long cycle-slip free carrier phase passes. Short carrier phase passes are useless for orbit determination, because of the need to estimate the ambiguity. Undetected cycle slips will introduce errors in our



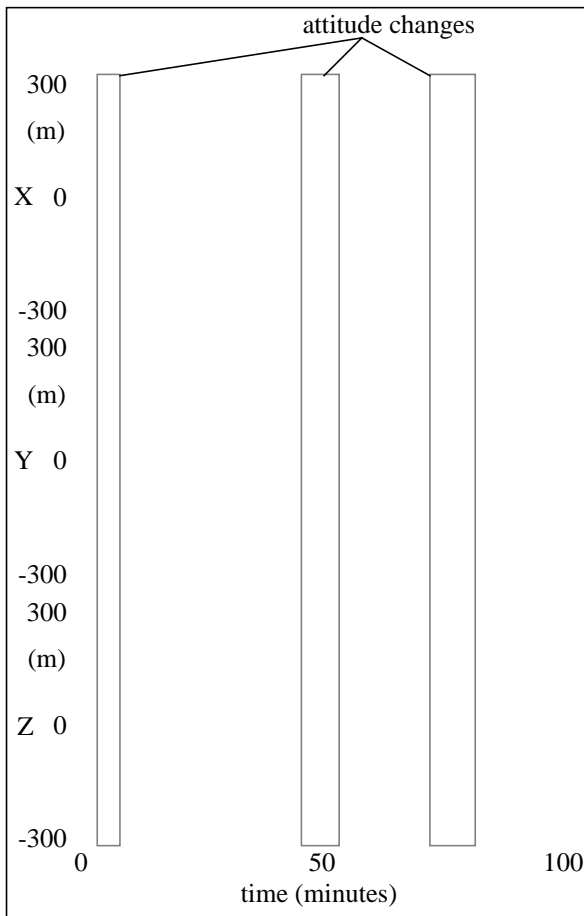
**Figure 5. Ionospheric corrected phase measurement**

derived measurements.

The first step in the preprocessing is then to obtain carrier phase and pseudo-range measurements at the same epochs as our ground based measurements, so they can be combined to obtain double differences. This process is very difficult because it has to be performed simultaneously with the cycle slip detection. We are currently investigating possible interpolating algorithms to obtain long cycle slip free carrier phases. The first data that should be checked with on-board GPS data is the on-board reconstitution of the position of the satellite. The earth-fixed positions obtained on-board can be fitted to an orbit. An example of this fit is shown in Figure 7. This is a one-orbit period in the middle of a 3-day arc of position measurements that were fitted using our orbit determination program. The



**Figure 6. Real data example of smoothed ionospheric correction**



**Figure 7. Difference between on-board derived position and fitted orbit**

residual fit was about 56 m per component, with higher residuals in x and y components than in z. The orbit was modelled using JGM-2 (70x70) gravity model and linear Cd's in 6 hour intervals. The Cd's so obtained were between 1.5 and 2.8 for a typical area of 9 m<sup>2</sup>. The orbit so computed can then be used to preprocess the basic GPS measurements.

In order to study the effect of the ionospheric delay another test run was performed using three hours of double difference pseudo-range measurements, combining ionospheric free pseudo-ranges from the ground stations with C/A pseudo-ranges from Astrospas. The orbits of the GPS satellites were those obtained by our routine IGS processing. In this test the pseudo-range residuals, due mainly to the uncorrected ionospheric delay, were of 11 meters.

Another possible test is to compute clock bias corrections and use precise GPS SV's orbits to perform precise pseudo-range point positioning. The ionospheric correction will be again the limiting factor for the accuracy of the reconstituted positions. We plan to obtain precise clock values for the period of the flight in order to compare these positions with those

obtained on-board.

## CONCLUSION

ESOC has developed a GPS Tracking and Data Analysis Facility that has demonstrated the feasibility of using GPS for precise orbit determination, with results of similar quality to those obtainable with other precise tracking methods, like SLR and DORIS. This facility can also be used to support missions for which an on-board GPS receiver is used for autonomous navigation. The Facility can analyze the results of the on-board navigation and it can obtain more precise off-line orbits that can be used to validate autonomous navigation using GPS. Work is on-going in order to provide higher precision orbits even for spacecraft that are not equipped with high precision GPS receivers.

## ACKNOWLEDGMENTS

Miguel Romay-Merino is gratefully acknowledged for helping us to describe the details of his work on SLR and DORIS orbit determination for Topex/Poseidon. The Astrospas data were kindly supplied to ESA by DARA (Deutsche Agentur fuer Raumfahrt-Angelegenheiten).

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