

Satellite Navigation Using GPS

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Introduction

The launch of the first Sputnik triggered the first challenge in satellite navigation, the determination of the characteristics of the orbit of the satellite, using the variations in the signal that was being radiated by the satellite. Very soon the idea of using the inverse process was developed: if by knowing your position you could determine the orbit of the

The Global Positioning System (GPS) is currently being used for a wide variety of applications. A GPS receiver on-board a spacecraft can provide the means for autonomous navigation and it also allows a very accurate reconstitution of the trajectory of the spacecraft when on-board recorded measurements are combined with ground based measurements.

This article outlines some of the basic concepts involved and presents the activities that the European Space Operations Centre is carrying out in the field of satellite navigation using GPS.

satellite, then it should also be possible to use the signal transmitted by a satellite in a known orbit in order to determine your own position. This concept was implemented in a series of satellites sponsored and operated by the US Armed Forces. First the Transit satellites were deployed, then the Timation and finally the NAVSTAR GPS system.

The focus of these programs was to provide the military forces of the US and its allies with precise positioning capabilities. In response the Soviet Union also developed and deployed similar Global Navigation Satellite Systems (GNSS): Tsikada and GLONASS.

Right from the beginning it was realized that

these systems could also be used for a wide range of scientific and other civil applications. New tracking methods that were not even foreseen by the original developers of the systems, like carrier tracking, were proposed and, as soon as it was possible, successfully tested and used.

One of the applications that was soon envisioned was the use of GPS for navigation of spacecraft. The first on-board receiver was installed and flown in a Landsat satellite even before the complete GPS constellation was deployed. Since that time more receivers have been flown on satellites, first as a demonstration of increasingly precise uses and now as the main operational means of navigation.

The NAVSTAR Global Positioning System

The NAVSTAR Global Positioning System, usually called GPS, consists of three components: a space segment of GPS satellites, a control segment that monitors and operates those satellites and a user segment that employs GPS receivers to observe and record transmissions from the satellites and perform position, velocity, attitude and time calculations.

The GPS Space Segment

The space segment is based on three-axis stabilized satellites orbiting in near-circular orbits with a period of half a sidereal day and an inclination of 55 degrees. There are six orbital planes, each of them with four satellites. This constellation provides global coverage with more than four satellites in view at all times.

The significance of the visibility of at least four

satellites is that the GPS system is intended to allow instantaneous real time determination of the user position (3 variables) and the time of the fix (one more variable). Previous positioning systems, like the methods used in the Transit and Tsikada systems, were based on the processing of several passes of data (requiring hours to days) and did not provide the instantaneous solutions that GPS (or GLONASS) offers.

The GPS satellites carry very stable atomic clocks that are used to derive the ranging signals. The basic signal for civil use, L_1 , has a frequency of 1575.42 MHz and it is modulated with a Clear Acquisition (C/A) Pseudo Random Noise (PRN) code at 1.023 MHz that is different for every satellite. The signal is also modulated with a 10.23 MHz Precise (P) code that is usually encrypted and only available to authorized users. On top of this there is a 50-bit-per-second modulation which is used to transmit the satellite ephemerides (predicted orbit and clock) and other information. Authorized users have also access to the Precise code on a second frequency L_2 , that allows users to correct for ionospheric propagation delays. Some receivers are able to measure the delay between the signal in the L_1 frequency and the L_2 frequency without access to the P code. There are plans to add in future satellites another frequency for civil users so they can easily correct for ionospheric delays.

The GPS Control Segment

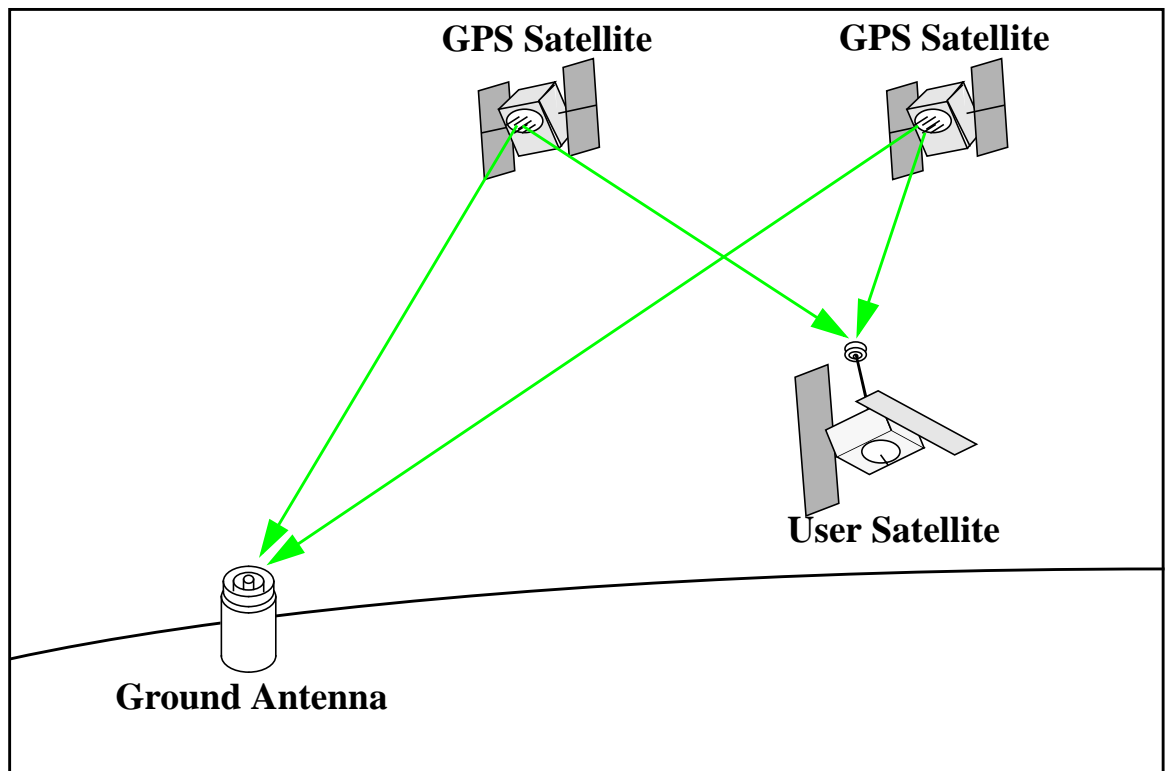
The GPS control segment tracks and monitors the signal from the GPS space segment and estimates the orbits and clock behaviour of the satellites. This information is uploaded to the satellites so it can be transmitted to users.

The GPS User Segment

The GPS user segment can perform two basic measurements of the GPS signals. It can compare the C/A or P code that it is receiving with a locally generated copy in order to compute the transmission delay between the satellite and the receiver. This measurement is called pseudorange. Pseudoranges to four or more satellites can be used to determine the position of the user once the position of the GPS satellites has been obtained using the ephemerides of the navigation message.

The second and more precise method is to obtain the difference in phase between the received carrier signal and a receiver generated signal at the same frequency. This measurement is known as the carrier phase observable and it can reach millimetre precision, but it lacks the accuracy of the pseudorange because the phase when the tracking is started can only be known with an ambiguity of an unknown number of times the carrier wavelength (about 19 cm for L_1)

Figure 1. Common observability of GPS satellites by ground and onboard receivers allows a better determination of the satellite orbit



Use of GPS for spacecraft navigation

The number of applications and users of the GPS system has exploded in the last years, well beyond any expectations. The latest receivers are cheap, small, with very good performance and easy to use.

One of the first scientific applications of GPS was to precisely determine the position of fixed ground antennas in order to study the dynamics of the Earth surface. Very soon it was realized that in order to obtain the best results it would be necessary to compute very precise orbits of the GPS satellites. A number of groups started to do this and in this way the first orbits that were precisely obtained using GPS were those of the GPS satellites themselves.

GPS has many advantages for the tracking of satellites orbiting the Earth. It provides unsurpassed observability, because low-Earth satellites are able to track six or more GPS satellites, with tracking arcs amounting to about half of the user satellite orbit. This can not be achieved by any ground based tracking station. This very good observability also makes the method robust. There is a high level of redundancy because orbits can be fitted even with only two GPS satellites being tracked at any time. When four satellites are tracked GPS allows for real-time autonomous determination of the position of the satellite, with an accuracy equivalent to that obtained with non-precise ground tracking methods. If a precise dual frequency receiver is used and

data is processed together with ground based data, GPS provides possibly the best accuracy that can be achieved in precise orbit determination.

The first user satellite to fly a precise GPS receiver was the TOPEX/Poseidon altimeter satellite. After that other satellites have been flown with different types of receivers. Table 1 details the different applications for a GPS receiver on-board a spacecraft.

ESA has been involved in GPS activities from the late eighties with the development of space qualified GPS and GPS/GLONASS receivers, the ESOC activities to support spacecraft navigation and, lately, within the ARTES program, the European Geostationary Navigation Overlay Service (EGNOS). EGNOS will complement the GPS system in order to provide European users with increased availability, integrity and accuracy for real time applications such as aircraft navigation.

It is foreseen that ESA will participate in the development of future Global Navigation Satellite Systems (GNSS) that may replace GPS, GLONASS and their augmentations for such purposes in the future.

GPS has been proposed as tracking or scientific instrument for several ESA spacecraft. It is the main positioning instrument envisioned for the Automated Transfer Vehicle (ATV), both for absolute navigation and for navigation relative to the International

Table 1. Applications of a GPS receiver for space navigation

Current uses:

- To determine the position and velocity of a satellite.
- To accurately determine the time of observations from other tracking or scientific instruments.
- To determine the attitude of a satellite. This can be accomplished by comparing the measurements obtained from different antennas.
- To collect GPS measurements that will allow a precise reconstitution of the orbit of the satellite.
- To collect GPS measurements that can be used to reconstitute the characteristics of the medium travelled by the signal: ionosphere and troposphere.

Future uses:

- The relative navigation of two spacecraft (currently being validated).
- The tracking of the launch and early orbit phases of rockets.
- The tracking of re-entering spacecraft, even to the point of autonomous landing.

Space Station. The ATV Rendezvous Pre-development (ARP) program is being carried out to validate methods for relative navigation that will be used for ATV, including relative GPS navigation. Other spacecraft for which a GPS receiver has been proposed include several of the Earth Explorer candidates and other future observation and scientific satellites (Metop, STEP).

ESOC involvement in GPS activities

ESOC has within the European Space Agency the responsibility to operate ESA spacecraft. This includes the Flight Dynamics activities needed to achieve and maintain their desired orbit and attitude. That is the reason why, as soon as GPS started to be proposed for spacecraft navigation, ESOC began to get ready to support ESA missions that might use the GPS system.

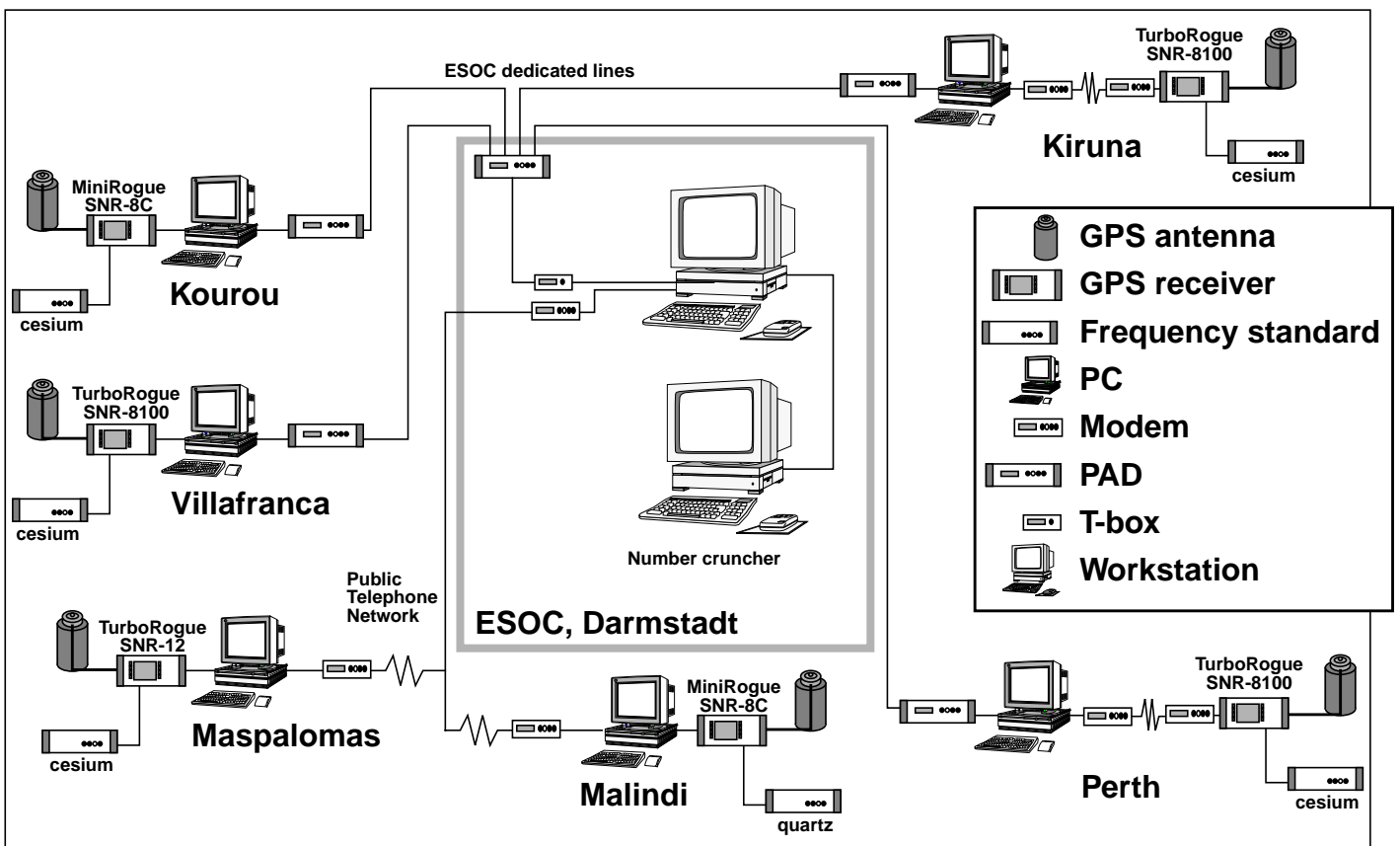
ESOC had an excellent opportunity to do so by contributing to the success of the International GPS Service for Geodynamics (IGS). Scientists were proposing to install a permanent network of precise ground based GPS receivers that would allow the monitoring of the movement of the Earth surface in order to better understand plate tectonics and local deformations that are the cause of earthquakes. The data from these receivers could be processed in order to obtain precise orbits

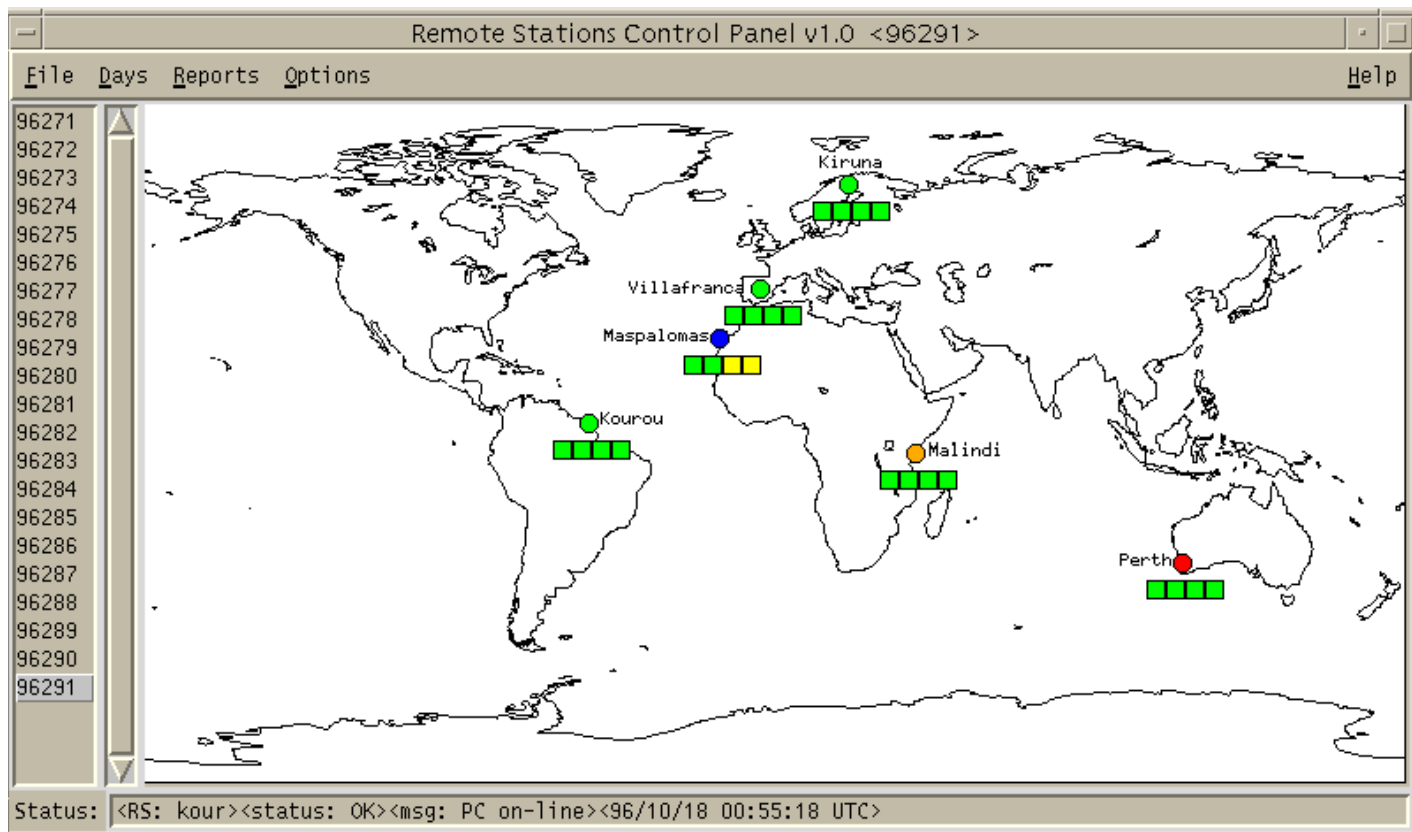
for the GPS satellites that would be used by geodesists in regional deformation studies. Within the terms of reference of the IGS was also provision of support to other applications including scientific satellite orbit determination. The assets which ESOC could contribute to the IGS were its network of ground stations in which receivers could be installed and its expertise, supported by in-house developed software, in precise orbit and geodetic parameter estimation.

Our first receiver was installed in Maspalomas (Spain) in June 1992 (Fig. 4). Receivers have also been installed in Kourou (French Guyana) in July 1992, Kiruna (Sweden) in July 1993, Perth (Australia) in August 1993, Villafranca (Spain) in November 1994 and Malindi (Kenya) in November 1995. Our precise estimation software was extended to include GPS measurement types for both ground based and spacecraft borne receivers. We have been providing data and increasingly precise GPS products for the last five years. Currently we provide:

- Raw measurement data from our six ground stations.
- Precise orbits of the GPS spacecraft.
- Earth orientation parameters (polar motion, length of day).

Figure 2. Current configuration of the GPS-TDAF





- Station coordinate solutions for those stations included in our analysis.
- GPS satellite clock information.

ESOC is currently an active IGS Analysis and Operational Data Centre and is specially involved in current discussions to extend the IGS to use space-borne receivers.

The ESA GPS TDAF

The ESA GPS Tracking and Data Analysis Facility (GPS TDAF) has been developed in order to support the GPS activities carried out by ESOC. It includes our network of ground GPS receivers, the necessary communication interfaces to allow the remote operation and data downloading from ESOC and the processing and analysis software needed to format the data and to obtain the precise products (Fig. 2). The system is highly automated and includes an easy to operate interface for the retrieval and the processing of the data (Fig. 3). The GPS TDAF is currently being extended to process GLONASS data and to include real-time monitoring capabilities that may be needed to support critical operational phases like rendez-vous.

Other recent developments are:

- The calculation of global and local ionospheric models that can be used to correct

one-frequency ranging and altimeter data.

- The implementation of a sequential filter to estimate spacecraft trajectories using the precise products obtained by the IGS analysis activities.

Role of the ESA operations ground segment in GPS navigation

The driving reason for implementing a GPS TDAF in ESOC was to provide ESA the capability to support the navigation of satellites equipped with GPS receivers. This support involves the following activities:

Support of critical real time GPS applications

GPS has been proposed as the absolute and relative positioning system for spacecraft going to the manned International Space Station. For this application is clear that the ground segment cannot be in-the-loop for the calculation of real-time trajectories of the spacecraft involved, because of the unavoidable delays that this will create. Still the ground segment has a role in monitoring the integrity of the signals that are to be used for critical operations.

This can be accomplished using a ground network of GPS receivers that is able to track all the satellites that the orbiting spacecraft

Figure 3. Remote Station Control panel of the GPS-TDAF. This panel is used to monitor the daily retrieval tasks.

may use. The navigation data and observations of these precisely located ground stations can be processed in order to check their integrity and to estimate the error in the signal for each GPS satellite. Badly performing satellites can be identified and it can be predicted how many healthy GPS satellites will be observable by the user spacecraft during the critical operations. This can also be done in real time in order to detect satellite failures that can affect the navigation solution of the user spacecraft, so that the information can be delivered to Mission Control and the bad GPS satellites can be excluded from the on-board computed navigation solution.

Another role of the ground segment will be to support the validation of the receivers and their correct functioning before critical operations are started. It can also assist in the fast re-start of receivers by providing up-to-date almanacs and other initialization data.

ESOC has installed GPS receivers in six ground stations and it is developing a real-time communication system that will allow for

the continuous monitoring of the GPS spacecraft visible from these ground receivers.

Precise Orbit Determination using GPS

GPS is one of the best tracking types for Precise Orbit Determination of Low Earth Orbit satellites because it combines high accuracy with unsurpassed observability. The high accuracy is obtained using the GPS carrier phase observable, free of ionospheric errors when dual frequency data is used. The unsurpassed observability is provided by the high number of GPS satellites that can be simultaneously tracked by an orbiting receiver.

ESOC has incorporated models for the most widely used GPS measurements in its Precise Orbit Determination software. This has been done both for the determination of the orbit of the GPS spacecraft and for the determination of the orbit of user spacecraft (spacecraft carrying a GPS receiver). The implementation has been validated using TOPEX/Poseidon data and the software is currently being used to support the ARP Flight Demonstrations. More information on these activities is given below.

Determination of the orbits and clocks of the GPS satellites

For some applications it is not needed to simultaneously solve for the orbits of the GPS spacecraft and the user spacecraft. The orbits and clock biases of the GPS spacecraft can be precisely computed and then held fixed for the computation of the orbit of the user spacecraft.

ESOC has been participating in the International GPS Service for Geodynamics (IGS) since it started and we have been producing precise orbit and clocks solutions for the GPS satellites. These ephemerides are estimated to be accurate to about 10 cm.

Our GPS orbit determination software is also being used for feasibility and validation experiments for the ARTES-9 EGNOS project.

Operational Orbit Determination using GPS

The facilities implemented for Precise Orbit Determination can also be used for Operational Orbit Determination to produce a very accurate orbit prediction and to calibrate manoeuvres. This on-ground determined orbit can also be used during the spacecraft check-out to assess GPS-based on-board orbit determination.

Figure 4. GPS antenna and pillar in Maspalomas, Spain.



For some applications it is not needed to have a very precise orbit prediction. In this case the GPS-based on-board generated positions can be used on the ground as observables in order to determine the orbit that will be used for orbit control, mission planning and station visibility predictions. This process can also assess the quality of the on-board generated positions.

In this context our GPS orbit determination software is going to be used operationally to determine the orbit of the Danish Ørsted geomagnetic research microsatellite.

Geophysical Parameter Estimation

Most of the activities listed before are possible because networks of precise geodetic receivers are currently deployed to support these and other applications. For the most accurate applications the position of the receivers in these networks has to be precisely determined, together with a number of other geophysical parameters. The accurate determination of the position of the ESA ground stations, the determination of Earth orientation parameters and the calculation of ionospheric calibrations can also support other projects that are not using directly GPS but need accurate location of the position of tracking antennas and correction for ionospheric delays.

ESOC is contributing to the estimation of very precise station coordinate solutions that include the ESA ground stations and through the IGS also to the activities of the International Earth Rotation Service (IERS). We are currently testing the use of GPS derived ionospheric models in order to correct one-frequency ERS altimeter measurements and the S-band ranging and doppler measurements used for the routine control of most spacecraft.

TOPEX/Poseidon precise orbit determination

TOPEX/Poseidon (T/P) is a joint US/French altimetric spacecraft launched in August 1992. The main scientific goal of this mission is to produce sea level maps to study ocean circulation and its variability. Very accurate orbit determination is vital to the success of this or any other altimetric mission. In fact, the fundamental quantity measured is the geocentric height of the sea surface, and this is obtained as the difference between the radial orbit position and the altimeter measurement proper. The orbit determination requirements for T/P were set to a very demanding 13 cm

error budget for the radial position. In order to satisfy this challenge an unprecedented effort was made to improve the gravity model of the Earth and, to further guarantee the best possible results in orbit determination, several tracking systems were placed on-board: retroreflectors for Satellite Laser Ranging (SLR), a DORIS receiver, and an experimental precise GPS receiver. This effectively has made the T/P spacecraft a veritable orbit determination laboratory that allows the intercomparison between different tracking techniques.

T/P has been of unique importance for the validation of techniques for GPS-based satellite navigation. It is equipped with a high precision dual-frequency GPS receiver producing long cycle-slip free carrier phase passes as well as pseudo-range measurements. It was launched when the GPS constellation was almost complete and when the IGS network of high precision GPS receivers had started to provide continuous globally distributed tracking data.

For our evaluation to intercompare the orbit restitution capabilities of the three techniques: SLR, DORIS and GPS a 10-day period was selected. For the GPS processing, T/P observations were used together with data from about 20 ground receivers from the IGS network. The orbit of the T/P spacecraft was then solved simultaneously with the orbits of the GPS spacecraft. The chosen data type was double difference phase measurements involving two GPS satellites and two GPS receivers.

The ephemerides generated using GPS and using SLR and DORIS were compared with each other and with external solutions obtained by the Delft University of Technology (DUT) and the Jet Propulsion Laboratory (JPL). The orbits show a remarkable agreement, with the difference in radial direction in the order of 2 cm, and along track and cross track differences in the order of 5 to 10 cm.

These results demonstrate the capability of the GPS-TDAF to produce very accurate results when precise data collected on-board can be combined with on-ground collected data from a network of high-precision GPS receivers.

The ARP flight demonstrations

ESA is developing the un-manned Automated Transfer Vehicle (ATV) that will serve as a logistic / resupply vehicle for the Interna-

tional Space Station (ISS). The ATV will perform a number of manoeuvres in order to rendezvous and dock with the ISS. GPS is baselined as the main positioning system for ATV. It will be used for autonomous absolute position determination and autonomous relative position determination with respect to the ISS. For autonomous absolute position determination the ATV will be equipped with a one-frequency GPS receiver that will provide position, velocity and time solutions. For autonomous relative position determination the ISS will also be equipped with a GPS receiver that will provide GPS observables for transmission to the ATV. The ATV will process them together with its own GPS observables in order to determine its position and velocity relative to the ISS.

The ATV Rendezvous Pre-development (ARP) project covers the pre-development of rendezvous technologies critical to ATV. One of the aspects that are covered by this project is the validation of relative navigation using GPS observables. For this three Flight Demonstrations (FD) are planned, in which the Space Shuttle will act as chaser and another spacecraft (Astrospace for FD1 and the MIR station for FD2 and FD3) will be the target. These spacecraft will carry one-frequency GPS receivers and will collect GPS data during the proximity operations. The data will be post-processed on the ground to validate the relative navigation algorithms.

The role of ESOC in these three ARP FDs is to compute reference trajectories (relative and absolute) for the spacecraft involved using all available measurements. These trajectories will be then used to compare with the results of the relative navigation filter. ESOC will obtain the trajectories using the following data:

- GPS observables (pseudorange and phase) and on-board derived positions from the two flying receivers.
- The ESOC precise orbit and clock solutions for the GPS satellites.
- Attitude data derived from the spacecraft Guidance, Navigation, and Control (GNC) system.

The data will be decoded and converted to an engineering format that then will be fed to a program which will produce the best estimate trajectories for the spacecraft. This program is called GPSBET (GPS Based Estimator of Trajectories) and it includes the following:

- Precise measurement models that use the GPS orbits and clocks computed by ESOC. The models include a centre of mass correction that is performed using the location of the particular antenna in the body-fixed axes and the attitude data.
- A multi-satellite orbit propagator that includes precise dynamic models and empirical accelerations.
- A Square Root Information Filter that processes all the information and produces filtered and smoothed estimates of the parameters.

We are currently processing data from the first ARP Flight Demonstration and we expect to achieve absolute positioning results with about 1 metre of accuracy and even better relative positioning accuracy.

Conclusion

The GPS system, originally deployed to allow very precise delivery of weapons, has demonstrated an incredible versatility of use for civil applications. GNSS systems are ideal to support many aspects of the navigation of spacecraft orbiting the Earth. They can support increased spacecraft autonomy and, when used together with ground collected measurements, they provide unsurpassed accuracy. The ESA GPS-TDAF is already supporting validation activities for navigation of spacecraft using GNSS systems and will as well be able to support preparations for a European contribution to future Global Navigation Satellite Systems.

Additional information on these activities, as well as links to other related World Wide Web sites, can be found under <http://nng.esoc.esa.de/>.

Acknowledgment

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