

ABSOLUTE AND RELATIVE NAVIGATION OF SPACECRAFT USING GPS: THE ATV RENDEZVOUS PREDEVELOPMENT FLIGHT DEMONSTRATIONS

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ABSTRACT

GPS is increasingly being used for a wide range of applications. Its use for spacecraft navigation has been already demonstrated for absolute real-time positioning and precise orbit determination. Now, in preparation for the proximity navigation of the ESA Automated Transfer Vehicle (ATV) around the International Space Station, spacecraft relative navigation using GPS has to be demonstrated. For this and within the ATV Rendezvous Pre-development (ARP) project, a number of Flight Demonstrations using the NASA STS and another spacecraft are going to be carried out. The spacecraft will carry GPS receivers and the data collected will be used to validate the algorithms that are being proposed for ATV relative navigation.

INTRODUCTION

ESOC/OAD has been developing and operating the ESA GPS Tracking and Data Analysis Facility (GPS-TDAF) in order to support spacecraft navigation. The Facility comprises a ground network of precise GPS receivers at ESA ground stations, a control centre in Darmstadt to operate and down-load these receivers and analysis software to use GPS in support of spacecraft navigation. The system has been used to support the International GPS Service for Geodynamics for the last five years, during which we have provided data from our ground stations, precise GPS orbits, estimates of the Earth orientation parameters and other products. It has also been used to obtain precise orbits of spacecraft equipped with GPS receivers, such as Topex/Poseidon.

The OAD role in the ARP Flight Demonstrations is to use its GPS-TDAF to provide a Best Estimate Trajectory (BET) for the spacecraft by processing the on-board recorded GPS data together with GPS data collected on the ground. The data collected on ground at the ESOC ground stations and other GPS tracking sites will be processed to obtain precise GPS orbits and clock offsets.

The precise GPS products will then be used to correct the data recorded on board in order to reduce the error of the raw GPS measurements. These corrected GPS measurements will be processed using an estimation algorithm based on a Square Root Information Filter, while the propagation of the spacecraft states will be done using dynamic models. The BET so obtained and other BETs obtained by NASA using other rendezvous sensors will be taken as the reference against which the results of the on-board relative navigation algorithm will be compared. The capability of the GPS-TDAF to obtain BETs has been validated with Topex/Poseidon GPS data.

1. THE AUTOMATED TRANSFER VEHICLE

The Automated Transfer Vehicle (ATV) is an ESA developed expendable and un-manned cargo transport vehicle for the supply of the International Space Station (ISS). Together with its cargo, the ATV forms a composite which will be launched by Ariane 5 from Kourou into Low Earth Orbit. After separation the ATV composite executes a set of manoeuvres to rendezvous with the ISS. After docking with the ISS the cargo is unloaded and the ATV remains attached to the station. After some time the ATV departs from the ISS and performs a controlled destructive re-entry in the Earth atmosphere.

The ATV is being designed to be highly automated, to be compliant with all stringent safety and reliability requirements for the ISS and to maximise the use of existing components and hardware in order to shorten development time and lower costs.

The ATV propulsion system comprises 8 main thrusters for orbital transfer operations and 4 clusters of 5 thrusters for braking and attitude control. The Guidance, Navigation and Control (GNC) architecture comprises redundant GPS and rendezvous sensor (RVS) equipment, 4 gyroscopes and 2 sets of redundant Earth and Sun sensors. The communications system includes S-band equipment for communication with and tracking by relay

satellites.

The GPS equipment is the main positioning system, both for the on-board determination of the position of the spacecraft and for on-ground determination and prediction of the orbit. The ISS will also to be equipped with a GPS receiver. When the ATV is within UHF range of the space station, the ISS sends to ATV its GPS observations so that the ATV can perform relative navigation using at least four commonly observed GPS satellites.

As far as concerns GPS, the navigation modes of the ATV are:

- Predicted mode between launch and GPS fix. For this period the orbit has been calculated on ground and stored on-board prior to launch. The circularisation burn will be performed during this phase.
- Absolute GPS navigation between the first GPS fix and the start of the relative navigation and after departure up to re-entry. During this phase the orbit will be computed on-ground and used to calculate the manoeuvres to rendezvous the space station and to depart and re-enter.
- Relative GPS navigation within the UHF range of the space station, before RVS navigation and up to departure.

2. ROLE OF THE GROND SEGMENT FOR ATV NAVIGATION

The ground segment plays a very important role for ATV navigation. Firstly, it designs the mission and determines the nominal sequence of operations. Secondly, it monitors the implementation and it commands for corrections to the nominal sequence.

For doing the monitoring the ground segment needs to be able to monitor the integrity of the GPS system and to determine and predict the orbit of the ATV during the non-attached phases. The monitoring can be performed using a system such as the one described in Ref. 1. The orbit determination can be performed using the on-board determined positions, the original raw GPS measurements or the tracking data acquired through use of relay satellites.

Using all these three sources will increase the reliability of the determination, allow for a check of the on-board determined positions, and act as a back-up during departure. A total loss of the on-board GPS system will imply a loss of mission if it occurs before the ATV is attached to the space station.

Another role that is frequently overlooked is the capacity of a properly set-up ground segment to assist in making a fast acquisition by the receiver. The ground segment can up-link an estimated orbit to the receiver and provide up-to-date almanacs of the GPS system. This may speed-up the time to first fix and reduce the time for re-acquisition after receiver re-start.

3. THE ATV RENDEZVOUS PREDEVELOPMENT

The ATV Rendezvous Pre-development (ARP) Project is being carried-out in order to increase European expertise on automated rendezvous technologies, so as to minimize ATV development risks and validate the technologies that will be used for ATV rendezvous. The ARP Project has been divided into three interconnected main areas:

- The ARP Kernel, for system level activities including the ground simulations and the flight demonstrations.
- The ARP Rendezvous Sensor (RVS), covering the development of the laser sensor to be used for the short range relative navigation.
- The ARP GPS, consisting in the procurement and adaptation of a GPS receiver to be used as sensor for long range relative navigation.

ESA has procured two Laben ARP GPS receivers derived from the Loral Tensor model that will be used in the Globalstar satellites. The ARP GPS is a one-frequency Standard Positioning Service (SPS) receiver with 9 continuous-tracking channels modified to output that raw measurements (code phase, carrier phase and doppler). The ARP Flight Demonstrations will involve the collection of GPS and RVS measurements that will be post-processed on-ground to tune and validate the relative navigation algorithms.

4. THE ARP FLIGHT DEMONSTRATIONS

Three ARP Flight Demonstrations are envisioned. The first one took place between November 19 and December 4 of 1996, during the Shuttle flight STS-80. GPS receivers and antennas were installed in the Orfeus-SPAS astronomy retrievable satellite that acted as target spacecraft. A GPS receiver was installed in the Shuttle cargo bay, with antennas located at the Extended Duration Orbiter (EDO) pallet. The Shuttle acted as chaser spacecraft,

The receiver installed in the SPAS was the ARP GPS receiver and the Shuttle was equipped with a Trimble TANS Quadrex six channel SPS receiver. Data was collected during separation and retrieval and also during an in-between period. Unfortunately the separation data was not collected simultaneously by STS and SPAS. In total there were about three hours of usable simultaneously collected data. GNC data was also obtained in order to reconstitute the attitude and thrusting of the spacecraft involved.

Two additional Flight Demonstration are now foreseen. They will include not only GPS data collection but also RVS equipment experiments. They will be performed by the Shuttle acting as chaser spacecraft and the Russian MIR station as target spacecraft. The ARP GPS receiver will be mounted on the Shuttle and GPS measurements will also be recorded and down-loaded from the DARA MOMSNAV receiver already installed in the MIR.

Data collected during the flight demonstrations will be processed on-ground to validate the relative navigation algorithms (Ref. 2). The output of these algorithms will be the trajectory of the chaser spacecraft with respect to a coordinate system based on the target spacecraft. In order to be able to show that this trajectory accurately represents the real trajectory that the spacecraft flew some reference trajectory is needed. This trajectory should be computed using a method different from that used to obtain the relative trajectory. Currently two methods are being proposed. The first approach is to use the Shuttle TCS laser system that can provide range and range rate between the two spacecraft. The second is to obtain absolute GPS trajectories for both spacecraft and to obtain the relative trajectory by differencing those. The absolute trajectory determination can be aided by GPS data collected on-ground that enables estimation and removal of the Selective Availability error in the GPS satellite orbits and clocks.

5. ESOC INVOLVEMENT IN THE ARP FLIGHT DEMONSTRATIONS

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) (Ref. 3). Within the terms of reference of the IGS there is a 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. Receivers have also been installed in Kourou (French Guyana) in July 1992, Kiruna (Sweden) in July 1993, Perth (Australia) in August 1993, Villafraña (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 space-borne receivers. We have been providing data and increasingly precise GPS products for the last five years. Currently we provide:

- Dual frequency raw measurement data from our six ground stations.
- Precise orbits of the GPS spacecraft, as daily rapid orbits and final orbits. The accuracy of these orbits is estimated to be of about 15 cm 1-d rms for the rapid and 10 cm for the final orbits (1 day and 10 day delay, respectively).
- Orbit predictions for the GPS spacecraft, with sub-meter accuracy.
- Earth orientation parameters (polar motion, length of

day).

- Station coordinate solutions for those stations included in our analysis.
- GPS satellite clock bias data that allows sub-meter pseudorange single point positioning.

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 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. The system is highly automated and includes an easy to operate interface for the retrieval and the processing of the data. 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 rendezvous.

ESOC has been involved in the ARP Project from its start, providing support in Ground Segment and Flight Dynamics aspects. When the need for a reference trajectory was identified ESOC was a natural candidate to provide it due to its expertise in GPS-based spacecraft orbit determination, as demonstrated by our Topex/Poseidon orbit determination activities (Ref. 4)

The role of ESOC in the 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.

6. ARP TRAJECTORY DETERMINATION USING GPS

The approach that ESOC is using for trajectory determination is based on the combination of on-ground and on-board collected data. The following data is being used:

- 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. These solutions are computed using data from a ground network of dual-frequency precise geodetic receivers.
- Attitude and manoeuvre data derived from the spacecraft Guidance, Navigation, and Control (GNC) system.

The flight data is first decoded and converted to an engineering format that then is 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.

The parameters that can be estimated include:

- User spacecraft position and velocity
- Clock bias, drift and ageing for each GPS receiver
- Empirical accelerations
- Air drag and radiation pressure coefficients
- Residual signal error for each GPS spacecraft. These parameters compensate for the errors in the precise ephemerides and for the error due to Selective Availability introduced when 30 second rate clock biases are interpolated.
- Phase ambiguities
- Parameters for ionospheric correction of one-frequency data

GPSBET can be run either in single satellite mode or in multiple satellite mode. The advantage of using the multiple satellite mode is that the parameters that will be common for the user satellites (residual ephemerides error, ionospheric model) will be more observable. If a common set of GPS satellites is being tracked by both user satellites, then receiver independent errors in the measurement model will be common for user satellites and the relative trajectory solution will be more accurate than the absolute solution.

GPSBET has been validated using dual frequency GPS data from Topex/Poseidon. T/P GPS data is available at 10 second rate. Dual frequency data allows for the analysis of the ionospheric effect estimation, because combinations can be created with different levels of ionospheric delay. Using T/P data had also the advantage of being able to compare the resulting trajectories with a very precise reference, the NASA POE.

6. PRELIMINARY RESULTS FROM ARP FLIGHT DEMONSTRATION 1

During the first ARP Flight Demonstration data was collected during the separation and the retrieval of the Orfeus-SPAS satellite and also during a short interval in-between. Unfortunately data was not collected simultaneously during separation, so only the in-between and the retrieval phases were relevant for relative GPS navigation.

In the in-between phase both the STS and the Orfeus-

SPAS collected data without performing any orbit or attitude manoeuvre. In this benign dynamic environment we were able to fit the pseudo-range observations to 3 m rms residual and the carrier phase to 2 cm rms. Formal absolute accuracies were of less than 1 meter and even better relative accuracies could be expected.

At the writing of this paper we are processing data from the retrieval phase. During this phase the Shuttle manoeuvred to approach and grapple the Orfeus-SPAS satellite. We will use the delta-v information derived from the Inertial Measurement Units in order to identify the Shuttle manoeuvres and to relax the constraints to the empirical accelerations around these times.

CONCLUSION

ATV will be the first ESA project in which GPS will be used operationally to navigate a spacecraft. In order to be validate the use of GPS the ARP Project is being carried-out, including Flight Demonstrations. ESOC is computing trajectories for the spacecraft involved in these flights by combining the on-board obtained measurements with precise GPS products obtained processing ground based data. The trajectories so obtained are expected to allow for the validation of the relative navigation algorithms that will be used for ATV.

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