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Operational Considerations of Using GPS for Spacecraft Navigation

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Abstract

The Flight Dynamics Facility (FDF) at the NASA Goddard Space Flight Center (GSFC) has provided operational spacecraft orbit support for many years, currently generating orbit products for about 20 satellites. To date, operational orbit determination in the FDF has been performed on the ground using data from ground-based or space-based tracking systems. Current development of spaceborne Global Positioning System (GPS) receivers is projected to have a significant effect on the support needed for operational satellite navigation. This paper identifies the functions performed in spacecraft navigation and examines and quantifies how the functions and support levels will be affected as onboard GPS receivers are implemented on spacecraft. Cases are considered spacecraft using or not using NASA ground and space networks resources.

1.0 Introduction

Interest in use of the Global Positioning System (GPS) for spacecraft navigation has grown considerably in recent years with the flight of several experiments and new spacecraft committing to the operational use of GPS. Often cited as drivers for this movement are reductions in ground operations, including elimination of traditional tracking, orbit determination, and state vector uploads to the spacecraft. Evidence is often anecdotal, focusing on only one or two issues. This paper examines the functions performed in support of spacecraft navigation and assesses the effect on ground systems.

1.1 Flight Dynamics Functions

The Flight Dynamics Facility (FDF) at the NASA Goddard Space Flight Center (GSFC) provides orbit, attitude, and TDRSS or station acquisition support for about 20 NASA and non-NASA spacecraft. FDF functions include analysis for mission planning, launch support, and routine operational support. FDF receives tracking data and telemetry and generates orbit, attitude, and acquisition products that are distributed to spacecraft control centers, scientists, and tracking networks. Figure 1 illustrates key interfaces and functions of the FDF.

FDF involvement with a spacecraft continues from the conceptual phases through the end of mission life. Support includes both analysis and operations. The following are considered as high-level navigation functions performed in the FDF:

- Mission design and orbit analysis
- Orbit determination
- Trajectory Control
- Scheduling and planning aid generation
- Acquisition data operations
- Calibration and verification of onboard system
- Onboard compute table generation
- Metric tracking data evaluation
- Anomaly resolution.

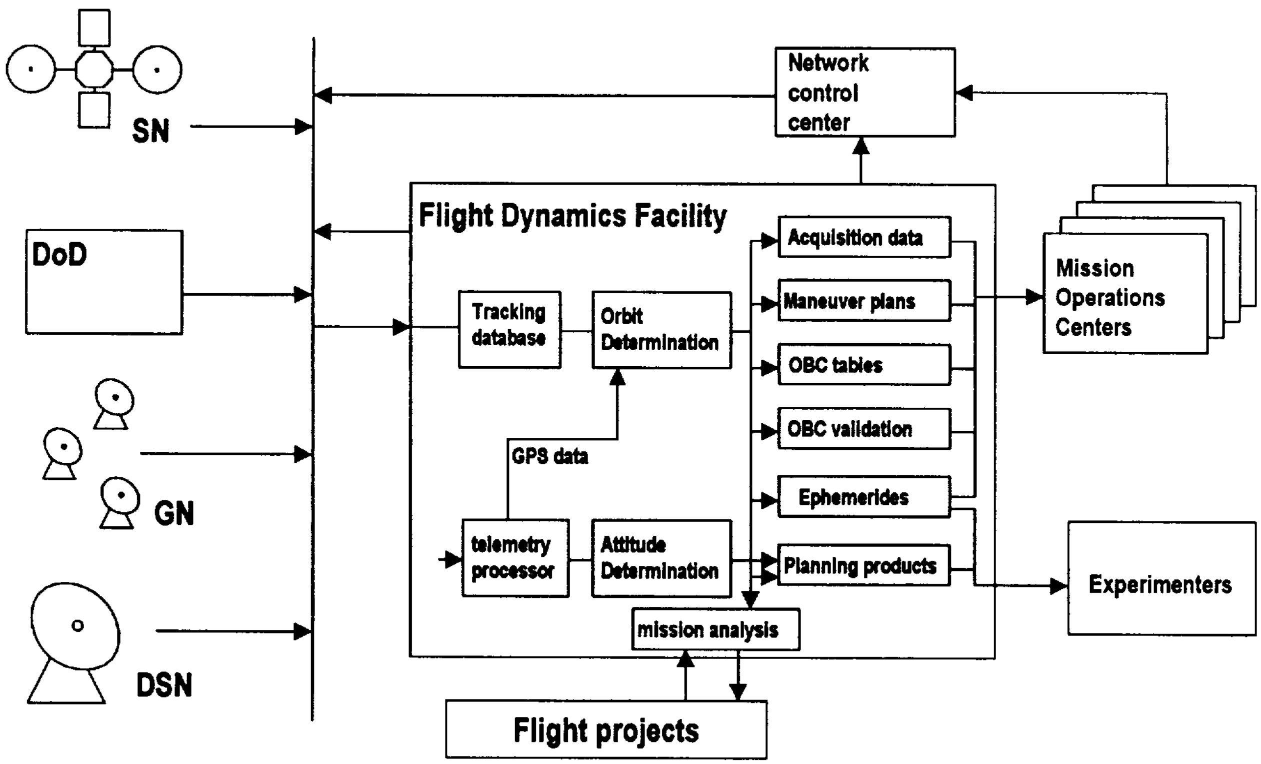

Figure 1. GSFC Flight Dynamics Facility overview

1.1.1 Mission design and orbit analysis

Given mission objectives, analysis is performed to determine an orbit that meets all requirements and constraints. Selection of the mission trajectory influences sensor placement on the spacecraft as well as power, attitude, and propulsion system design and requires close coordination between instrument developers, spacecraft designers and flight dynamics engineers in the spacecraft design phase.

Maneuver strategies must be developed for missions requiring propulsion for altitude or ground track maintenance, station keeping, rendezvous, reentry, etc. Elements of these studies may include trajectory optimization, minimization of fuel usage, orbital decay/lifetime projection, and reentry targeting. These activities continue through the mission in response to altered mission requirements or changes in spacecraft performance.

Other important considerations include error analysis to ensure that orbit accuracy requirements are met with the given tracking inputs, and analysis to determine launch windows.

1.1.2 Orbit Determination

Spacecraft trajectories may be estimated from a variety of observational types—ranges, Doppler, angles, and vectors are routinely used. As shown in Figure 1, FDF receives tracking data from NASA ground and space networks as well as Department of Defense (DOD) sites and others. Tracking data is automatically captured, pre-processed, and stored in the FDF tracking database for orbit determination by the Goddard Trajectory Determination System (GTDS).

For most FDF-supported missions routine orbit determination is performed three day per week in a largely automated process, including automated quality assurance. Orbit operations personnel are on call or provide support during launches or critical orbit maneuvers.

1.1.3 Trajectory Control

Maneuver sequences are planned to adjust an orbit to meet mission requirements. The ideal maneuver in terms of the mission orbit may conflict with communications, power, or other constraints, so the spacecraft operators are closely involved with maneuver planning and give final approval of maneuver plans. Following a maneuver, the achieved orbit is analyzed to determine actual performance of the spacecraft thrusters. Thruster calibration and bookkeeping of fuel used are important in identifying thruster malfunction and planning subsequent maneuvers, particularly for the first maneuvers following launch when the performance is not well known and may be changing. Special post-maneuver orbit determination for rapid evaluation or thruster performance is performed following critical maneuvers.

1.1.4 Scheduling and Planning Aids

Ephemerides from the definitive orbit determination process serve as the basis for generating predictive orbits and scheduling and science planning aids. Users of NASA's space network, ground network, or Deep Space Network are required to deliver projected orbits as far as two weeks in advance for network scheduling. Orbit-based products are generated to meet the requirements for spacecraft operation and science instrument management. Events such as eclipses or view periods and geometrical relations between the spacecraft and sun, for example, are computed from the predicted orbit. Attitude and orbit information are often combined to generate products for antenna pointing or scheduling viewing for instruments.

1.1.5 Acquisition Data Operation

Acquisition data are generated for the ground and space networks during launch and routine operations phases. Acquisition data are used for antenna pointing to a spacecraft.

1.1.6 Onboard system calibration

This analysis is performed during launch and routine operations to ensure the integrity of the onboard navigation algorithms. Onboard vectors returned in telemetry are compared to the ground-based orbit to validate performance.

1.1.7 Onboard Computer Support

Spacecraft typically obtain orbit information onboard from polynomial fits to a predicted orbit or an orbit propagator. Both cases require uploading information to the spacecraft onboard computer (OBC). In the first, a table of coefficients is uploaded, and, in the second, a single state vector is used.

1.1.8 Metric Tracking Data Evaluation

This work is performed during launch and routine operations phases to evaluate the tracking network integrity in support of the navigation, and to help resolve ground tracker equipment problems.

1.1.9 Anomaly Resolution

While no specific activities will be identified here, anomaly resolution is mentioned to acknowledge the need to deal with unexpected events during all phases of support.

1.2 Baseline support levels

Two missions were examined to provide representative levels of Flight Dynamics support. The Upper Atmosphere Research Satellite (UARS) and the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) were selected because they bracket the range of products produced by FDF in number and type. UARS performs periodic restoration of its frozen orbit, is supported by Tracking and Data Relay Satellite System (TDRSS), and requires many planning products for its multiple instruments. SAMPEX is tracked from the ground, has no propulsion, and has few product deliveries. Table 1 shows Flight Dynamics support staffing for the two spacecraft in the defined classifications.

Navigation Function	UARS	SAMPEX
1. Mission design and orbit analysis	0.2	0.2
2. Orbit Determination	0.2	0.2
3. Trajectory Control	0.3	0
4. Scheduling and planning products	0.8	0.3
5. Acquisition data operations	0.1	0.1
6. Calibration and verification of onboard system	~0	~0
7. Onboard computer table generation	0.1	0.1
8. Metric tracking data evaluation	0.2	0.2
Total	1.9	1.1

Table 1. Recurring operations support levels per year of mission support (man-years)

2.0 Effects of GPS on FDF support

At this time, the first spacecraft are implementing GPS receivers for operational use. Without long-term operational history, a level of performance was assumed for this study. GPS receivers have been proposed, ranging from simple data collection devices to units capable of full orbit determination and trajectory control. The receiver assumed here produces output suitable for use by onboard control systems and of sufficient accuracy to replace the definitive ephemeris.

2.1 Flight Dynamics Functions

The following sections assess the impact of a spacecraft using GPS on functions performed within the FDF.

2.1.1 Mission design and orbit analysis

Little changes in this area for spacecraft navigating using GPS. Mission design presents unique requirements for each spacecraft. For many missions in typical low, circular orbits for which post-processing is not required, error analysis can be eliminated assuming that the receiver has been proven to meet its specifications, and the specifications satisfy mission requirements.

2.1.2 Orbit determination

GPS has the potential to eliminate the need for routine definitive orbit determination for most missions. The onboard real-time and definitive requirements are met by the GPS standard positioning service levels of performance of 100m horizontal and 156m vertical at 95% probability. For missions with tighter requirements, post-processing will still be required. While GPS positioning is adequate for most missions, the velocity accuracy stated for many receivers is insufficient for ephemeris prediction and generation of long-term planning products. It is recommended that a navigation filter be included in the GPS receiver to improve the velocity solution over point solutions.

While orbit determination may be eliminated, operational savings are expected to be small given the high degree of automation in the ground support process. Orbit determination is one step in the product generation process, and its elimination amounts largely to a small reduction in CPU utilization. For facilities without orbit determination capability, this represents a greater savings in providing independence from network requirements, although orbit determination software is becoming more commonly available with commercial mission analysis software.

2.1.3 Trajectory Control

With the assumed autonomous navigation receiver, maneuver planning is still done on the ground. Again, little changes in this function except for the source of the input ephemeris. Once a labor-intensive activity, maneuver planning is recently becoming an automated process within the FDF.

The need for thruster calibration and fuel bookkeeping are not affected by GPS. Thruster calibration will require new techniques because post-maneuver orbit determination is necessary to evaluate thruster performance during a maneuver. The strength of GPS in trajectory control is that post-maneuver recovery of position knowledge is nearly instantaneous, so table uploads for post-maneuver conditions are not needed. If confidence in the propulsion system and GPS receiver are high real-time support for maneuvers may be reduced or eliminated.

The real-time nature of GPS orbit determination holds promise for completely autonomous navigation, including orbit maintenance and stationkeeping. Early development autonomous orbit control is under way.

2.1.4 Scheduling and planning Aids

Requirements for predictive products are not changed by the incorporation of GPS. Input to the process is switched from the definitive ephemeris to a GPS-derived state. It should be noted that GPS standard positioning service (SPS) performance for unfiltered, point solutions of velocity is less accurate than the traditionally determined ephemeris, and the effect on predictions should be considered against mission requirements. As a result of more capable spacecraft computers and instruments, more orbital event and pointing functions are being performed onboard, reducing ground support requirements.

2.1.5 Acquisition Data Operations

With the current NASA networks, GPS has minor impact on acquisition data operations. Again, the source of the input state vectors changes, but the generation and delivery do not. Changes to network operations designed to simplify scheduling and take advantage of GPS-derived states are under consideration.

2.1.6 Onboard System Calibration

The nature of the onboard system calibration function will change for GPS users, but the need to perform periodic check on onboard navigation performance remains. This function would migrate from the FDF to the mission operations centers.

2.1.7 Onboard computer Support

GPS can potentially eliminate some of the current table or vector uploads. The savings here will be seen in reduced system complexity, not in operations costs; with recent spacecraft, vector uploads amount to a mouse click to select from a list of available vectors. The GPS receiver represents a new spacecraft system, that requires management by the flight operators, and depending on the receiver design, the number of uploadable parameters may actually increase to accommodate initialization, modes of operation, and tuning parameters, although the uploads are expected to be less frequent than current practice. Orbit propagation may still be necessary if the spacecraft cannot power the receiver continuously or as a backup capability.

2.1.8 Metric tracking data evaluation

The current function is eliminated for a GPS user spacecraft. The equivalent function would be autonomous integrity monitoring within the receiver. Depending on the level of acceptable risk, the operations center may require external information on GPS integrity.

2.2 Support Levels

Table 2 gives an update of the mission support levels from Table 1 to reflect the effects of using onboard GPS navigation with no definitive post-processing. In addition support is estimated for a mission using its own ground station and having no propulsion.

Navigation Function	**UARS**	**SAMPEX**	**independent**
1. Mission design and orbit analysis	0.2	0.2	0.2
2. Orbit Determination	0	0	0
3. Trajectory Control	0.3	0	0
4. Scheduling and planning products	0.3	0.3	0.3
5. Acquisition data operations	0.1	0.1	0
6. Calibration and verification of onboard system	.1	0.1	0.1
7. Onboard computer table generation	~0	~0	~0
8. Metric tracking data evaluation	~0	~0	~0
Total	1.5	0.7	0.6

Table 2. Recurring operations support levels per year of mission support (man-years)

3.0 Other considerations

This survey has focused on functions performed within the FDF, but related functions are performed within the mission operations centers. Figure 1 shows a clear separation between FDF and the mission operations centers. However, as the FDF transitions from mainframe to distributed systems, the separation is becoming less distinct, and generation of scheduling and planning aids is becoming more common within the mission operations centers, saving some overhead and special support.

Spacecraft clock maintenance has been performed by flight operations teams using data provided by the FDF. Here, too, the process has become automated, so minimal savings will be realized in terms of operator workload by a GPS-user spacecraft. The compelling argument is more in the simplification of design for spacecraft and ground support systems realized by using GPS for timing.

Also neglected have been the FDF attitude determination functions for spacecraft using GPS as an attitude sensor. GPS attitude determination for spacecraft is in the experimental stages, so impacts on ground attitude support are not yet clear. Some missions may realize substantial reductions in hardware costs with GPS attitude determination.

4.0 Conclusions

In reviewing the functions performed in the FDF it is seen that support levels for a spacecraft using NASA network resources for communication are moderately reduced, primarily in the areas of routine orbit determination and tracking data evaluation. The trend in automation of ground-based orbit determination will reduce the degree of savings. Generating products and planning maneuvers are larger efforts than orbit determination, and greater operations cost savings can be achieved by including the functions onboard the spacecraft or by automating the processes on the ground. Automation minimizes workload, but it does not reduce support system complexity. GPS offers the possibility of eliminating some functions and simplifying the support system.

Less capable ground stations, at university, for example, will realize the full benefit of GPS navigation, being independent of the constraints and costs of network utilization for tracking and communications scheduling. Autonomous orbit control opens the potential for automatic orbit maintenance and relative navigation, including autonomous rendezvous and formation flying.

Current methods meet the requirements of presently supported spacecraft and can meet the requirements of all but a few future missions. Substantial reductions in operations support can be realized with continued automation on the ground and improved spacecraft flight software; the more compelling arguments for GPS spacecraft navigation are, then, not in elimination of functions but in an expansion of the realm of mission possibilities.