WAKESHIELD WSF-02

GPS EXPERIMENT

Final Report
NCC9-35

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September 1995

GPS Tracking Experiment of a Free-Flyer Deployed from Space Shuttle

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ABSTRACT

Shuttle mission STS-69 was launched on September 7, 1995, 10:09 CDT, carrying the Wake Shield Facility (WSF-02). The WSF-02 spacecraft included a set of payloads provided by the Texas Space Grant Consortium, known as TexasSat. One of the TexasSat payloads was a GPS TurboRogue receiver loaned by the University Corporation for Atmospheric Research. On September 11, the WSF-02 was unberthed from the Endeavour payload bay using the remote manipulator system. The GPS receiver was powered on prior to release and the WSF-02 remained in free-flight for three days before being retrieved on September 14. All WSF-02 GPS data, which includes dual frequency pseudorange and carrier phase, were stored in an on-board recorder for post-flight analysis, but "snapshots" of data were transmitted for 2-3 minutes at intervals of several hours, when permitted by the telemetry bandwidth. The GPS experiment goals were 1) an evaluation of precision orbit determination in a low altitude environment (400 km) where perturbations due to atmospheric drag and the Earth's gravity field are more pronounced than for

higher altitude satellites with high precision orbit requirements, such as TOPEX/POSEIDON; 2) an assessment of relative positioning using the WSF GPS receiver and the Endeavour Collins receiver; and 3) determination of atmospheric temperature profiles using GPS signals passing through the atmosphere. Analysis of snap-shot telemetry data indicate that 24 hours of continuous data were stored on board, which includes high rate (50 Hz) data for atmosphere temperature profiles. Examination of the limited number of real-time navigation solutions show that at least 7 GPS satellites were tracked simultaneously and the on-board clock corrections were at the microsec level, as expected. Furthermore, a dynamical consistency test provided a further validation of the on-board navigation solutions. Complete analysis will be conducted in post-flight using the data recorded on-board.

INTRODUCTION

The Wake Shield Facility (WSF) is a free-flying spacecraft deployed from the Space Shuttle for the purpose of growing thin semiconductor films for advanced electronics in an ultra-vacuum environment. The ultra-vacuum is created in low Earth orbit by a 4 meter diameter stainless steel disk with a mass of 1979 kg flying with its velocity vector perpendicular to the disk. The vacuum in the disk wake is expected to be 1000-10,000 times better than Earth-based laboratories can achieve. The WSF is a NASA-funded University of Houston experiment, with Space Industries Incorporated (SII) serving as the principal hardware development partner.

Launch of WSF occurred on STS-69, launched from Kennedy Space Center on September 7, 1995, 10:09 CDT. Since this was the second flight of the WSF, it was designated WSF-02. Release of WSF-02 to free-flight was at 06:25 CDT on September 11. The orbit parameters for this flight included an altitude of about 400 km, near zero eccentricity and inclination of 28.5 degrees. The WSF-02 was planned to operate in free-flight for about 48 hours, but operations were extended to 75 hours. The satellite was retrieved at 08:59 CDT on September 14 and Endeavour landed at Kennedy Space Center on September 18 at 06:38 CDT.

The spacecraft design and the orbit parameters make the WSF-02 a suitable platform to conduct other experiments. Several additional payloads were arranged to be WSF-02 Cooperative Experiments, including those provided by the Texas Space Grant Consortium (TSGC). The TSGC payloads were known as TexasSat. As one of the TexasSat components, The University of Texas at Austin proposed to fly a high precision GPS receiver on WSF-02 for the following purposes:

- examine the low altitude space environment and the effect of atmospheric drag and Earth gravity on the motion of the WSF in free-flyer mode,
- evaluate GPS dual-frequency receiver performance in a high precision operation mode that does not require access to the Department of Defense encryption of the GPS signals,
- assess ability to use GPS in a relative satellite positioning mode using the Shuttle GPS receiver and the WSF GPS receiver,
- use the WSF GPS data to obtain atmospheric temperature profiles from the GPS signals that pass through the atmosphere, referred to as "occultations".

Each of the experiment goals will contribute information to other space flight programs. The assessment of low Earth orbit accuracy is important for future satellites that will require high accuracy orbits. Although the 1335 km altitude TOPEX/POSEIDON (T/P) has demonstrated the ability to determine few-centimeter accuracy orbits in three-dimensions [Schutz et al., 1994; Yunck et al., 1994], no demonstration in very low Earth orbit with a high precision GPS receiver has been conducted. In addition, the relative positioning with GPS is potentially important for Space Station applications. The determination of atmospheric profiles will augment and enhance the measurements now being collected by the GPS/MET program [Ware and Exner, 1995].

In the following sections, the GPS receiver characteristics and the operational constraints are described. The operation of the GPS receiver through deployment and retrieval are given in a later section, along with the preliminary results obtained from the in-flight operation. Based on these results, preliminary conclusions are given in the final section.

WSF-02 GPS EXPERIMENT DESCRIPTION

The WSF/GPS experiment developed into a collaboration with the University Corporation for Atmospheric Research (UCAR), which is primarily interested in the GPS goal directed toward determining atmospheric temperature profiles. UCAR has been funded by the National Science Foundation and others to conduct such experiments on the MicroLab 1 satellite, launched in April 1995. UCAR acquired three GPS receivers based on the JPL/Osborne TurboRogue design. These receivers are referred to as the GPS/MET version of the TurboRogue. The availability of the GPS/MET backup receiver for the WSF flight was anticipated well before MicroLab 1 launch, but the availability was complicated by factors introduced by both GPS/MET and Shuttle launch schedule considerations.

The GPS/MET TurboRogue receiver is a flight version of the commercially available geodetic version. This flight version is now marketed by Allan Osborne Associates as the TurboStar. Thermal and vibration tests of the WSF-02 flight unit were conducted at the Ball Aerospace facility in Boulder, CO. This 2.3 kg receiver uses 17 watts during tracking and the dimensions are 25x25x10 cm. The receiver measures pseudorange and carrier phase on both L1 and L2 using a cross-correlation technique when the GPS satellites are transmitting in anti-spoofing mode. The receiver can track up to eight GPS satellites simultaneously. The receiver hardware design, tracking integrated circuits and software were developed at JPL for NASA and flight software enhancements were implemented by JPL under contract to UCAR.

The GPS experiment design was influenced by the bandwidth of the Wake Shield telemetry, especially during operation of the primary WSF experiment of gallium arsenide (GaAs) film growth. During these periods, the full telemetry bandwidth (9600 baud) was dedicated to this experiment. In addition, some GPS experiment objectives required high rate data collection, e.g., a 50 Hz sample rate, which could not be met with the telemetry bandwidth throughout the free-flight operation. With these considerations, it was apparent that all data should be recorded onboard for post-flight analysis. Nevertheless, other requirements for limited real-time data existed, such as health status and to support a NASA Johnson Space Center (JSC) real-time experiment organized by Heather Hinkel and Russell Carpenter, with the participation of Astronaut Jim Newman.

With the considerations for real-time and on-board storage of all data for post-flight analysis, NASA/JSC designed and constructed a solid-state recorder, which was capable of storing 80 mbytes of data. Recorder status information, as well as GPS pseudorange data and navigation solutions, were forwarded to the Shuttle and to the ground operation centers via the WSF telemetry stream. Ground telemetry commands enabled switching the receiver operation (and hence the recorder operation) to reduce the number of occultations recorded, thus slowing the rate of data collection. The atmospheric temperature profile analysis required the high data rate, which was the initial operation mode at receiver power on. Since the recorder had limited capacity, a telemetry command was available to reduce the number of occultations recorded, known as "low data rate".

The GPS antenna placement was a compromise between conflicting requirements. The ideal antenna orientation for atmospheric studies using the signal occultation is to have the ground plane perpendicular to the velocity vector, but facing in the anti-velocity direction. This orientation was achieved on MicroLab 1. On the other hand, the preferred orientation for precision positioning studies has the antenna facing the zenith direction to enable viewing all satellites with optimum geometry. Since these directions are orthogonal, a compromise was necessary. Additional constraints for the antenna placement were imposed by the Wake Shield.

A side view of the Wake Shield is shown in Fig. 1. While the ideal location for the antenna was the epitaxy housing on the wake side, contamination concerns prevented the placement of the antenna in this area. The compromise location for the antenna ground plane was the outer rim on the zenith side. An additional constraint imposed by WSF-02 required the ground plane to remain outside the epitaxy housing field of view. As a consequence, the ground plane was oriented 26° with respect to the zenith, as shown in Fig. 1. In order to accommodate the change in aerodynamics imposed by the antenna ground plane, similar "trim tabs" were placed elsewhere to provide balancing torques.

The antenna placed on the ground plane is a micro-strip antenna manufactured by Ball Aerospace. This antenna is identical to the antenna used with GPS/MET on MicroLab 1. An 0.5 db noise figure preamplifier was acquired from Miteq.

WSF-02 DEPLOYMENT AND RETRIEVAL

Space Shuttle Endeavour was oriented in a gravity gradient (GG) attitude prior to the WSF-02 deployment operations. The GG orientation was used to eliminate contamination of WSF-02 by Endeavour's attitude thrusters. The Endeavour orientation in GG mode is shown in Fig. 2, which also illustrates the orbiter velocity vector (V).

The WSF-02 was removed from the cross-bay carrier (unberthed) using the Remote Manipulator System (RMS) at 00:51 CDT, September 11, 1995. Mission Specialist Newman maneuvered Wake Shield into the "ram clean mode", an orientation with the wake-side of WSF-02 directed to the incoming wind (opposite the normal orientation of the satellite). The purpose of the ram clean orientation was to use the relative wind to remove contaminants from the wake-side. In this orientation, the GPS antenna was on the Earth side, an undesirable orientation for activation of the GPS receiver. The WSF was held in this mode for about 2.5 hours.

After completion of the ram cleaning, WSF-02 was moved with the RMS under Mission Specialist control to the normal attitude orientation with the wake-side directed in the anti-velocity vector direction and the ram-side facing the incoming wind. The GPS antenna was on the zenith side as well. While attached to the RMS, the WSF attitude determination and control system (ADACS) underwent checkout. This checkout was conducted for about 45 minutes. Fig. 2 shows WSF-02 in the ADACS checkout mode orientation. The TurboRogue receiver was powered up early in the ADACS checkout mode for the reasons given below at approximately 03:45 CDT.

The WSF-02 was moved with the RMS to the release position after completion of the ADACS checkout. This position is directly above the payload bay. Nominal release of WSF-02 was within 30 minutes after moving from ADACS checkout to the release orientation. However, communication problems delayed the release by one orbital revolution to about 06:25 CDT on September 11.

After release from the RMS, a nitrogen thruster on the WSF-02 provided a small thrust of 0.25N for approximately 14 minutes to increase the separation between the WSF-02 and the Shuttle. In this period, the Endeavour thrusters continued to be quiet to meet the WSF-02 contamination avoidance requirement. During the thrust period WSF-02 moved past the port side of the Shuttle and then above the Shuttle nose. A second thrust period of WSF-02 was not conducted. Instead, the separation induced by the initial thrust produced a separation of about 12 km, where the Shuttle maneuvering system was activated to further increase the separation to 63 km.

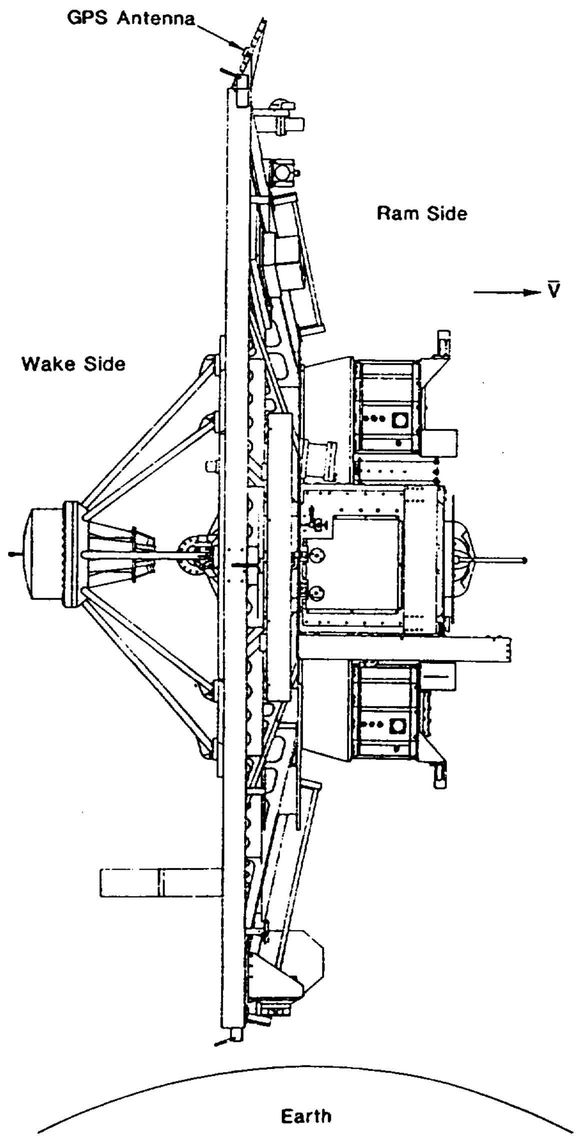

Fig. 1. Side View of Wake Shield Spacecraft

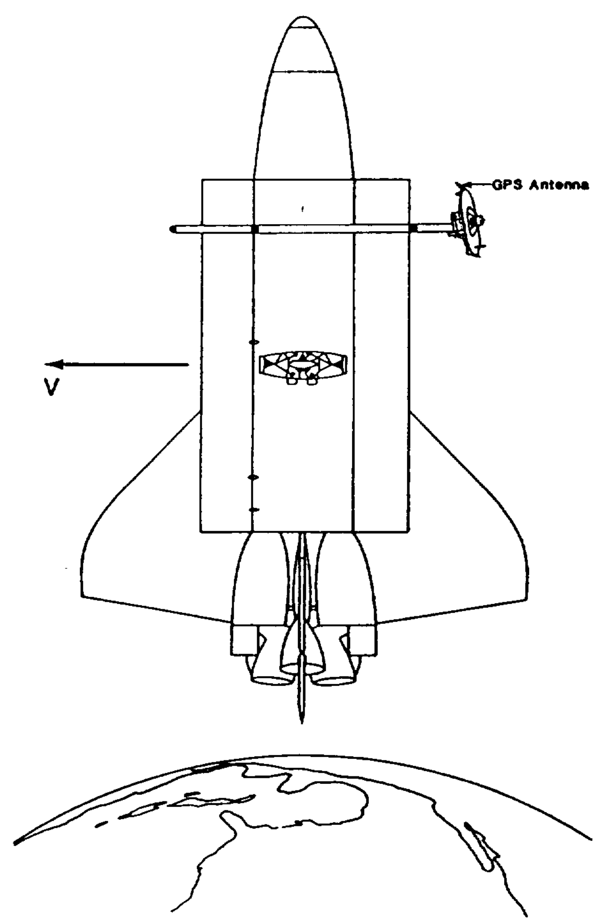

Fig. 2. WSF-02 in ADACs Checkout Orientation

The WSF-02 had been planned to operate in free-flight for about 48 hours; however, ADACS excursions were experienced and steps were taken to correct the system. These steps reduced the time available for the primary epitaxial film growth while in free-flight. As a result, the free-flight was extended to about 75 hours.

After completion of the primary experiment, the Shuttle crew maneuvered Endeavour to the vicinity of the WSF-02. The free-flyer was grappled by the RMS at 08:59 CDT, September 14. WSF-02 remained on the RMS for a few hours before being stowed into the payload bay. Endeavour landed at Kennedy Space Center at 06:38 CDT, Monday September 18.

GPS RECEIVER TESTS AND OPERATION

The solid state recorder, which used flash memory technology, was designed to provide power to the TurboRogue and communicate with the receiver via the receiver's RS-422 interface. In turn, the recorder was attached to the Wake Shield power distribution bus and communicated with the WSF-02 telemetry bus via an RS-485 interface. Because of the telemetry bandwidth considerations, the available telemetry commands were limited to the following:

- Recorder/receiver power on/power off
- Switch receiver data rate to low rate
- Activate/deactivate snap-shot of receiver data
- Reformat disk

As data were output from the receiver to the recorder, it was held in a buffer before writing to the solid state "disk". Under command, the snap-shot data were extracted from the buffer and sent to the WSF-02 telemetry bus. The data contained in the real time snap-shot were:

- Recorder temperatures
- Disk sectors used
- Data rate (high or low)
- Time and pseudo-range from receiver
- Time, receiver position (x,y,z) and clock correction

Various tests were conducted with the receiver and recorder during the year preceding the launch. A test of radio frequency interference (RFI) was conducted at the League City (TX) SII facility in December 1994. No RFI problems were detected while other WSF-02 experiments were activated.

In March, 1995, a test of the WSF-02 TurboRogue was conducted at JSC using a GPS signal simulator which created signals that were consistent with an orbiting receiver. On April 14, 1995, as part of final testing of the receiver/recorder at JSC, a short baseline (2 m) test was conducted with the WSF-02 TurboRogue and a Collins MAGR, similar to the receiver used on Endeavour. During April 18-20, 1995, the TurboRogue was integrated to WSF-02 at Hangar A/E, Cape Canaveral Air Force Station (FL). A receiver test was conducted using a Dorn-Margolin antenna located outside the clean room containing WSF-02. The coaxial cable with the D-M was attached to a "re-radiating" antenna, which was placed about 0.5 m from the WSF-02 antenna. The test was conducted using the WSF-02 power and telemetry bus. Although difficulties were encountered with the RFI environment in the vicinity of Hangar A/E, proper placement of the D-M antenna outside the hangar to shield it from the RFI sources resulted in a successful preflight test. The receiver was configured for flight at Hangar A/E on May 26 with software that had been tested in orbit on MicroLab 1. Data from the test was left in the recorder, which used 3.97% of the capacity.

The TurboRogue receiver on WSF-02 was activated prior to release from the RMS while in the ADACS checkout mode. The reasons for planned activation during this period were as follows:

- WSF would be in normal attitude or near-normal attitude (e.g., each axis within 30° of nominal attitude),
- WSF would still be attached to the RMS, thus enabling a short baseline calibration with the Shuttle Collins receiver early in the mission,
- WSF/GPS would likely be locked on GPS satellites when released from RMS to provide GPS data during the WSF thrusting period.

Experience with the similar GPS receiver on MicroLab 1 and signal simulations performed at NASA/JSC showed that full GPS lock-on could require up to 30 minutes from power on. Since the last pre-flight receiver test was conducted in May, 1995, under static operation at Kennedy Space Center, the receiver had no meaningful a priori information at the September 11 power on. The almanacs were nearly four months old and a reasonable a priori position was not available to the receiver. At power on, the receiver systematically searched GPS PRN, C/A correlation and doppler space until sufficient tracking data are available to determine the state vector. In summary, the TurboRogue searched for GPS satellites over all expected doppler values until it located C/A signals. These signals were analyzed using discrete Fourier Transforms to enable lock on the C/A code and acquire metric data.

RESULTS

At this writing, only preliminary results are available based on the snap-shot telemetry data. The full analysis will be conducted with the data recorded on the solid state disk, which will be available in early October.

Fig. 3 shows WSF-02 in free-flight, as seen by the Endeavour crew. The illustrated view shows the ram side and the GPS antenna ground plane is clearly visible as the protrusion on the "top" side, i.e., the side away from the Earth. The GPS receiver/recorder is in the enclosure 90° counterclockwise from the antenna.

Several snap-shots of data were collected following receiver turn on. These snap-shots were produced under ground command and most had durations of 2-3 min. The snap-shots are summarized in Table 1, which also shows the telemetered solid state disk use. Examination of the first four snap-shots shows that up to seven GPS satellites were tracked simultaneously during the snap-shot periods. The receiver-computed navigation solution, included in the telemetry, shows that the receiver clock was steered to GPS time since the computed clock correction was generally a few microseconds.

As evident from Table 1, the recorder accumulated data from the TurboRogue during several flight regimes. First, about 2.5 hours of data were collected with the WSF-02 attached to Endeavour with the RMS. Second, data was collected during the WSF-02 thrust period. And third, approximately 20 hours, of free-flight data were acquired. In addition, the Collins GPS receiver on Endeavour acquired data throughout the TurboRogue period, so various studies of relative positioning from GPS can be performed. The reason for the apparent premature tracking termination after 24 hours will be determined in the post-flight review of the recorded data and the hardware state.

Fig. 3. Endeavour View of WSF-02 Ram Side

TABLE 1. Summary of GPS Snap-Shots and Events

Time	Event	Disk Use (%)
September 11, 1995		
03:48 CDT	Receiver/recorder power on*	3.97
06:00 CDT	Snap-shot 1	Not avail.
06:25 CDT	WSF-02 release to free-flight	
06:27 CDT	WSF-02 thrust start	
06:41 CDT	WSF-02 thrust stop	
10:48 CDT	Snap-shot 2	12.49
15:00 CDT	Snap-shot 3	24.31
18:05 CDT	Snap-shot 4	25.25
21:22 CDT	Snap-shot 5	26.22
September 12, 1995		
03:05 CDT	Snap-shot 6	27.58

[All subsequent snap-shots show 27.58% used]

The rate of data accumulation in the solid state recorder through Snap-shot 3 shown in Table 1 is consistent with the expected occultation rate (50 Hz). However, the disk accumulation rate after Snap-shot 3 suggests that fewer occultations were being recorded. The occultation algorithm used in the receiver has been thoroughly tested on MicroLab, but the algorithm does rely on expected spacecraft attitude. No real-time attitude information was provided to the receiver. The reason for the apparent change in occultation scheduling will be investigated further in post-flight analysis.

An initial assessment of the data acquired in the snap-shots was conducted by evaluating the dynamical consistency of the (x,y,z) position solutions. In this test, a sampling of (x,y,z) from the free-flight snap-shots 2, 3 and 4 were used as "observations" for a dynamical orbit determination. In other words, the WSF-02 orbit was modeled with a large gravity field (degree and order 70 JGM-3), atmospheric drag, solar radiation pressure and other small perturbations. In one test, the (x,y,z) "observations" were fit with the University of Texas Orbit Processor (UTOPIA) over the 8 hours of the snap-shots and the WSF-02 initial state was estimated. The observation residuals had a root mean square (rms) of about 60 m. The experiment was repeated, but a drag parameter was estimated also and the resulting fit produced residuals with an rms of 20 m. The level of the residuals is consistent with GPS Selective Availability. This test demonstrated that the navigation solutions, derived from the pseudorange, give a dynamically consistent orbit at the expected level, thereby providing a strong indication that the GPS data acquired during the WSF-02 flight are valid.

The estimated orbit parameters for WSF-02 from the UTOPIA processing were:

Semimajor axis	6782 km
Eccentricity	0.0008
Inclination	28.45°
Equatorial altitude	404 km

CONCLUSIONS

A TurboRogue GPS receiver was carried on the second flight of the Wake Shield Facility. The receiver successfully operated for approximately 24 hours beginning at 03:48 CDT, September 11, 1995. Based on limited telemetry, high quality measurements were made by the receiver and all objectives of the experiment are expected to be met. Two anomalies were observed: 1) premature termination of tracking, possibly associated with high temperatures, and 2) the receiver appeared to stop scheduling occultations after 12 hours. These anomalies will be resolved with the post-flight return of the flight hardware and recorded data.

The dual frequency pseudorange and carrier phase measurements will be used to compute and study precision orbits for a low altitude (400 km) satellite. The techniques used for the precision orbit determination will be based on methodologies successfully applied to higher altitude satellites, such as TOPEX/POSEIDON. In addition, studies will be performed of relative positioning between the WSF-02 and Endeavour, using the Collins receiver on Shuttle and the TurboRogue on WSF-02.

ACKNOWLEDGEMENTS

This experiment was supported, in part, by the Texas Space Grant Consortium and the NASA Johnson Space Center under grant NAG9-750 and NCC9-35. The Wake Shield is supported by NASA Grant NAGW-977. Thanks to John Ries for the UTOPIA processing of WSF/GPS data.

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