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GPS as an Orbit Determination Subsystem*

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Abstract

This paper evaluates the use of Global Positioning System (GPS) receivers as a primary source of tracking data for low-Earth orbit satellites. GPS data is an alternative to using range, azimuth, elevation, and range-rate (RAER) data from the Air Force Satellite Control Network antennas, the Space Ground Link System (SGLS). This evaluation is applicable to missions such as Skipper, a joint US and Russian atmosphere research mission, that will rely on a GPS receiver as a primary tracking data source.

The Detachment 2, Space and Missile Systems Center's Test Support Complex (TSC) conducted the evaluation based on receiver data from the Space Test Experiment Platform Mission 0 (STEP-0) and Advanced Photovoltaic and Electronics Experiments (APEX) satellites. The TSC performed orbit reconstruction and prediction on the STEP-0 and APEX vehicles using GPS receiver navigation solution data, SGLS RAER data, and SGLS angles-only (azimuth and elevation) data. For the STEP-0 case, the navigation solution based orbits proved to be more accurate than SGLS RAER based orbits. For the APEX case, navigation solution based orbits proved to be less accurate than SGLS RAER based orbits for orbit prediction, and results for orbit reconstruction were inconclusive due to the lack of a precise truth orbit. After evaluating several different GPS data processing methods, the TSC concluded that using GPS navigation solution data is a viable alternative to using SGLS RAER data.

I. Introduction and Background

Detachment 2, Space and Missile Systems Center performs test, evaluation, and operations in support of U.S. Air Force research satellite programs. Orbit and telemetry operations are conducted through the global Air Force Satellite Control Network (AFSCN) and the Test Support Complex (TSC) located at Onizuka Air Station in Sunnyvale, California. The TSC currently performs orbit determination using range, azimuth, elevation, and range-rate data from a Space Ground Link System (SGLS) ground antenna network.

Orbit states for AFSCN vehicles must be determined and propagated with sufficient accuracy (approximately 1 minute in-track) to support antenna scheduling 2-3 weeks in advance. The AFSCN currently operates approximately 100 on-orbit vehicles. In addition to this, activities such as ground site testing, launch rehearsals, and maintenance/downtime compete for time with the AFSCN's 16 ground antennas. Large propagation error can lead to replanning and scheduling of the satellite contacts. These scheduled contacts can be lost due to conflicts with other network users. A minute is a large in-track error for a low-Earth satellite orbit prediction but it happens with dynamic atmosphere conditions and especially if a scheduled on-orbit maneuver is canceled or changed.

GPS receivers have been placed on several space vehicles, primarily as a data source for precise orbit determination in a non-realtime mode. Detachment 2 has processed GPS data for its vehicles, the Space Test Experiment Platform Mission 0 (STEP-0), the Radar Calibration (RADCAL) satellite, and the Advanced Photovoltaic and Electronics Experiments (APEX) satellite. The STEP-0 spacecraft uses a Rockwell Advanced Satellite Technology (AST) V six channel GPS receiver. RADCAL and APEX use a Trimble Advanced Navigation Sensor (TANS) Quadrex, coarse acquisition (C/A), GPS receiver. Future programs, such as Skipper, a joint US and Russian

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atmosphere research mission, will use a GPS receiver as the primary source of orbit tracking data. The TSC vehicles with GPS receivers are summarized in Table 1.

Table 1. Detachment 2 Spacecraft with GPS Receivers

Spacecraft	Launch	Orbit Inclination/Size	Mission
RADCAL	Jun 93	89.5 deg / 800 x 800 km	Radar Calibration U.S. Government space ranges
STEP-0	Mar 94	105 deg / 550 x 560 km	Autonomous navigation, laser and radio frequency measurement
STEP-2	May 94	82 deg / 600 x 800 km	Support Signal Identification Experiment
APEX	Aug 94	70 deg / 380 x 2500 km	Advanced battery and solar cell experiments
Skipper	Sep 95	98 deg / Initially 800 x 800 km, then 135 x 800 km	Atmosphere measurement, US/Russian joint mission

Though many TSC vehicles have GPS receivers, Skipper is the first TSC mission for which GPS will be the primary tracking data source. A SGLS ranging transponder is not being placed on the vehicle because of cost. Orbit prediction accuracies for Skipper must be sufficient to perform perigee raise maneuvers after low perigee operations near an altitude of 135 km. The end-of-mission activities include taking atmospheric measurements as the vehicle re-enters within site of the Kwajelien Atoll or the Kaena Point radar in Hawaii. Orbit determination and prediction will be challenging due to the limitation of only four ground contacts per day and a high drag environment due to a low perigee altitude. Using angles-only tracking data for orbit fits, even for eight contacts per day, can yield mediocre results (kilometers of error). Obtaining a reliable drag (B-factor) solution is the biggest problem since an error in this parameter will yield large errors in the propagation.

There are currently three options available for obtaining orbit position required for Skipper mission planning, scheduling, and experiment evaluation: GPS, SGLS angles only, and Air Force Space Command Space Surveillance Center (SSC) orbital elements. The current plan is to use navigation solutions from the Trimble TANS receiver to produce orbits. The backup plan is to use azimuth and elevation from SGLS and/or use SSC element sets.

The only orbit state information available to the TSC, other than SGLS based ephemeris, is from external agencies. Without the tracking data, the TSC obtains orbital elements from the SSC. For vehicles that have had an on-orbit anomaly such as a power or transmitter failure, commanding contacts are attempted until options are exhausted. It is crucial that the AFSCN antennas be pointed within the 0.25 degree half beamwidth (approximately 4 km at 1000 km range) for these recovery attempts. In this case, the pointing information is solely dependent on the SSC elements or on the propagation of aging TSC orbit elements.

Using STEP-0 and APEX GPS data processing, the TSC evaluated the use of an on-board GPS receiver as an orbit determination subsystem. GPS orbit determinations were compared to the SGLS based orbit determination system. The RADCAL satellite is not used in this study since it does not have a SGLS transponder. In addition, the TSC operates the STEP-2 which has a GPS receiver. The TSC does not have access to this data since payload telemetry is collected at another location.

II. Tracking Data and Orbit Determination Systems

The TSC performed orbit determinations for the STEP-0 and APEX spacecraft using SGLS, GPS navigation solutions, and SGLS angles-only data. Table 2 contains the data types and quantity used for orbit determination. The data types and amount are similar for both the STEP-0 and APEX vehicles. Twenty-four hour data spans were used for all the test cases. Data gaps of up to 2 hours exist in some STEP-0 GPS data spans. The SGLS and angles-only tracking data are not continuous. There are gaps of several hours between some ground contact times. Contact time for the STEP-0 vehicle is approximately 8 - 12 minutes. APEX is in a higher orbit, 380 x 2500 km, and its contact times vary from 10 - 20 minutes.

Table 2. Data Fitting for STEP-0 and APEX Orbit Reconstruction

Orbit Determination Data Source	Data Density STEP-0	Data Density APEX	Span (Days)	Data Fitting Methodology
GPS Nav Solutions	1/minute	1/minute	1	Batch Fit
SGLS R,RR,Az,El	100 points per contact (approx 8 contacts/day)	60 points per contact (approx 5 contacts/day)	1	Batch fit
Az, El (angles-only)	100 points per contact (approx 8 contacts/day)	60 points per contact (approx 5 contacts/day)	1 2*	Batch fit
Raw GPS	1/sec	1/sec	1	Differential GPS

* APEX used two days of angles-only data

Since most people outside the AFSCN are not familiar with the SGLS data, Table 3 describes the uncertainties in the four SGLS measurements. In some cases the uncertainties are due limitations in the modeling capabilities of of AFSCN observation processing and orbit determination software. The totals for uncertainty are worst case since the uncertainties are just summed.

Table 3. AFSCN SGLS Worst Case Measurement Uncertainties

	Measurement Type			
Uncertainty Type	**Azimuth**	**Elevation**	**Range**	**Range Rate**
Data Noise	0.02 deg	0.02 deg	5 meters	1 cm/sec
Bias	0.02 deg	0.02 deg	15 meters	1 cm/sec
Refraction*	0	0.02 deg	100 meters (15)**	3 cm/sec
Station Location	0	0	5 meters	0
Time Bias***	0	0	7 meters	4 cm/sec
Total	0.04 deg	0.06 deg	134 meters (47)	9 cm/sec

* The current AFSCN software models Troposheric refraction with a monthly average model and does not model Ionospheric refraction. This is not a measurement limitation but a software one.
** The large Range uncertainty is due to the unmodeled Ionospheric refraction around maximum solar activity at low elevations. This number is significantly less (15 meters) if the data used is limited to elevations above 10 degrees and throughout the "cooler" portion of the solar cycle.
*** The time bias for all stations is 1 millisecond.

The GPS receiver characteristics/configuration for STEP-0 and APEX are summarized in Table 4. APEX uses the TANS receiver which uses six channels to track and process coarse acquisition (C/A) code[1]. This receiver is not space hardened. The AST V receiver was designed to collect and process both the C/A code and precise (P) code. Since STEP-0 was launched after the full operations capability declaration of the GPS constellation, it does not receive P code, except from one of the older Block 1 GPS satellites. Hence, the STEP-0 receiver is effectively C/A-code-only with the current status of the GPS constellation.

Table 4. GPS Receiver Configurations used in Study

Receiver	Antennas	Channels	Code Processing	Pseudo-range	Carrier Phase
AST V (STEP-0)	1	6	C/A and P	Yes	Yes*
TANS (APEX)[1]	3	6	C/A only	Yes	Yes

* 1 sec destructive count - long periods (minutes) of carrier could not be reconstructed

Three different astrodynamic software systems were used to process the orbit tracking data from both vehicles. These are summarized in Table 5. The Command and Control Segment (CCS) used the WGS-84 41 x 41 geopotential, Jacchia 60 static atmosphere, and solar and lunar perturbations in a least squares batch fit for SGLS and angles-only orbit determination.

Table 5. Orbit Determination Software Systems

Orbit Software	Description
CCS	Orbit and telemetry processing system from the U.S. Air Force that performs orbit determination using SGLS track data.
MIRAGE	GPS differential processing system from the Jet Propulsion Lab used for processing TOPEX and modified to handle STEP-0 receiver data format.
TRACE	Astrodynamic analysis package from the Aerospace Corporation that can perform orbit determination on Earth-fixed Cartesian ephemeris such as GPS navigation solutions.

Since CCS does not perform differential correction on Earth fixed Cartesian vectors, the Trajectory Analysis and Orbit Determination Program (TRACE) system was used to fit the GPS navigation solutions. It uses similar force modeling and least squares technique as does CCS for performing the orbit determinations and propagation. Editing was performed to remove nonvalid or noisy navigation solutions.

The differential GPS solution for STEP-0 used the Jet Propulsion Lab's Multiple Interferometric Ranging Analysis and GPS Ensemble (MIRAGE) software. This system uses data from the NASA world-wide GPS receiver network so that it can effectively remove selective availability (SA) effects. MIRAGE uses the most sophisticated force modeling of the three systems. The force modeling includes a 50 x 50 truncated Joint Gravity Model (JGM) geopotential, Drag Temperature Model (DTM) atmosphere, solid earth and ocean tides, solar radiation, and empirical accelerations[2].

All orbits were reconstructed using 24 hour data spans except for APEX angles-only orbits, which used 2 days of data. For the STEP-0 orbit reconstruction cases, the differential GPS trajectory is used as a truth baseline to judge accuracy performance. APEX used a SGLS based orbit as a comparison baseline since a differential GPS based orbit was not available.

For the orbit propagation comparisons, the reconstructed orbits are propagated for one week and compared to a truth baseline. Fourteen days of SGLS based reconstructed orbits are used for the orbit prediction truth for both STEP-0 and APEX. Figure 1 shows an overview of the orbit determination and comparison process. Angle-only orbits are included in both the reconstruction and prediction test cases since the TSC wants to evaluate a backup orbit capability for the Skipper program.

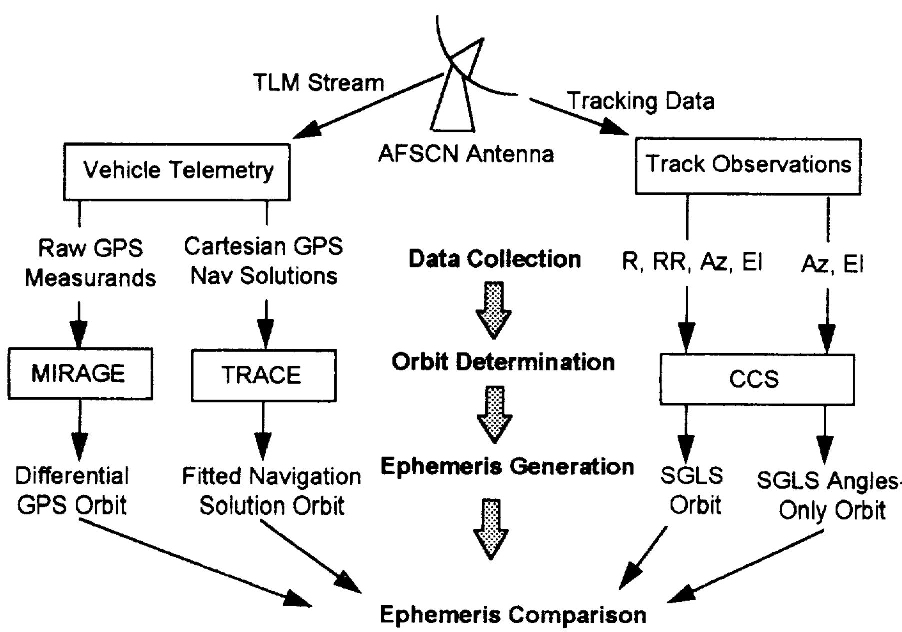

Figure 1. Orbit Determination and Ephemeris Comparison Process

III. Orbit Reconstruction

Differential GPS processing was performed for the STEP-0 vehicle. This yields position accuracy better than 10 m (3 sigma) [2]. Figure 2 shows STEP-0 orbit reconstruction accuracy compared to the differential GPS based ephemeris. Both the navigation solution fits and SGLS show consistency within a 30 m RMS. Orbit determination results using the once-per-minute navigation solution fair better with an average RMS difference for the six days of 15.7 m. Over the same comparison spans, SGLS showed an average root mean square (RMS) difference of 22.6 m. These position difference RMSs are based on a 24 hour span of three dimensional ephemeris differences at five minute increments. The differential GPS based ephemeris is used as the baseline since it is considered to have the best absolute accuracy.

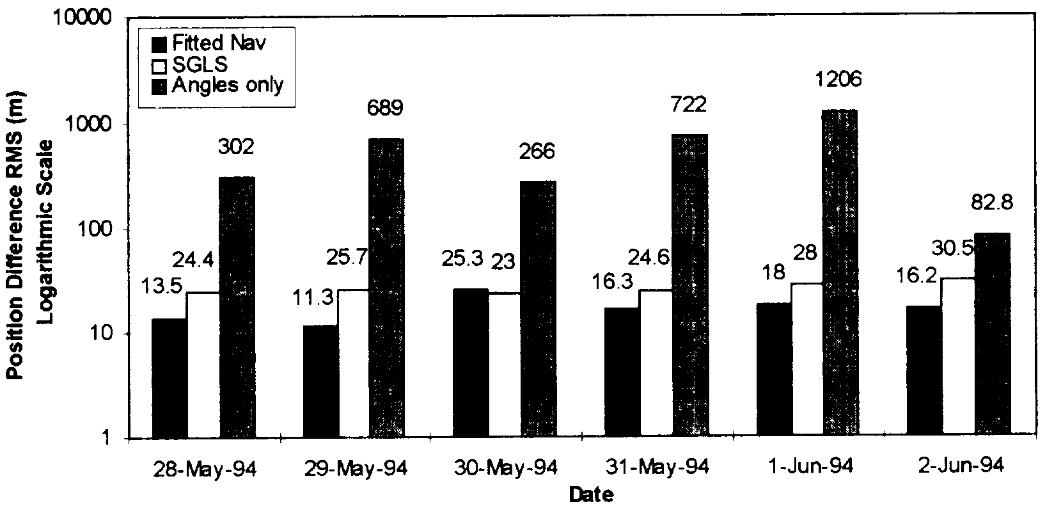

Figure 2. SGLS, Fitted Navigation Solutions, and SGLS Angles-only Orbits Compared to Differential GPS Based Orbit (STEP-0)

Orbit determination residuals for a STEP-0 navigation solution fit are shown in Figure 3. This case is representative of all the STEP-0 navigation solution fits. It has an RMS of the 3-D position residuals of 56.6 m and a standard deviation of 27.0 m. The prominent errors here appear to be induced by SA. Many of these orbit determination runs had data gaps of a couple hours. This was due to lost telemetry or that the receiver was not tracking and provided non-valid navigation solutions.

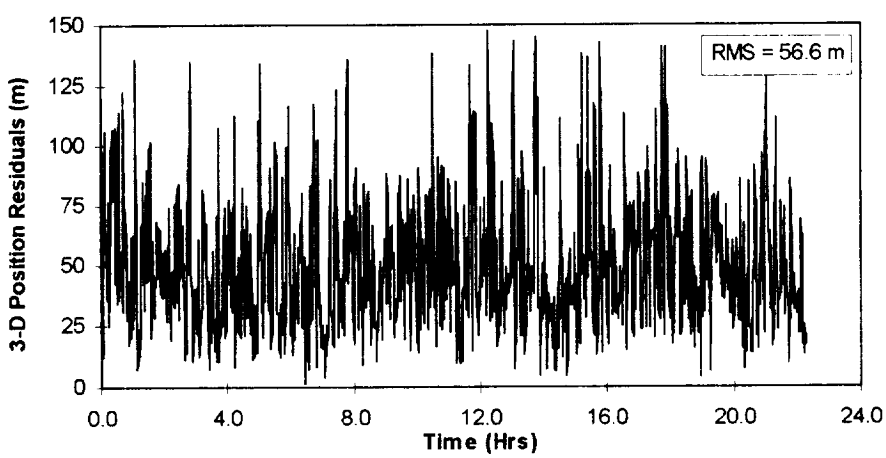

Figure 3. Residuals for STEP-0 Navigation Solution Fit, 31 May 1994

Since APEX does not have highly accurate ephemeris available, such as differential GPS solutions, GPS orbit determination results are compared to a SGLS baseline. Figure 4 shows fitted navigation solutions and angles only orbits compared to a SGLS baseline. Note that these angle-only orbits use two days of data. Results were so bad with one day fits that an additional day of data was used. The additional day is prior to the date of the test case as shown in Figure 4.

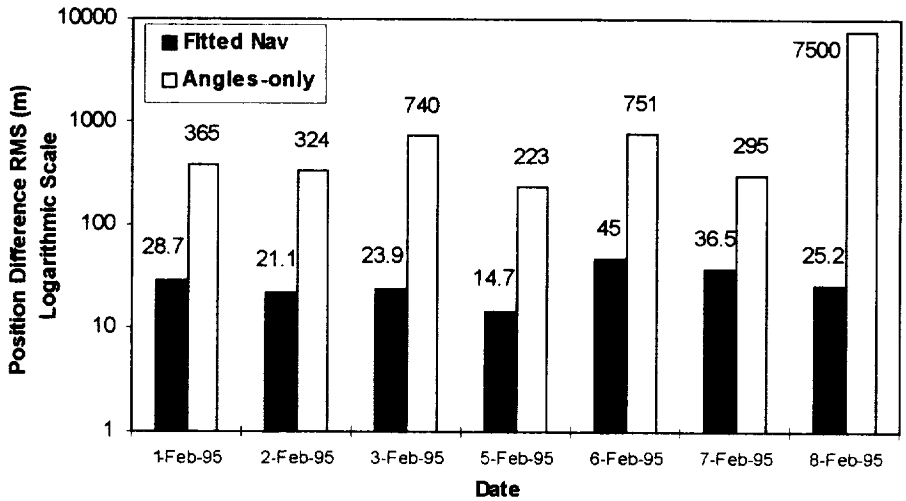

Figure 4. Fitted Navigation Solutions and SGLS Angles-only Orbits Compared to SGLS Based Orbit (APEX)

Orbit determination residuals for an APEX navigation solution fit are shown in Figure 5. It has a 3-D position residual RMS of 72.5 m and a standard deviation of 33.5 m. The RMS is 12 m higher than that for the STEP-0 navigation solution residuals. Since these orbit comparisons are at different time periods, it is possible that the GPS constellation SA implementation level could be different. It also might be attributed to both the receiver performance and vehicle orbit differences. APEX's perigee is 380 km and ionospheric signal delay could have contributed to the error at lower altitude regions.

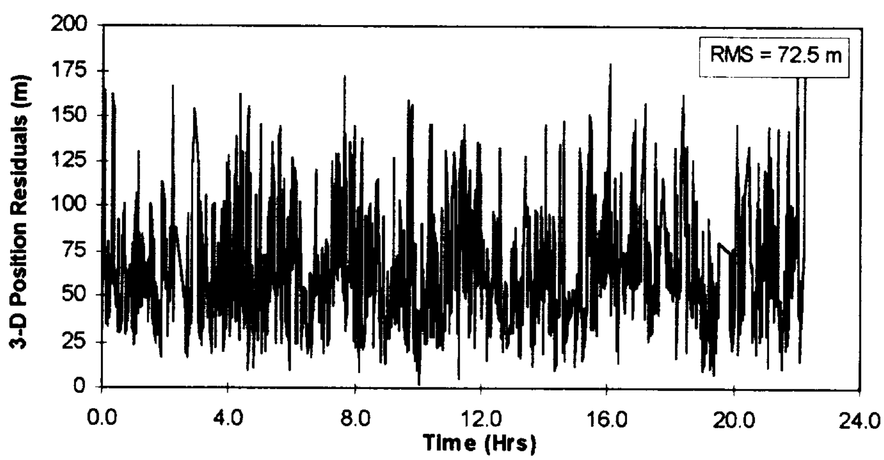

Figure 5. Residuals for APEX Navigation Solution Fit, 1 Feb 1995

IV. Orbit Propagation

The propagation results use the same orbit determination cases as used in the reconstruction comparisons as described in Table 2. The differential GPS orbits are not used in the propagation performance cases and an additional day of STEP-0 orbit determinations was added for June 3. Each test case uses and orbit based on one day of orbit determination data (two days for APEX angles-only) and propagates it for one week. Seven days of tracking data were used for both the STEP-0 and APEX test cases. These were propagated and compared to 14 days of reconstructed SGLS 24 hour truth orbits.

Figure 6 shows the average error growth for one week of propagation for STEP-0. Note that these prediction errors are the average of all seven cases. For example, the day four value of 46 km in Figure 6 is the average prediction error for each of the seven angles-only orbits at the four day point. For all seven of the SGLS predictions, the standard deviation was nearly 50% of the average prediction error. For example, the second day SGLS average prediction error of 1.05 km had a standard deviation of .51 km. This is 48% of the average prediction error. The average standard deviations for all seven days of navigation solution, SGLS, and angles-only predictions were 77%, 50%, and 63% of the prediction error values, respectively.

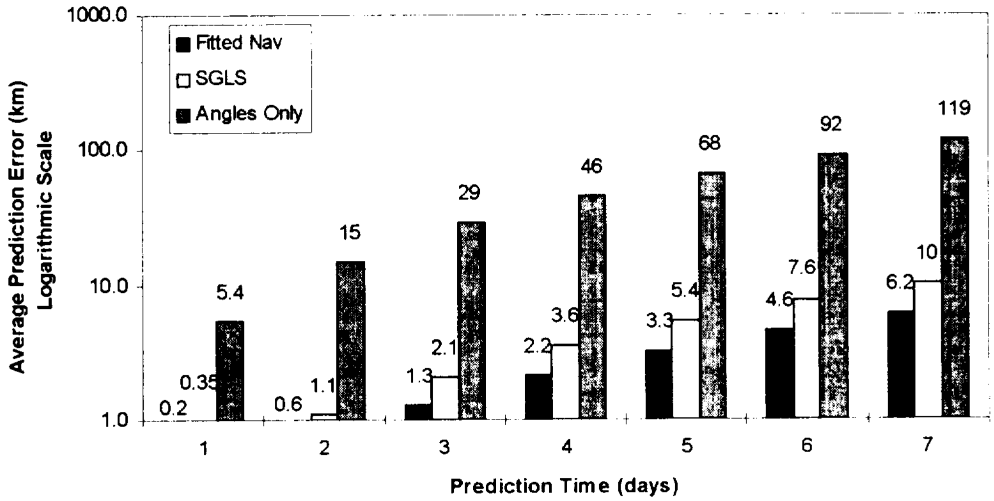

Figure 6. Propagation Error for Fitted Navigation Solutions, SGLS, and Angles-only Orbits Compared to SGLS Truth Baseline (STEP-0)

Even for the best atmosphere models, density uncertainty is generally the greatest error source in low earth orbit propagation. High amounts of solar activity increase atmospheric density at a given orbital altitude. If the solar activity during the orbit propagation period is not approximately the same as during the orbit determination period, this leads to significant in-track prediction errors. Figure 7 shows the F10.7 and Ap indices during the time of the STEP-0 test case propagations. Orbits determined in the time from about 30 May to 1 June will be predicting with a drag that is to high. Hence, the vehicle will be predicted to arrive earlier than actual arrival over ground sites. Prediction accuracies for orbits generated from 29 - 31 May had significantly higher prediction errors than the other orbits.

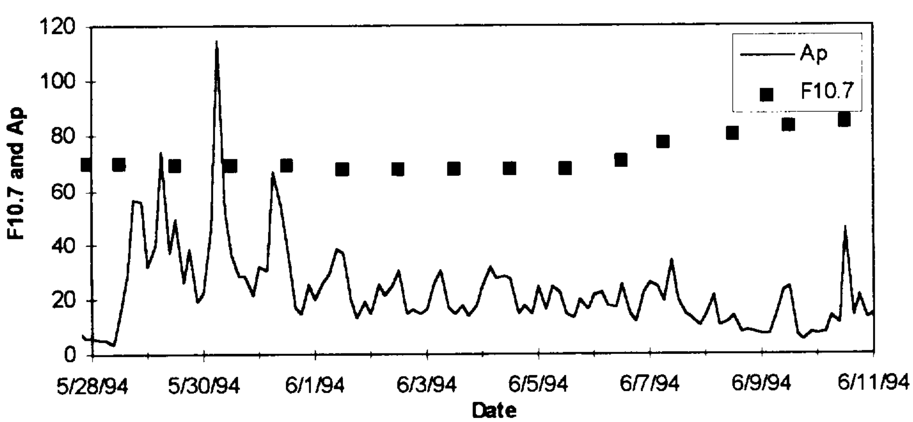

Figure 7. F10.7 and Ap indices from May 28, 1994 - Jun 11, 1994

Figure 8 shows an average error growth for up to a one week propagation for APEX. SGLS 24 hour fits were used as the truth baseline just as was done for the STEP-0 predictions. Figure 6 is composed of an average of propagation errors from seven different test cases. Each of these cases, which are referenced by the date of the actual raw data used, were produced using the fitted navigation solutions, SGLS, and angles only respectively. The average standard deviations for all seven days of navigation solution, SGLS, and angles-only predictions were 49%, 77%, and 93% of the prediction error values, respectively. Figure 9 shows the solar activity for this test period.

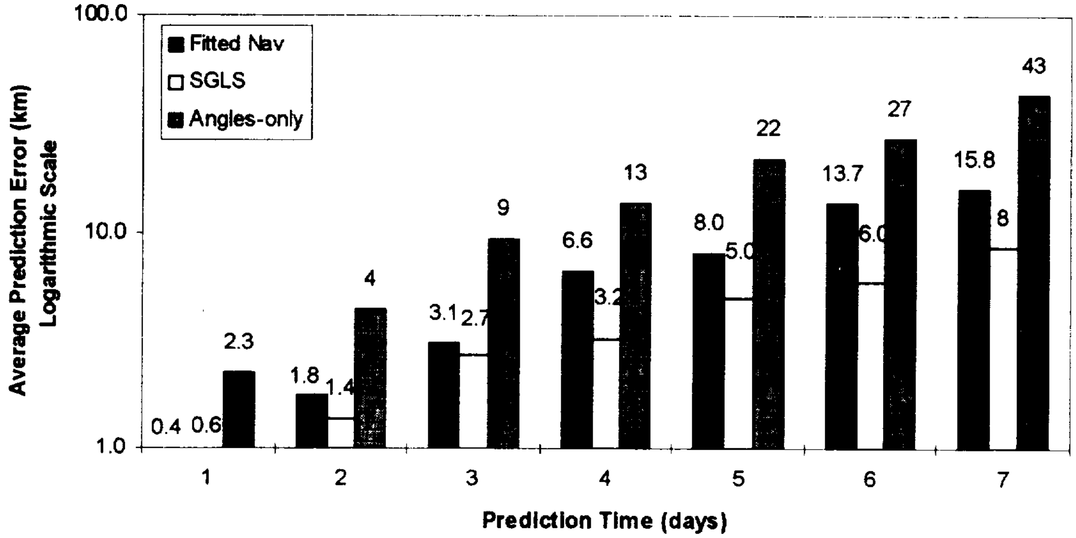

Figure 8. Propagation Error for Fitted Navigation Solutions, SGLS, and Angles-only Orbits Compared to SGLS Truth Baseline (APEX)

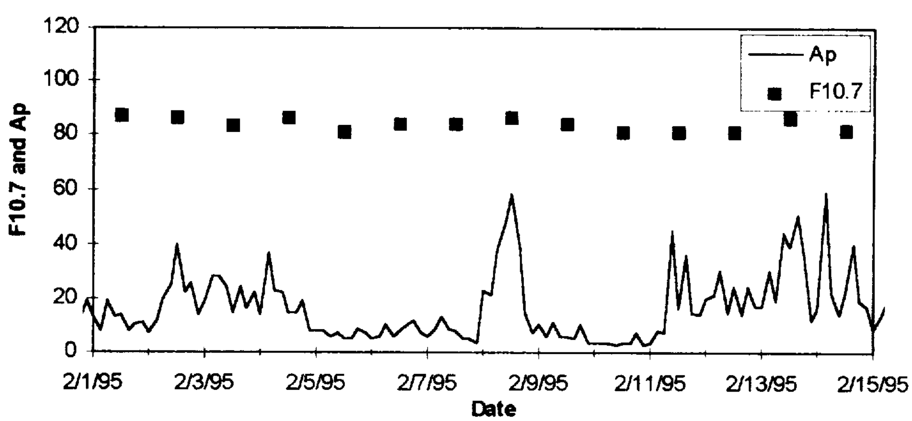

Figure 9. F10.7 and Ap indices from Feb 1, 1995 - Feb 15, 1995

Using angles-only for both one and two day fit spans provide solutions that are an order of magnitude less accurate than normal SGLS or GPS. The orbit reconstruction test cases are not optimized for prediction performance. Ideally, orbit propagations over a week should use more than one day of orbit determination data. Increasing the length of the fit span helps mitigate solar activity spikes and would improve prediction for both STEP-0 and APEX. Further study in this area should look at a variety of data spans during differing solar conditions. Also, an additive deweighting least squares fit could have been used in this study. Past TSC experience has shown additive deweighting generated orbit predictions are more sensitive to atmospheric disturbances.

Based on the STEP-0 and APEX orbit prediction results, it would appear that the TSC should encounter little problem in supporting Skipper orbit determination operations. Even if angle-only fits are used with at least a two day fit span, this would probably be sufficient to communicate with the vehicle. A problem exists: Skipper will operate at a perigee as low as 130 km and will be performing orbit maneuvers every 48 hours on its way down from 800 km to 130 km. Hence two days of orbit determination will not be available and orbit propagation will not be as accurate as STEP-0 or APEX when the Skipper orbit reaches a low perigee.

V. System Considerations

Most work in the space based GPS navigation area has focused primarily on accuracy. Tremendous results have been achieved by JPL for the Ocean Topography Experiment (TOPEX/POSEIDON) program where 3-D position accuracies of approximately 13 cm have been achieved. But does it make sense to use GPS on other types of vehicles where accuracy requirements are not so stringent.

There is a wide range of downlink bandwidth requirements required for GPS orbit determination. If only tens of meters accuracy is required then a few hundred navigation solution vectors should suffice for orbit determination. This may only amount to 100 - 200 kilobytes of data per day. The STEP-0 GPS receiver produced data at one second intervals and produced 25 MB per day of GPS data. This raw data included the pseudo-range and carrier phase, navigation solutions, and almanac data.

SGLS is the orbit determination method of choice from the TSC perspective due to the large amount of software and infrastructure that is already in place. A vehicle or mission designer may not be so constrained in this choice. Orbit determination using SGLS is a very well established process which only requires periodic software and procedural updates. Using other systems that support GPS data processing require the TSC to develop support software and integrate this with current software and hardware.

VI. Operational Considerations

An on-orbit GPS receiver is one more payload that must be managed and integrated into vehicle ground operations and on-board resources. Using a GPS receiver, rather than the traditional SGLS transponder for tracking data, has many of the same operational risks as well as benefits.

Reliability is a paramount concern, especially considering the experience the TSC has had with both the STEP-0 and APEX receivers. APEX relied on the real-time Cartesian navigation solutions from the TANS receiver for attitude and payload operations control. This implementation was terminated after receiver data problems caused attitude anomalies. There was no on-board filter that evaluated the position/velocity values or receiver time for validity. An on-board orbit propagator is probably a much more robust solution for obtaining ephemeris data for a processor even though memory errors could certainly cause the same attitude anomalies. An on-board propagator has traditionally been used for obtaining this data for other satellites.

The AST-V receiver on STEP-0 has not been capable of providing tracking data since August 1994 and had many other periods of tracking difficulty prior to this. If an operations center requires very accurate predictions, then a large data gap caused by a malfunctioning receiver could be detrimental to certain orbit operations.

A major benefit of using a GPS receiver is that it can reduce the number ground station supports. For example, a low earth vehicle could store 24 hours of GPS data and then transmit this during one station contact. For a vehicle using the traditional ground based SGLS observations, additional contacts are required to collect track data, since one contact per day is insufficient for quality orbit determination. This is an extreme example but shows that an on-board GPS receiver would negate the need for additional tracking passes. If a program wants to alleviate the concerns associated with having an orbit determination system, then SSC element sets are an option. For agencies that work with the U.S. government, SSC element sets can be made readily available and an orbit determination subsystem would not be required. This configuration does create a lack of autonomy for certain orbit related operations.

VII. GPS Orbit Determination Subsystem Evaluation Summary

A summary GPS and SGLS orbit determination options are shown in Table 6. An attempt was made to account for the different factors that should be evaluated when selecting an orbit determination methodology. This table only considers GPS orbit determination options along with SGLS and does not look at other methods such as Doppler, laser ranging, or a combination of different data types.

Table 6. Evaluation of GPS Processing Methods

Method	Accuracy	Labor	Data Volume	Comments
Single Navigation Solution	> 60 m	Light	Very Small	No drag solution. Large propagation error. Test case not run.
SGLS	> approx 50 m	Light	Small	Current TSC method
Orbit Fit over C/A code Navigation Solutions	20 - 40 m	Light	Small	STEP-0 test cases
Orbit Fit over Navigation Solutions with SA removal	5 - 15 m[4]	Light	Small	RADCAL method. Used SA algorithm knowledge. Requires secure environment. Used GPS almanacs.
Orbit Fit over P code Navigation Solutions	< 5 - 15 m	Light	Small	No test cases investigated. Requires encryption keys.
Differential GPS using receiver pseudo-range only	< 10 m	Heavy	Large	Large CPU and disk usage. STEP-0 test case. Uses carrier phase data from GPS ground network
Differential GPS using pseudo-range and carrier phase.	< 1 m	Heavy	Large	Large CPU and disk usage. Current TOPEX method.

Stated accuracy values are approximate and in most cases have been achieved and documented by different agencies. No examples of performing orbit determination with P code based navigation solutions was referenced. This chart does not try to extrapolate these results to all orbit regimes and conditions. It does attempt to show different methods used in achieving different levels of on-orbit accuracy. JPL has proven differential GPS processing to the sub-meter level.

The labor ratings refer to the approximate amount of personnel hours required to complete data editing and orbit determination with current TSC methods. A labor rating of Light means less than two hours, Medium is two to four hours, and Heavy is greater than four hours. The Data Volume category includes all tracking data plus any other data necessary. For the differential case this would include such items as GPS initial orbits, NASA receiver network data, solar flux, and receiver measurands. All of the options except for differential GPS require a small amount of data, meaning less than a couple of megabytes (MB).

The differential GPS processing performed by the TSC and JPL is a very intensive computational process. To perform differential GPS processing one must obtain data from the NASA GPS ground receiver network. The TSC would use approximately 14 MB of this data for a one day fit. If continuous spans of very accurate ephemeris are needed, such as required by the TOPEX mission, then a satellite program must be willing to invest in software automation tools, hard disk storage, and trained analysts/programmers. On the other extreme, the TSC has found that fits using the receiver navigation solutions are a straight forward process that many organizations could take advantage of.

VIII. Conclusion

The orbit determination methodology used for a particular program is very dependent on required accuracies, existing infrastructure, and compatibility requirements. The TSC has determined that navigation solutions at the once per minute rate would provide better or comparable accuracy than the current SGLS system. If a spacecraft flown by the AFSCN requires greater than 10 - 20 meters accuracy, then the spacecraft program must be prepared to invest in software development and ground processing to perform differential processing. Another option to meet these accuracies is to obtain access to the classified P code or SA removal process.

Many factors besides accuracy should be considered before deciding on GPS as an orbit determination subsystem. GPS data must be budgeted into the spacecraft telemetry. labor and processing is required if a satellite program requires better than 10 m accuracy. Further study into the orbit determination subsystem evaluation should examine the following areas:

1) Navigation solution density relationship to orbit determination accuracy
2) Quantification of labor spent on spacecraft orbit data processing
3) Downtime of different GPS receiver models while on orbit
4) Differential GPS processing for the APEX data

IX. Acknowledgments

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