**Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum**

GPS TIME INTERVAL AND STATE MEASUREMENT FOR PARCS

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Abstract - **A science-quality space GPS receiver is being studied for the Primary Atomic Reference Clock in Space (PARCS) mission. The PARCS flight experiment is an International Space Station (ISS) payload that will conduct investigations into the laser cooling of atoms, time interval measurement, and fundamental physics. The receiver will make GPS carrier phase observations, to transfer the frequency measurements made by other PARCS subsystems to the ground and to determine the the experiment's precise position and velocity.**

The receiver is based on the Jet Propulsion Laboratory's BlackJack radiometric instrument. This is a dual frequency, codeless design that is a veteran of multiple spaceflights. The major challenges for its use on PARCS derive from the ISS environment, for example, the antenna field of view, multipath sources, and potential electromagnetic interference. Simulations indicate that the restricted field of view will be the main limitation, and that the receiver antenna should be tilted away from the ISS structure by ~30° for better results. The use of GPS ground networks and data analysis techniques to provide a total measurement system adequate to meet PARCS' requirements will need to be examined further.

Keywords - **GPS receiver, carrier phase, time interval transfer, PARCS, Space Station**

I. INTRODUCTION

The Primary Atomic Reference Clock in Space (PARCS) mission is part of NASA's Microgravity and Fundamental Physics Program. The flight segment is an experiment package that will be deployed on the outside of the International Space Station (ISS) [1]. This package is planned around a Cesium-based atomic frequency standard. Major subsystems include the Cesium source and beam tube with associated Ramsey cavities and shielding, a laser system for atom cooling and launching, an oscillator to support the microwave detector package, and a GPS receiver/antenna. The PARCS Principal Investigator is from the National Institute of Standards and Technology, and major development work is being performed the Jet Propulsion Laboratory (JPL). PARCS will be available for launch from late 2007.

The PARCS science goals, summarized in Table I, span a range of activities, from demonstrating the laser cooling of atoms in space to the creation of a very accurate clock and fundamental physics investigations. The GPS Subsystem contributes to 60% of the formal science goals by providing for GPS carrier phase time interval transfer from PARCS to the ground and by supplying state information – time-tagged position and velocity – needed for gravitational and relativistic effects to be considered in post-processing. The measurement goals for the transfer of the second provide the greatest challenge, with the goal being an accuracy of 100 ps over an averaging period of 10 days.

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

II. RECEIVER DESIGN TRADES

The GPS Subsystem comprises a GPS receiver, an antenna, and the cable between them. The receiver is a version of the JPL-designed "BlackJack" space receiver. This is a dual-frequency, codeless design which can simultaneously track signals from up to 16 GPS space vehicles (SVs), using up to 4 antennas. In addition to the usual features expected of space instruments, e.g. reduced mass, volume, and power consumption, it has been optimized to produce high-quality science observables while remaining relatively low cost. Some typical performance parameters are given in Table II.

BlackJacks have been used on 7 previous space missions, and several more are in the planning stage (Table III). With the exception of the Shuttle Radar Topography Mission (SRTM), which was Shuttle-based and therefore of deliberately short duration, all BlackJacks flown are still operating. The design is based on experience gained from two previous generations of JPL space receiver. These were known as the TurboRogue Space Receivers (TRSR) I and II. The first TRSR I comprised the GPS-MET experiment, launched on MicroSat-1 in 1995 [2].

TABLE I
GPS AND PARCS SCIENCE GOALS.

Mission goal	GPS measurement goal	Success weight
Laser cooling of atoms	Not applicable	20%
Accurate space clock	Time: 100 ps Position: 10 cm Velocity: 0.12 mm/s	30%
Space-ground frequency difference	Position: 100 cm Velocity: 1.2 mm/s	30%
Comparison of different clocks	Not applicable	20%

TABLE II

SOME PARCS BLACKJACK RECEIVER OPERATING PARAMETERS.

Parameter	Value / Range
Mass (without antenna/cables)	4.0 kg
Dimensions	25 x 25 x 15 cm
Power consumption	15 – 17 W
Operating temperature	-10°C to +40°C

The ISS is a unique space platform with its own benefits and drawbacks. The baseline location for PARCS is on the Japanese Experiment Module's Exposed Facility (JEM-EF), which is at the forward (+X) end of the Station and offset to the port side (port and starboard are defined relative to the velocity vector; port is therefore in the –Y direction in Fig. 1). PARCS will be sited at location 1 or 5, both of which are on the forward-facing side, or at location 11, on the JEM-EF's upper surface (Fig. 2). Among the many benefits of this placement are relatively generous operating resources, by spaceflight standards. For example, the PARCS mass budget at JEM-EF location 1 is ~500 kg, while the physical envelope is approximately 1.00 x 1.85 x 0.80 m. Up to 3 kW of power will be available, and a fluid loop can be used for cooling. Commands and data will be routed through an Ethernet connection. Additionally,

TABLE III

OPERATIONAL BLACKJACK RECEIVERS.

Mission	Launch date[a]	Science goal
SRTM	2/11/00	POD[b] for interferometric mapping
CHAMP	7/15/00	POD for gravity science and radio occultation
SAC-C	11/21/00	POD and radio occultation
Jason	12/7/01	POD for ocean altimetry
GRACE	3/17/02	POD for gravity science and radio occultation
FedSat	12/14/02	Non-precision orbit determination
ICESat	1/12/03	POD for laser altimetry

[a] mm/dd/yy format
[b] Precision Orbit Determination

PARCS will be transported to the Station by the Space Shuttle, which has a benign launch environment compared to expendable rockets. The low Earth orbit occupied by the ISS (altitude ~400 km, inclination 51.7°) means that the radiation environment will be lower than for most BlackJack missions.

While the ISS is a good platform for PARCS there are some significant issues to resolve from the point of view of the GPS Subsystem. One is the visibility of the sky, and

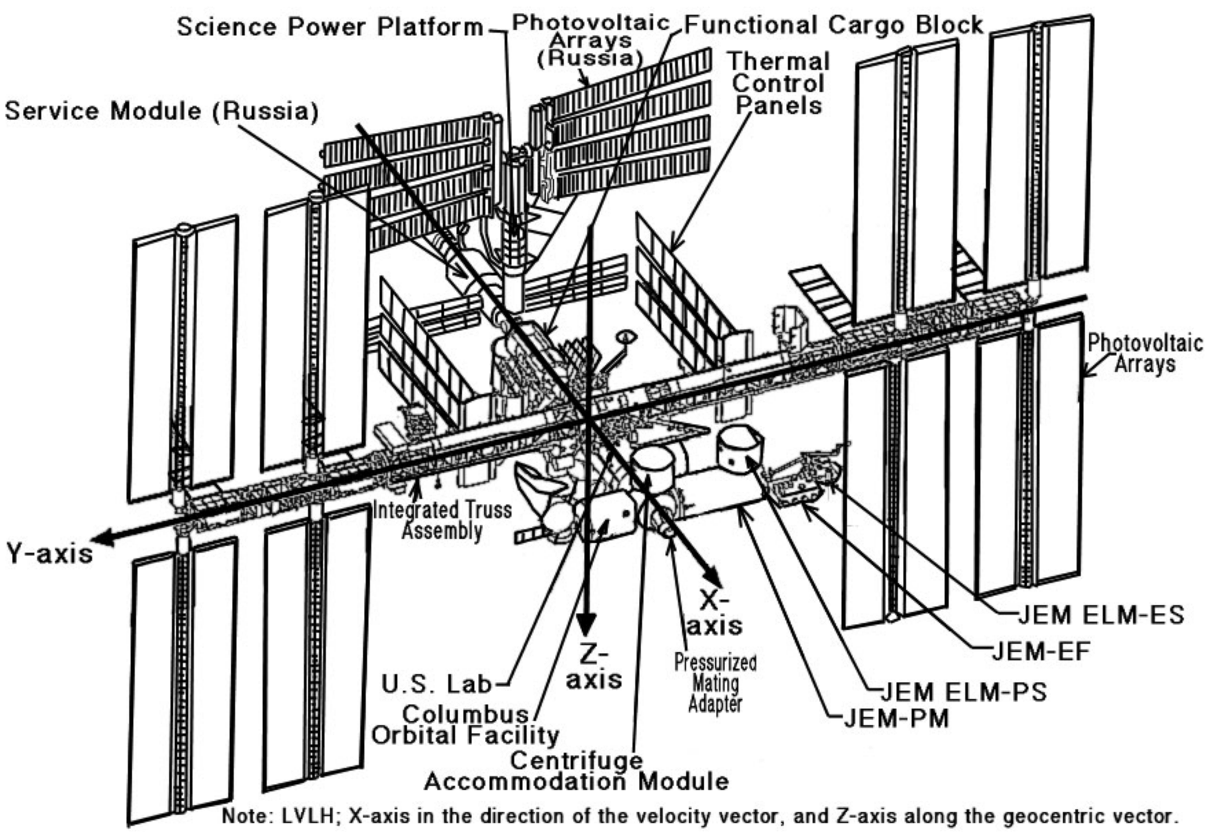

Fig. 1 The International Space Station final configuration (from [3]).

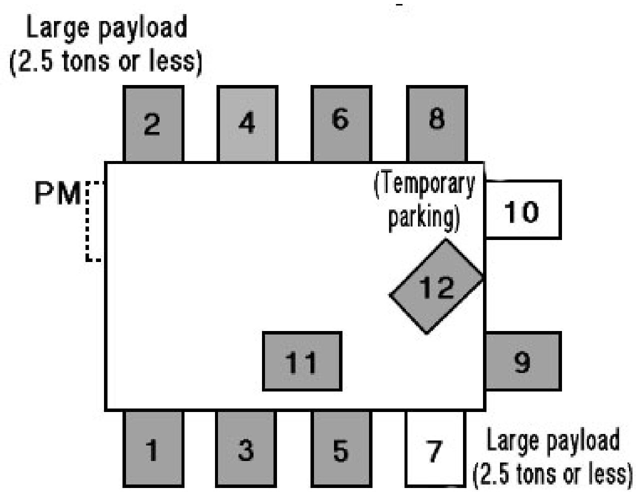

Fig. 3 Plan view of the JEM-EF showing attach locations. Forward is down in this diagram, and the JEM-PM is to the left (from [3]).

thus the GPS SV constellation. The ability to simultaneously trace ray paths to many GPS satellites and track their signals is critical to making accurate measurements. As well as the number of tracks it is important to achieve a spread of ray paths, to improve the accuracy of the GPS state solution, e.g. as represented by the Position Dilution of Precision (PDOP) metric. Modifying the BlackJack to track signals from other Global Navigation Satellite Systems (GNSS) in addition to GPS, i.e. Russia's GLONASS and Europe's Galileo, is an option that would increase the complexity and cost of the subsystem.

Results reported in this paper concern simulations of GPS visibility from PARCS, but there are other design issues that should be mentioned, and which have been recognized in more detailed studies of the GPS carrier phase technique, such as [4]. These include multipath – reflections of GPS signals from parts of the Station structure – and the temperature dependence of the GPS signal delays in the analog hardware, e.g. amplifiers, filters, and cables [5]. Other issues are an evaluation of the ISS electromagnetic environment for potential interference and the reconstruction of phase breaks, such as those caused by receiver resets. Receiver resets occur more frequently in space than on the ground, mainly due to factors related to orbital velocity, which gives rise to demanding tracking conditions, and the orbital radiation environment.

A final point is that the consideration of GPS Subsystem design described here is only part of what will be needed to meet PARCS' goals. In-flight the subsystem will provide observations that will be post-processed with the output of a larger measurement system. Components of this system will include ground GPS receiver networks, to evaluate GPS SV orbits and clock behavior, and models of the forces acting on the GPS SVs, the ISS, and the Earth.

III. GPS Visibility Simulation

GPS SV visibility simulations were performed for JEM-EF location 1, which is the baseline attach point for PARCS, and for an alternate position on the upper surface of the starboard truss, just inboard of the Solar Array Joint (close to the label "Integrated Truss Assembly" in Fig. 1).

Fig. 1 gives an intuitive sense of the obstructions visible from these locations. From the JEM-EF the starboard-wake quarter is almost entirely blocked by the JEM Pressurized Module (JEM-PM), while the wake direction from ISS local horizontal to an elevation of ~40° is blocked by the integrated truss assembly and the top edge of the port radiator group. To port, and a little to starboard, the view is obscured by the rotating solar arrays. It is obvious from this

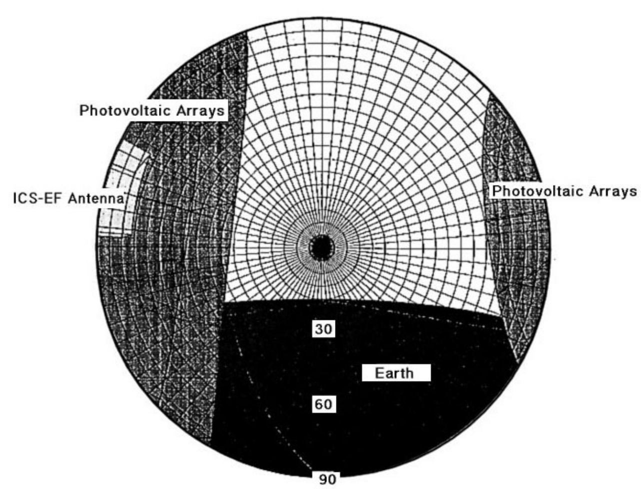

Fig. 2 Hemispherical field of view from JEM-EF location 1, centered on the forward direction (from [3]). The black region is the Earth, the dark gray is the region that could be occupied by the solar arrays, and the light gray area is a static obstruction. The grid uses 5° increments.

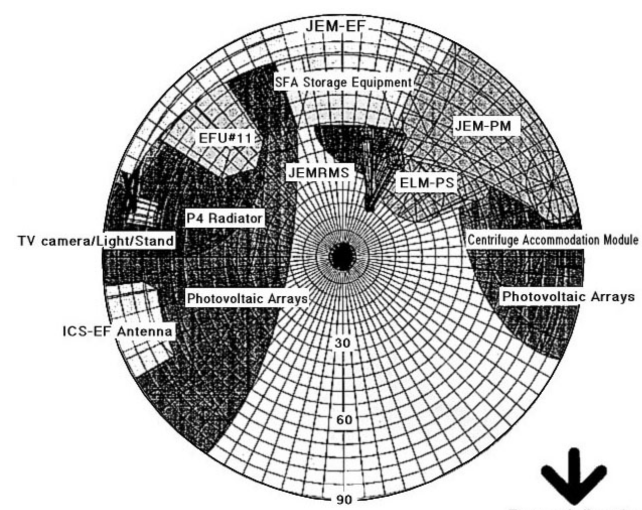

Fig. 4 Hemispherical field of view from JEM-EF location 1, centered on the zenith direction (from [3]). The grid uses 5° increments.

inspection that the best views of the GPS constellation will be obtained by mounting the GPS antenna on the upper face of PARCS, near the forward edge. Quantitative field of view data for this location was obtained from [3] (Figs. 3 and 4) and by examination of various drawings and models of the ISS final configuration. Unfortunately the final ISS configuration is some years away, so a definitive description of the ISS is hard to find, but [3] is consistent with other estimates.

Fig. 1 shows that the main obstructions for the S-truss location are the solar arrays, especially those in the nearby starboard array. In the wake direction the Russian Science Power Platform (SPP) is a significant obstruction. Other obstacles include some of the forward pressured modules and, under some conditions, the starboard radiator group. Quantitative data for the S-truss location was hard to acquire from literature. Instead masks were estimated using simulations of the views from the location provided by the Space Station Payloads Office [6]. Although these descriptions were less accurate than those for the JEM-EF, the approximation was tolerated because the location is not the PARCS baseline.

For both locations the static obstacles were easily represented, but the motion of the solar arrays presented a problem. They rotate once per orbit, which with the Station's orbit period of ~90 minutes corresponds to ~4°/minute. They continue rotating during eclipse, to maintain alignment with the Sun vector. Additionally, a joint at the base of each array provides a second degree of freedom, required to maintain array pointing over a longer timescale. The Sun angle, β, between the ISS orbit plane and the Sun vector, varies from –75° to +75° with a period of ~60 days (Fig. 5). The angle subtended by the array width will therefore vary from a minimum at β close to 0°, i.e. "edge on", to a maximum at high values of $|\beta|$, where the arrays are almost perpendicular to the vector to the antenna. The position of the radiators groups on the wake side of the truss also vary with β, although their impact is less significant than that of the solar arrays and only has a small impact in the JEM-EF case.

Estimating the variation of these obstructions was difficult, and in any case the JPL GIPSY software used in the simulation did not support time-varying field of view masks. Instead best and worse case conditions were initially examined, in the hope of usefully bounding the situation. The best case assumed that none of the solar arrays were in view, i.e. that the dark gray arcs in Figs. 3 and 4 were not obstructed. A variation where the SPP was not present was also considered for the S-truss case. The construction of the SPP is subject to funds being available in Russia. The worse case assumed that all of these regions were blocked, all of the time. In fact, the best case is close to the expected situation, as the arrays block a small fraction of the sky at any given time, and sometimes none, e.g. when the arrays are parallel to the antenna plane. The frequency transfer analysis was averaged over multiple days, and data from periods of poorer visibility could be removed to improve results. The worse case was too pessimistic.

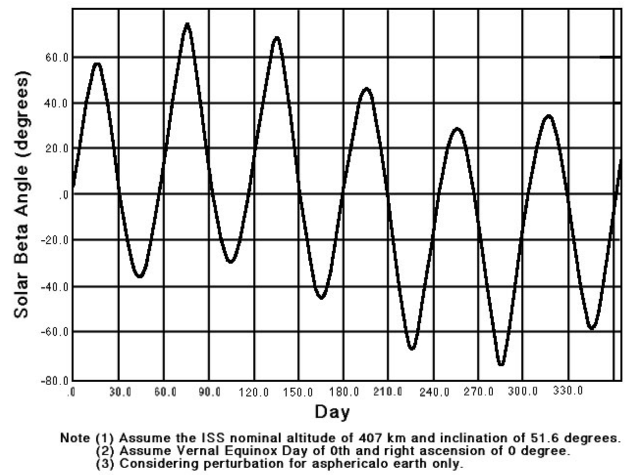

Fig. 5 Variation of sun angle at the ISS (from [3]).

PARCS will be operated during designated ISS microgravity periods. These fall between Shuttle resupply and reboost missions, and last ~30 days at a time. During these periods the Station assumes Torque Equilibrium Attitude (TEA) mode, which balances the aerodynamic and gravity-gradient forces on the structure. TEA mode will result in the ISS X-axis being ~10º "nose down" relative to the velocity vector. The X-axis will also be rotated a few degrees away from the velocity vector in the local horizontal plane, i.e. a yaw offset.

Another variable considered was the boresight of the GPS antenna. At an altitude of 400 km the Earth's limb is ~20º below local horizontal and it is clear that by tilting an antenna away from local vertical the part of the sky close to the Earth can be viewed. For the JEM-EF location 1 this means moving the boresight in the direction of the ISS +X axis (forward). The view that is lost is the mostly obstructed region at low antenna-relative elevations in the –X direction (Fig. 4). Both of these conditions are desirable, so additional simulations were done for the JEM-EF with forward tilts, relative to the Station, of 10º, 20º, 30º, and 40º. For the S-truss location there is perhaps a slight gain from tilting a single antenna away from the SPP and the starboard arrays, i.e. forward and to port. A better option might be to cover the wider field of view to using two antennas, one tilted forward and the other aft. Simulations were therefore studied for a single zenith-pointing antenna and for an "all sky" case, to simulate two antennas tilted by 20º in opposite directions and including the view down to the Earth's limb. The two antenna case cannot quite view the whole sky, but the area not covered will be obscured by the truss.

The simulation used real GPS SV orbit and clock data from Sept. 1998. It was assumed that the receiver would be able to track all SVs that were in view. The motion of the ISS was not modeled. Instead its state was determined independently at 5 min. intervals. JPL's GIPSY software was used to obtain multiple clock solutions using 4 hr. batches of data over a 12 day period. Alternative schemes, such a

TABLE IV

JEM-EF SIMULATED ERRORS FOR TEA MODE + 30° ANTENNA TILT.

Visibility	Radial position, cm	3D velocity, mm/s	Clock, ns	Frequency uncertainty
Best	2.1	0.06	0.11	4.5e-17
Worse	1490	104	9.95	2.0e-15

TABLE V

BEST CASE SIMULATED ERRORS FOR THE JEM-EF.

Antenna tilt	Radial position, cm	3D velocity, mm/s	Clock, ns	Frequency uncertainty
0º	3.8	0.14	0.160	6.28e-17
10º	2.5	0.07	0.125	4.91e-17
20º	2.2	0.06	0.115	4.53e-17
30º	2.1	0.06	0.113	4.45e-17
40º	2.1	0.06	0.112	4.42e-17

clock rate solution determined with a single multi-day data batch, and a rate determined by a linear fit to two 4 hr. solutions at the beginning and end of a 12 day period, were considered but did not perform as well.

IV. RESULTS

For JEM-EF location 1 the attempt to bound the flight conditions was not useful. Table IV shows the best and worse case results for an antenna with no forward tilt. The worse case results do not come close meeting the mission requirements, but as this case is not realistic the data do not advance the GPS Subsystem design.

Table V shows best case results for various antenna tilts, in addition to the 10º tilt of the ISS in TEA mode. The advantage conferred by tilting is obvious. The results improve as the extra tilt approaches 20º (plus that from TEA mode), at which point the Earth's limb is 10º above the antenna plane in the forward direction, and SV are visible close to the Earth limb to either side, improving the geometric spread of ray paths. Tilts of 30º and 40º bring barely discernable improvements. Recall that for this study tracks from all simulated SVs were used. In reality the antenna gain falls rapidly close to the antenna horizon. Elevation cut-offs of 8-10º are typically applied in GIPSY processing, so a tilt of ~30º might be considered optimum.

Simulated errors for the radial position are much better than the requirements, reaching 1-2 cm. However, many errors present in the entire measurement system are not modeled in this study, so the actual performance will be worse. The best examples of precision orbit determination (POD) by BlackJack receivers are currently being demonstrated by the Jason and GRACE missions, where radial

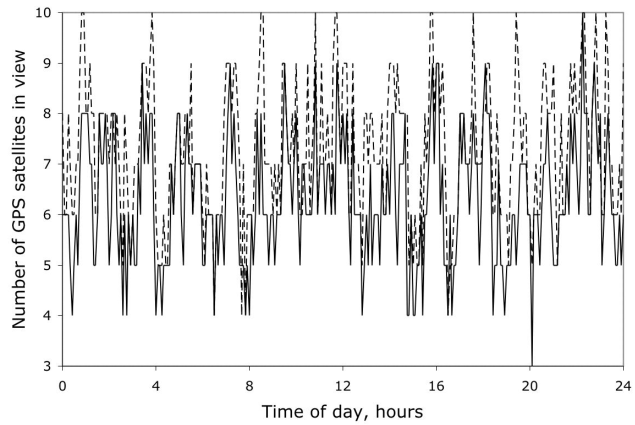

Fig. 6 A 24 hr. timeseries showing the number of GPS SVs tracked by the PARCS GPS Subsystem during the simulation. Results are shown for an antenna aligned with the ISS +Z direction (solid) and for one with a 30° of forward tilt (dashes).

position is being determined to 1-2 cm (1 sigma) in post-processing [7]. POD conditions for these spacecraft are better than for PARCS, however. For Jason the orbit is higher, 1330 km, where aerodynamic forces acting on the spacecraft are reduced. GRACE's orbit is similar to the ISS', at ~500 km, but the POD antennas have unobstructed view of the sky, and the spacecraft surfaces are simpler, allowing aerodynamic and solar radiation pressure forces to be more easily modeled.

Simulated errors for the 3D velocity are also less than the requirements in Table 1, but closer to them than the positions, while the time interval transfer performance over 12 days is worse than the goal. As with the position, these results are likely to be better than the actual mission, assuming no improvements in the overall measurement system.

Fig. 6 shows the number of GPS SVs visible over a 24 hr. period. The average number of SVs tracked is 6.3, rising to 7.3 with 30º of antenna tilt. There are 18 instances where only 4 SVs are visible, reduced to 4 instances with the tilted antenna. As a GPS receiver must track at least 4 SVs to generate state solutions this improvement may be the most

TABLE VI

SIMULATED ERRORS FOR THE S-TRUSS LOCATION.

Number of antennas, SPP	Radial position, cm	3D velocity, mm/s	Clock, ns	Frequency uncertainty[a]
Single, no SPP	1.68	0.043	0.097	3.82e-17
Single, SPP	8.01	0.878	0.229	9.02e-17
Multiple, no SPP	0.93	0.024	0.077	3.02e-17
Multiple, SPP	1.88	0.423	0.097	3.81e-17

[a] over a 12 day averaging period.

important advantage of the tilted antenna. Although solutions generally improve the more satellites that are tracked there is a particular benefit in tracking at least 5, as this allows the BlackJack to detect internal tracking anomalies and take corrective action autonomously. A plot of the PDOP for the same period demonstrates a slight improvement with antenna tilt.

The results for the simulation of the S-truss location are with a single antenna when the SPP is absent are slightly better than for the JEM-EF (Table VI). However, with the SPP in place the solutions degrade significantly, and it is unlikely that the measurements would meet PARC's requirements in either radial position, 3D velocity or frequency uncertainty. The benefits of using multiple antennas are immediately obvious from the results. The radial position error is reduced to less than 1 cm, while the frequency uncertainty over 12 days of ~3 x 10^{-17}. Even with the SPP in position the results are roughly equivalent to those from the single antenna at the JEM-EF location 1.

V. Conclusions

JPL's BlackJack space GPS receiver design is being adapted for use on the PARCS atomic clock in space mission. It will provide time interval transfer using the GPS carrier phase technique, and position and velocity determination for the study of gravitational and relativistic effects. Flying on the ISS lessens some traditional challenges for flight experiments, such as the resource allocations (e.g. mass, power, data rates) and the expected launch stresses and in-orbit radiation environment. However, new challenges are introduced, which include multiple, time-vary multipath sources, equipment temperature control, and visibility of the GPS constellation.

Some simulations of GPS visibility have been made, to provide inputs to implementation trades for the PARCS GPS Subsystem and in an attempt to bound the performance of the instrument. Considering the field of view at the baseline location on the JEM-EF and the attitude of the ISS in microgravity mode, a single antenna with a tilt of ~30^{o} in the direction of the ISS +X axis (roughly, forward) gives the best performance. An alternative site, on the starboard side of the top of the ISS main truss, provides the interesting possibility of using two antennas to improve the number and geometric spread of satellites tracked. This option would introduce additional considerations, such as the varying path delay through two sets of hardware and the software needed to support track scheduling. This option has not been considered further as this is not the baseline location for PARCS.

Acknowledgments

The authors would like to thank members of the PARCS Project and the Tracking Systems and Applications Section at JPL for discussions of the mission and the data analysis process. Information concerning ISS configurations were contributed by a variety of personnel at JPL and NASA.

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