5-72968

NASA/TM—2002-211349

AIAA–2002–1037

Incident Energy Focused Design and Validation for the Floating Potential Probe

James Fincannon
Glenn Research Center, Cleveland, Ohio

January 2002

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Prepared for the
40th Aerospace Sciences Meeting and Exhibit
sponsored by the American Institute of Aeronautics and Astronautics
Reno, Nevada, January 14–17, 2002

National Aeronautics and
Space Administration

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January 2002

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Incident Energy Focused Design and Validation for the Floating Potential Probe

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Abstract

Utilizing the spacecraft shadowing and incident energy analysis capabilities of the NASA Glenn Research Center Power and Propulsion Office's SPACE (System Power Analysis for Capability Evaluation) computer code, this paper documents the analyses for various International Space Station (ISS) Floating Potential Probe (FPP) preliminary design options. These options include various solar panel orientations and configurations as well as deployment locations on the ISS. The incident energy for the final selected option is characterized. A good correlation between the predicted data and on-orbit operational telemetry is demonstrated. Minor deviations are postulated to be induced by degradation or sensor drift.

Introduction

Questions concerning hazards associated with the ISS vehicle's interaction with the orbital plasma environment initiated the need to build the FPP. Although ISS hardware called the Plasma Contactor Units were built to mitigate the plasma environment, the FPP, by monitoring that environment, would provide essential data required to operate the ISS safely by 1) verifying the existence of charging and arcing phenomena, 2) assessing thermal coating degradation rates and 3) determining the possibility of shock hazards for extravehicular activity crew members.

Because the need for this device came late in the ISS development process, it was necessary to expedite its design, construction and deployment (a joint effort between NASA Glenn Research Center, NASA Johnson Space Center, Design Net, and Invocon) so that it could be launched within four months. This was done to coincide with the deployment of the U.S. photovoltaic power modules. These modules, with their large solar arrays, were thought to be the primary mechanism or catalyst for the plasma hazards. This time limit mandated the use of existing hardware suitably pre-qualified for manned flight usage.

While FPP hardware was being developed in this mode, a key question that needed to be addressed was the optimized placement of the device within the ISS environment. A number of design requirements had to be addressed. The FPP required adequate clearance for the probes to observe the plasma environment without blockage by ISS hardware. In addition, since FPP required an independent communications system, its antenna required an adequate field of view of its sister antenna on ISS. Complicating matters further was the requirement that the FPP not structurally modify the ISS hardware (i.e. either be at a pre-existing attach site or one easily adapted without structural changes). Finally, since the FPP could not be electrically connected to the ISS power system, it needed an independent solar power supply which was adequately free of shadowing induced by surrounding ISS hardware.

This paper addresses the incident energy aspect of the design process only; the other requirements were considered separately during FPP site selection and design and are not reported here.

Analysis Goal

For most spacecraft power system designs, solar panels are sized based on the device power requirements and its orbital characteristics. In the fast paced FPP design environment, however, the availability of pre-existing solar panels together with rough initial estimates of power needs and capability mandated two FPP solar panels of fixed size and characteristics. These panels were composed of crystalline silicon cells with each panel about one foot on each side and with fixed orientation (i.e. no gimbals or sun-tracking capability). Unfortunately, since the original rough sizing estimates did not sufficiently take into consideration the nuances of the ISS orbital characteristics, range of flight attitudes and shadowing, the availability of adequate incident energy for FPP operation became an issue. Because no variation in solar panel size was permitted due to time and hardware constraints, it became necessary to use SPACE's incident energy analysis to try to alleviate the potential energy shortfalls by reorienting the solar panels (to accommodate the wide variety of flight attitudes and orbit orientations) and by adjusting the FPP height (to reduce shadowing effects).

Analysis Method

Because the primary concern was whether the pre-sized solar panels would provide sufficient energy to operate the FPP, the author utilized the SPACE computer program to assess the candidate sites and configurations.

SPACE has been and continues to be the primary tool used by the ISS program to predict power system capability for the U.S. power system.[1–4] This computer program has the capability of performing time-varying shadowing and incident energy calculations within the ISS environment for user specified surfaces. SPACE has been used in the past to assess the incident energy for the solar panels on the Zarya and Zvezda, the Russian Science Power Platform, the European Space Agency's Automated Transfer Vehicle, the Naval Research Laboratory's Interim Control Module, various proprietary ISS power systems, various ISS experimental payloads as well as various proposed ISS solar dynamic power systems.[5,6]

Using SPACE, the analyst is able to represent not only the entire geometry of the spacecraft, but also its changing features (e.g. the presence of the Space Shuttle (STS), deployment and movement of hardware, rotation of solar arrays and radiators). The orbital characteristics and ISS orientation are integrated parts of the tool.

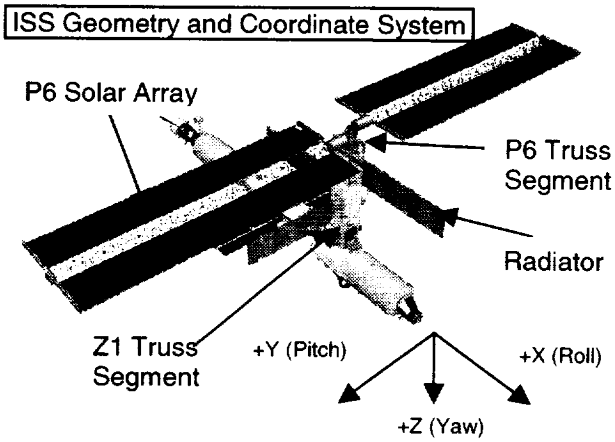
By defining the FPP geometry and solar panels within the tool, it is possible to characterize the shadow patterns on the FPP's solar panels and to quantify the incident energy impinging upon those panels.

Analysis Time Period

Initial requirements for the FPP indicated that it would be used for a period of time covering the ISS assembly stages from 4A through 8A. The time period covered is from December 2000 to December 2001.

ISS Geometry

During this time period, the U.S. P6 solar arrays and P6 truss segment are temporarily placed on the Z1 truss segment. The other primary ISS hardware that exists on-orbit during this time period includes the Zarya and Zvezda Russian modules, various pressurized mating adapters, the Unity node, the Destiny laboratory module (added on Stage 5A), miscellaneous reboost and resupply modules, three radiators (added on Stages 4A and 5A), airlock (added on Stage 7A) and the S0 truss segment (added on Stage 8A). Of this hardware, the primary moving components are the U.S. solar arrays and the Zarya and Zvezda solar arrays. These solar arrays only rotate about their lengthwise axis. This figure illustrates both the ISS geometry, the ISS coordinate system and orientation rotational axes.



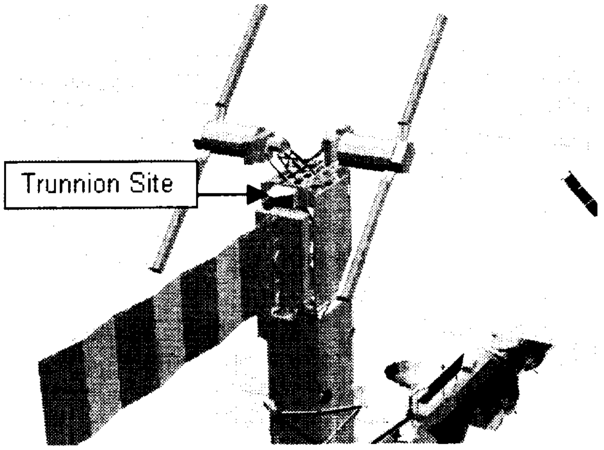
In addition to the above, the STS is sometimes docked to the ISS. The STS docks to the ISS at two different pressurized mating adapter locations during this time period; a nadir Unity port (for Stage 4A and 5A) and a forward Destiny port (for other Stages).

Existing SPACE geometric models of the ISS were used for the analysis. However, some model fidelity enhancements were made to increase the accuracy of the shadowing analysis. This involved the components close to the FPP near the zenith end of P6 (e.g. gimbal hardware and its support and attachment structure, and zenith face baseplate detail with trunnions).

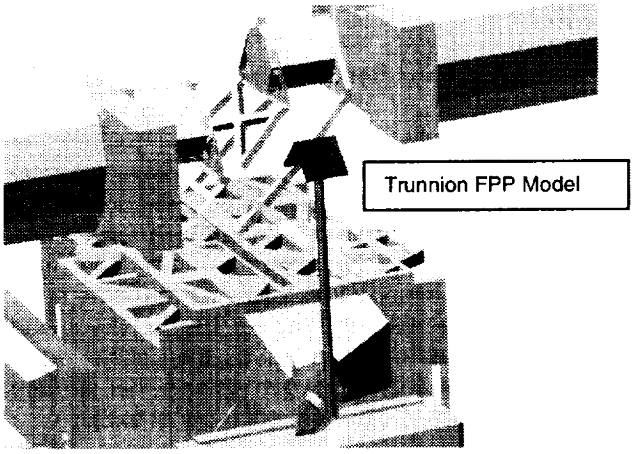
FPP Geometry

Models built of the FPP were created using commercial solid modeling software and then integrated into the SPACE ISS geometry model.

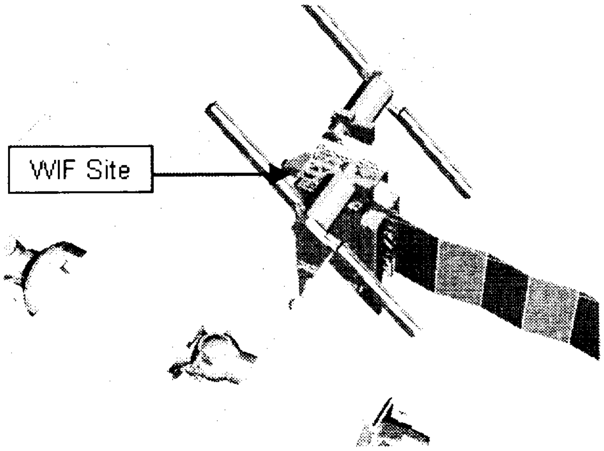
The initial proposed FPP deployment site was one of the P6 truss segment trunnions originally used to attach the truss segment within the STS bay. The trunnion in the +X location above the +X P6 radiator was selected.



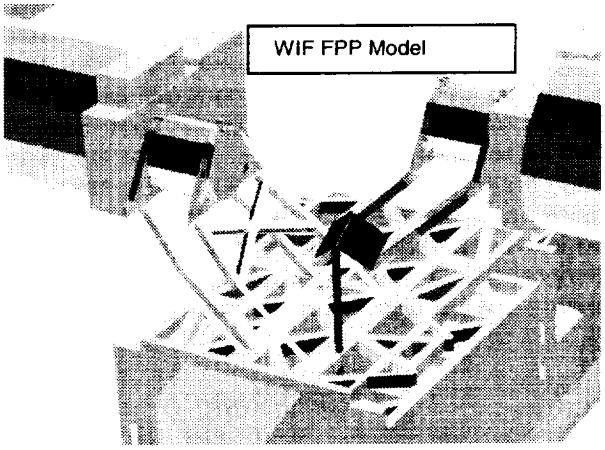
The concept was to attach the FPP to a support rod such that the rod points in the –Z direction to get probe viewing clearance and reduce shadowing impacts. The FPP solar panels were to be arranged from the end of the rod such that one panel was at 45 degrees in the X-Z plane, the other –45 degrees. Thus, in appearance, the solar panel would look like a tent pointing in the –Z direction. Models for a variety of rod heights (zero to nine feet) were created because the FPP was below the P6 solar array plane and likely to incur significant shadowing and power penalties, so an optimum height was of interest.



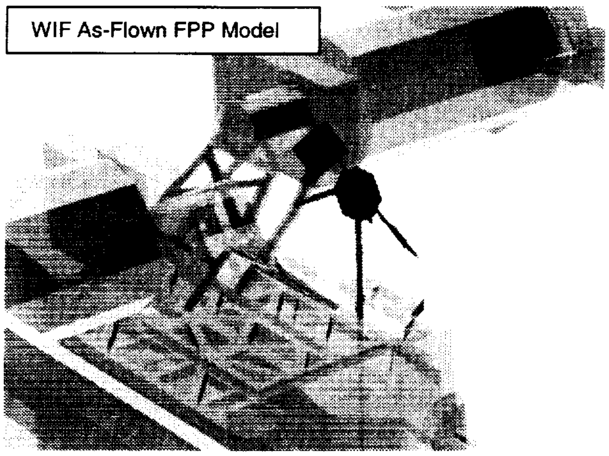
Later in the design process (due to communications, structural and mechanical considerations), it became clear that it was necessary to locate the FPP elsewhere. The zenith end of the P6 truss segment worksite interface (WIF) sockets were identified as good locations to attach the FPP structurally to the truss since the sockets were designed for moderate loads and had a standardized attachment interface.



At this time in the design process, it became clear that the optimum orientation of the solar arrays did not match the original tent configuration. Models for several different orientations were considered, with the ultimate configuration of the solar panels being a tent (as before) rotated about the Z axis by 90 degrees and canted aftward about the Y axis by 30 degrees.



The final FPP as-flown design implemented the recommended solar panel configuration in a different appearing yet energy equivalent way. A geometry model of this version was created, including hexagonal body, probes, antenna, support pole, solar panel supports and solar panels. The thermal blanket attached to one side of the FPP was omitted.



ISS Orbit Variation

ISS orbits at a 51.6 degrees inclination with very little variation. The orbit can be approximated as circular with an altitude that varies from 180 to 220 nautical miles. For the FPP analyses, altitude was assumed to be 190 nautical miles.

ISS Solar Variation

The altitude and inclination are used with the solar beta angle and other information to determine the Sun angle on the solar panels. The solar beta angle is defined as the angle between the orbital plane of ISS and a line drawn between the Sun and Earth. As the Earth travels around the Sun and the ISS orbit moves around the Earth, the solar beta angle varies in a complex sinusoidal fashion from –75 degrees to 75 degrees. Rather than execute analyses for every day of the year when the FPP was to be operational, it is easier to simply analyze the range of solar beta angles (which repeat through the year) permitting both a comprehensive representation of the incident energy and computational time savings.

ISS Flight Modes

During the FPP operation period, the nominal ISS flight orientations are XvvZnadir and Xpop. XvvZnadir has the ISS velocity vector pointing in the +X direction with the P6 solar array lengthwise axis along the Y axis and the P6 truss pointing in the –Z direction. For Xpop, the ISS is yawed by –90 degrees for negative solar beta angles and +90 degrees for positive solar beta angles. The ISS is continuously rolled such that, with respect to the Sun during an orbit, the ISS appears to not be changing orientation. The two yaw angles permit the Russian core modules to be on the Sun-ward side. Xpop is used at higher (>37 degree) absolute solar beta angles to enhance the power on the solar arrays since, in XvvZnadir, with one axis only of solar array rotation, there are significant cosine losses. Although it may be impractical to use XvvZnadir for high absolute solar beta angles (>52), the flight rules to allow this mode for all solar beta angles. A wide variety of transient flight modes exist that have been ignored for the purposes of the analyses presented in this paper.

ISS Attitudes

Because of mass distribution fluctuations, atmospheric drag and momentum control attributes, the ISS is normally not in a pure flight attitude. For ISS design purposes for XvvZnadir, the assumed flight attitude can vary from the reference attitude (i.e. the yaw, pitch, roll or YPR is zero degrees for each axis) from +15 and –15 degrees for each axis when the STS is not docked. When the STS is docked, the pitch range changes to 0 to +30 degrees. For Xpop, the deviation from the Xpop reference attitude can be for yaw and roll –10 to +10 degrees, while for pitch the attitude can vary between +5 and –15 degrees for when the STS is not docked, and 0 to +30 degrees for when it is docked. Because of the difficulty to predict and generalize analyses for all possible attitudes, attitude variations were neglected for the analyses and a YPR of (0,0,0) degrees was assumed.

Result Format

SPACE determines the shadow pattern of surrounding hardware projected onto each solar panel and reports the percentage shadowed for each time step in the orbit. In order to assess the incident energy, this shadowing information must be integrated into the Sun angle for that time step. SPACE does this by taking the unshadowed percentage and multiplying it by the cosine factor (cosine of the angle between solar panel surface normal and the vector from solar panel to Sun).

There are several ways to examine the incident energy and compare design options. Examination of actual incident energy quantities is only useful if details of the power system are available. For design trade studies, it is sufficient to quantify the incident energy in terms of a percentage.

A depiction of the incident energy percentage profile through the orbit provides the analyst with an understanding of the orbit times with shadowing and helps characterize the fluctuations in energy through the orbit. Optionally, by averaging the incident energy percentage for the insolation time period, the analyst can compare various solar beta angles and examine the effect of shadowing and off-pointing over that range. However, from an optimization point of view, averaging the incident energy percentage over the entire orbit is the most useful method. With this metric, the analyst can quantify the incident energy weighted according to the amount of insolation in that orbit. For example, the longer the insolation periods, the lower the insolation average incident energy has to be if one wishes to maintain a smooth energy distribution over the solar beta range for the various flight modes.

Early analysis results

At the trunnion site, for Xpop, the FPP received shadowing from the P6 hardware since it is on the anti-Sun side. Adjustment of the FPP location using a rod height between 4 to 6 feet and shifting of the FPP slightly along the Y axis minimized this problem. For XvvZnadir, not only did considerable shadowing occur through the range of solar beta angles, but since the solar panels were optimally oriented for a solar beta angle of 0 degrees, a considerable cosine effect was observed (although a benefit of the panel orientation was the relatively flat energy profile through orbit insolation). The only way to reduce shadowing was to increase the FPP height above the P6 solar array plane since most shadowing was due to these solar arrays (at >50 degree absolute solar beta angles; a small amount of shadowing was due to the P6 truss and the P6 +X radiator at <50 degree absolute solar beta angles). Nine feet approximated a 'no shadowing case'. However, because of the diminishing benefits of increased rod length for higher absolute solar beta angles, a maximum of 6 feet seemed appropriate, and for a realistic structure, a value between 4 to 6 feet was considered valid.

Analysis Results: WIF Site

Optimized solar panel orientation and height

At the WIF site, an iterative analysis was performed to determine the optimum configuration, location and orientation for the two solar panels. Varying the solar panel angles enables the incident energy over the solar beta angle range to be more uniformly distributed. Based on the fact that FPP operation was desired for the entire range of solar beta angles for XvvZnadir, it became clear that it was necessary to change the original tent configuration such that the solar panels pointed in the +Y and –Y axis (and –Z) directions (essentially a rotation of the tent about the Z axis). To determine the correct angle, one typically uses the mid-point between the solar beta angle range, in this case 37 degrees. This angle would provide optimum pointing on one panel at a solar beta angle of 37 degrees (the other solar panel would likewise have optimum pointing for –37 degrees solar beta angle). However, since the roll attitude is –15 to +15 degrees, this extends the 'effective' solar beta angle range to be accommodated up to 90 degrees. Therefore the midpoint would be 45 degrees. This panel angle results in a 'tent' of solar panels with a 90 degree tent (apex) angle (or 45 degree half apex angle). Iterative analysis results confirmed this design optimum.

Inspection of the Xpop flight mode and attitudes indicated, although it is naturally an incident energy-rich ISS orientation, at least a nominal cant towards the aft of the ISS was necessary. The same approach used for the tent apex angle determination was used for the Xpop-required cant angle. Although Xpop could be expected over the entire solar beta angle range, because the ISS yaws differently for positive versus negative, only 0 to +75 degrees needed to be considered. The 'effective' solar beta angle must be adjusted to account for the attitude extremes. The pitch of –15 degrees (for STS not attached) results in +90 degrees at one extreme, and a pitch of +25 degrees (for STS attached) generates an effective angle of –25 degrees at the other extreme. This results in an estimated cant angle in the 30 to 40 degree range. Iterative analysis showed the optimum cant angle to be 30 degrees.

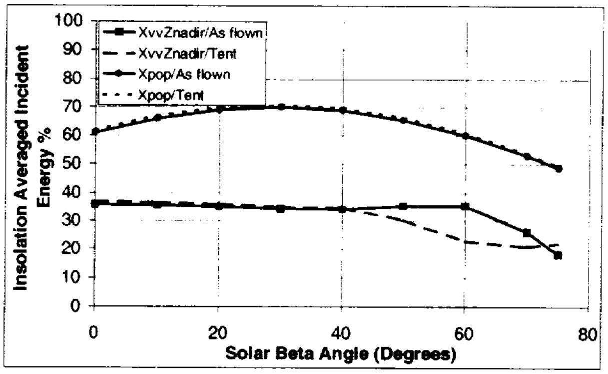
These combinations of apex angle and cant angle maintained a nominal incident energy in both flight modes over the solar beta and attitude range.

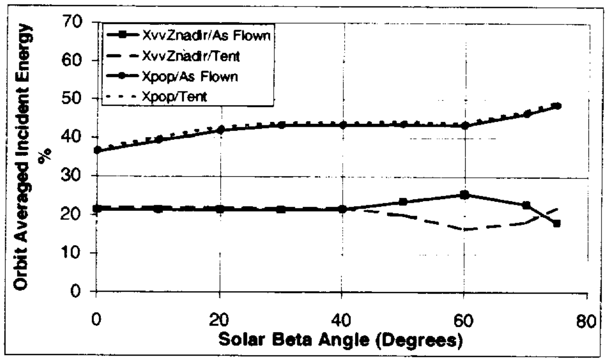
Note that the effect of canting results only in a shifting of the incident energy temporally during XvvZnadir, with only minor reductions of energy for the cant angles considered. A 30 degree cant represents a temporal shift of energy by 8 minutes. The positive cant angle shifts the XvvZnadir solar panel incident energy distribution towards the end of insolation where shadowing is least. Cant angle must be moderate because too high of a cant angle and a STS docking induced attitude would have too high an impact on incident energy.

Iterations on height showed that 24 inches from the P6 zenith face to the bottom tip of the solar panels was an appropriate compromise to achieve a viable incident energy for the design range.

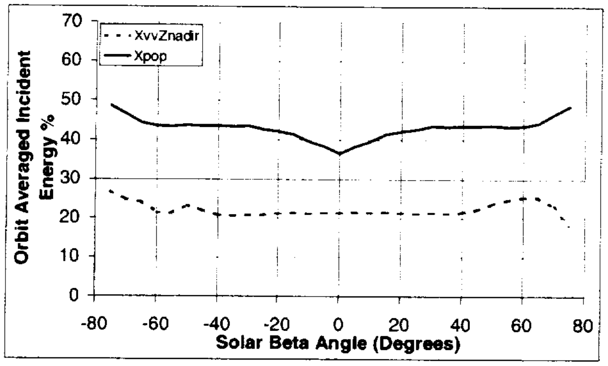
As Flown Design Predictions

For various reasons, the solar panels were displaced along both the X axis and the Z axis. Therefore, the distance to the bottom tip of the aft FPP solar array is 24 inches to the P6 face while the forward one is 45 inches. After modeling and analyzing this version, it was found that the incident energies compared well, with the primary difference occurring at the high solar beta angles for XvvZnadir. This was due to one solar panel being higher away from the P6 truss, thus delaying the onset of P6 solar array shadowing.

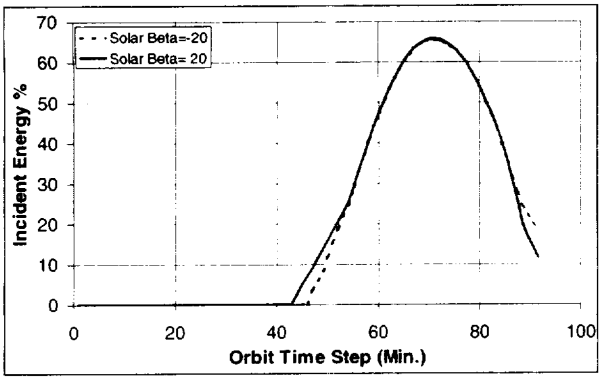


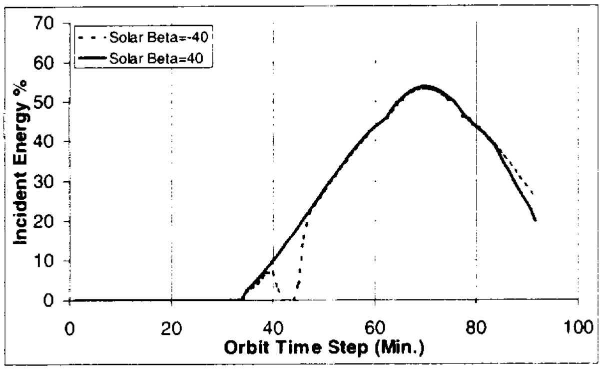


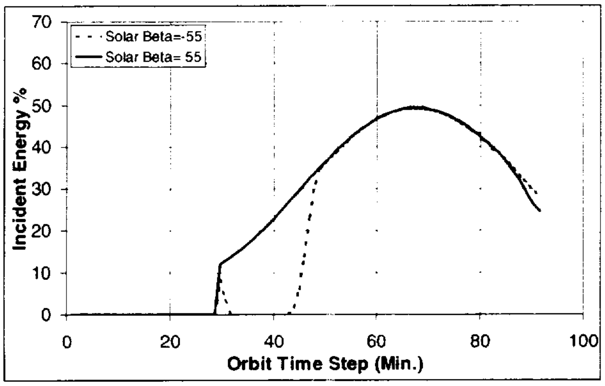
The following figure shows the orbit averaged incident energy for the two flight modes over the entire solar beta angle range.

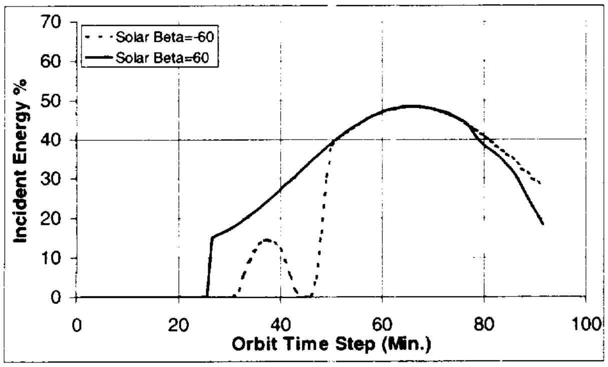


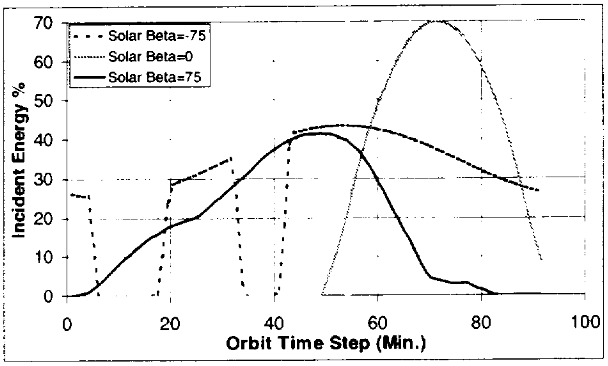
The following figures illustrate the incident energy percentage (averaged for both FPP solar panels) through typical solar beta angles. These solar beta angles were selected because they are representative incident energy profiles and illustrative of the shadowing effects. Eclipse begins each orbit at time 0. The eclipse duration for solar beta of 0 degrees is 37 minutes, for 20 degrees is 36 minutes, for 40 degrees is 34 minutes, for 55 degrees is 29 minutes, for 60 degrees is 26 minutes and for 75 degrees is 0 minutes. Data was generated in one minute time steps. Because the STS rarely affects the FPP incident energy by way of shadowing (only by way of attitude), no STS geometry was included. The flight mode is XvvZnadir (YPR=0,0,0). Significant shadowing occurs around 40 degrees solar beta and increases beyond that point. The figures show that because of the asymmetrical nature of the WIF site, shadowing from the P6 solar arrays occurs at the higher solar beta angles. Since the FPP is closer to the +Y P6 solar arrays, moderate to large negative solar beta angles cause shadowing for parts of the orbit while for the same positive solar beta angles, the FPP benefits from being deployed farther away from the –Y P6 solar arrays. A solar beta angle of 0 degrees results in no shadowing, while the extreme solar beta angles of ±75 degrees obtain shadowing from not only the solar arrays but also adjacent structure.



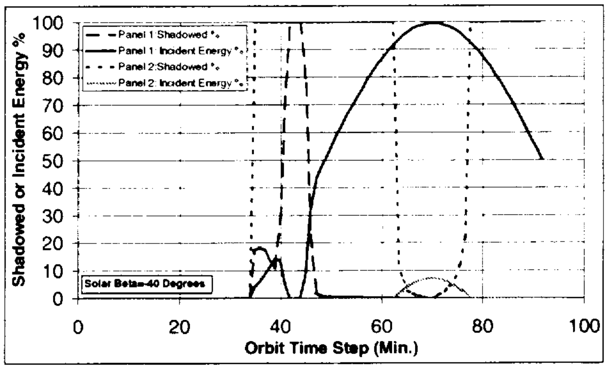




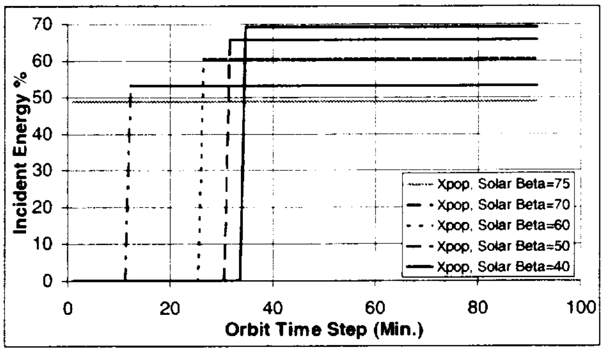




The following figure illustrates the shadowed percentage and incident energy percentage for each solar panel for a solar beta angle of –40 degrees. Shadowing on one panel early in the orbit is due to the P6 solar array.



The next figure shows that the incident energy profiles through the orbit for Xpop are constant. Each panel has the same energy through the orbit because this flight mode maintains a constant Sun-view orientation and has no shadowing.



Validations with On-Orbit Telemetry

Operational History

The FPP was deployed in December 2000 on STS flight 97 (ISS Stage 4A). Since that deployment, on-orbit operation of the FPP has been intermittent. Housekeeping telemetry was generated during the following time periods: December 8, 2000, January 26, 2001 – February 10, 2001, February 15, 2001 – February 18, 2001, and April 9, 2001 – April 22, 2001. Although there were data dropouts in the above periods, the operation of the FPP for those periods was fairly continuous. Approximately 350 orbits of housekeeping data were obtained with a sampling rate of about 1 sample every 20 seconds.

Attempts were made to determine the cause of the intermittent behavior. An examination of the solar beta angle for the periods showed that the FPP only (but not always) operated between –8 and 48 degrees (the range traversed was –75 to 57 degrees). Because the solar beta angle operation relationship was not consistent, the implication of more than one contributing factor to the problem was strong. One of the factors thought to be the cause was that the FPP solar panels were not getting sufficient energy, despite predictions to the contrary. This could have been induced by incorrect FPP installation and deployment. In order to verify these aspects, a comparison of the incident energy predictions with the on-orbit housekeeping telemetry was made.

Comparison Assumptions

Before presenting comparison results, it is necessary to understand more than the operational assumptions used to make the predictions previously presented. For the predictions, assumptions had to be made on ISS behavior to limit the number of analyses to a manageable, usable and generalizable set. Namely, the solar arrays were assumed to track the Sun with one axis. However, after deployment of the U.S. solar arrays on ISS Stage 4A, complexities in operating the ISS power system became apparent. These caused the operation of the solar array tracking to deviate from the nominal one axis sun tracking assumption. Because of anomalies in the as-flown ISS solar array beta gimbals as well as attempts to address charging environment safety concerns, it became necessary for the ISS Program to operate them in complex ways in an attempt to prevent possible problems. These operational modes included locking the solar arrays at specific angles, partially tracking them during the orbit, tracking them at a fixed rate or some combination of these. Incident energy analysis cases were executed for a few of these modes and it was found to only affect results for high absolute solar beta angles (>45 degrees). For those times the energy may improve or be reduced moderately depending on the exact lock angle or tracking mode.

For the predictions, pure attitudes were used, but in operation, the attitude can vary substantially through the orbit. Knowledge of both the flight attitude and flight mode need to be considered for comparisons. Attitudes, especially those induced by the STS, can cause the FPP incident energy distribution within an orbit to shift substantially. For the time period in question, the STS induces a pitch change (about the Y axis) which is simply a shifting of the pure-attitude incident energy data forward or backward in time depending on the pitch direction (four degrees of pitch would shift the data one minute in time). It is thus necessary to obtain from ISS telemetry the gimbal angles, vehicle attitude and solar beta angle to perform a comparison.

Data Reduction

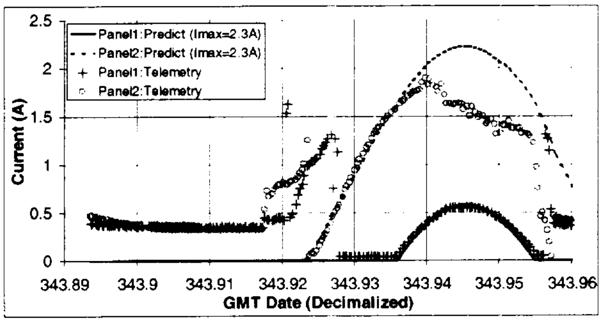
Another consideration that must be made prior to comparison is the sensors from which data are to be obtained. Since the prediction involved incident energy (not power system or electrical design, sizing, modeling or simulation), it was not easy to utilize the housekeeping sensor data directly. Those sensors provide data based on current and voltage at various points in the FPP. However, one telemetry sensor set was identified as providing most nearly what was needed for a comparison. These sensors measured the controlled bus current for each solar panel circuit. Initial examination of typical orbits showed that these sensors, during eclipse, show the battery discharge current. During insolation, when no sun was being seen by the solar panels, the current appears erroneous (i.e., non-zero), which is supposed to be indicative of the fact that the solar panel is at or near the zero voltage level of its current-voltage characteristic curve. For comparison purposes, these points can safely be ignored because they have no relationship to incident energy impinging upon the panels. Later in insolation, the current used for FPP operation or battery charging is regulated or reduced indicating that the batteries are fully charged or being charged at their maximum rate and the excess energy (current) is being left on the solar panels or shunted. Although ideally it is the unshunted solar panel current that is required for comparison purposes, since sizable portions of the insolation part of the orbit are not shunted, they may be used to validate the incident energy predictions.

To translate the incident energy predictions into data that can be compared with the telemetry, certain assumptions had to be made. Since string effects have been ignored, the assumption was made that energy and current were proportional. Assuming the solar panel operates at the maximum power point (Pmax=16.9W, Imax=2.3A), the predicted solar panel current level would be obtained by multiplying the incident energy prediction by Imax.

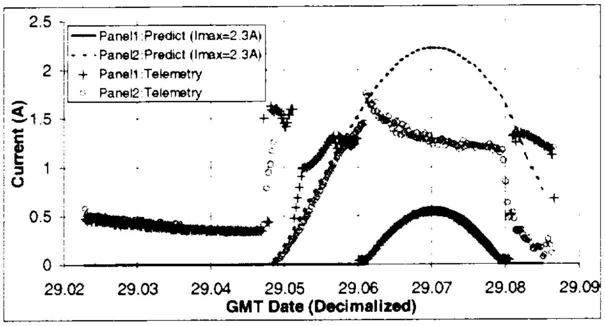
Validation Comparisons

By examining the shape of the curves in the following figures it is possible to validate that the FPP is correctly oriented and placed. Regrettably, shadowing could not be validated because no telemetry data occurred during shadowing intensive periods. The absolute current values are useful (assuming no sensor error) in identifying possible solar panel degraded performance. The comparison figures show orbits starting with the beginning of eclipse. Orbits were selected on the basis of having minimal data dropouts and not being transitional flight modes or attitudes (i.e., movement of ISS after STS is docked).

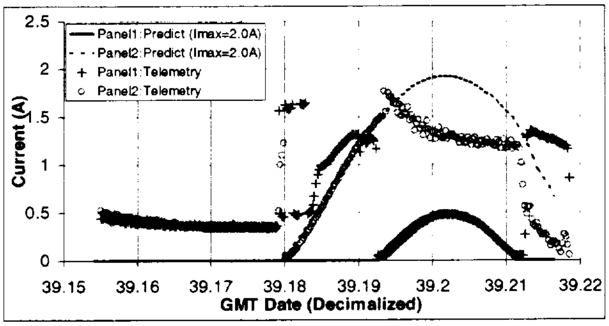
The first comparison occurred for December 8, 2000 (GMT 343). This orbit had the STS docked to the ISS nadir Node port, a XvvZnadir flight mode with YPR of (0, 10, 0) degrees, gimbals locked and a solar beta angle of about 30 degrees. The unshunted parts of the curves seems to match the predicted values well.



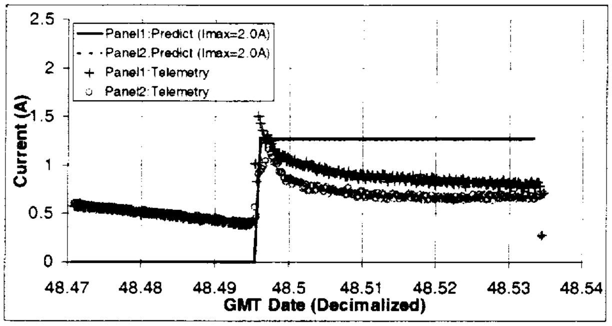
The next comparison occurred when the FPP resumed operation on January 29, 2001 (GMT 29). The STS was not present, a XvvZnadir flight mode with a YPR of (0,–8,0) degrees, gimbals locked and the solar beta angle was about 30 degrees. The conditions were similar to the December data, and seemed to match the predictions.



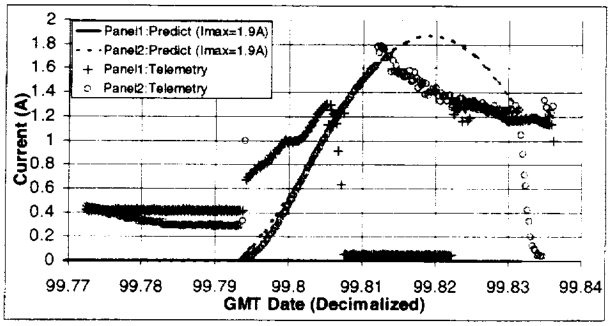
Another comparison was for February 8, 2001 (GMT 39), when the STS was not present, a XvvZnadir flight mode with a YPR of (0,–13,0) degrees, gimbals locked and the solar beta angle was about 30 degrees. Although this case was like December, this time a variation was noted. It was necessary to use an Imax value of 2.0 to obtain a good correlation. No unusual ISS activity took place during the 10 day interval between the two comparisons. FPP housekeeping data shows two data dropouts corresponding to the local peak of solar beta (around 38 degrees). Based on FPP operation at higher solar beta angles, these dropouts seem unlikely to have caused the Imax drop. Another possibility that must be considered is sensor drift.



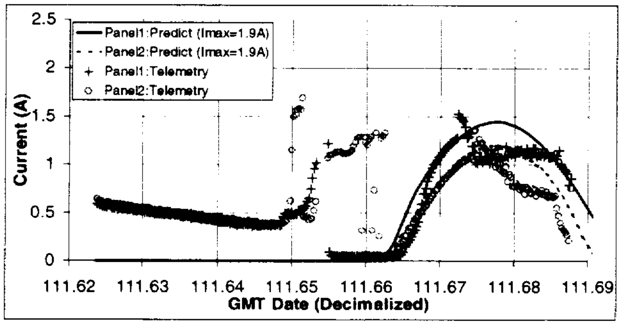
On February 17, 2001 (GMT 48), one of the only Xpop periods of FPP housekeeping data was obtained. This had the STS present, an Xpop flight mode with a YPR of (0,–6,0) degrees, gimbals locked and a solar beta angle of about –5 degrees. It was not possible to deduce the Imax based on the data, but 2.0 was assumed for comparison. Based on the characteristics of this sensor, it seems that solar panel current is shunted to varying degrees throughout insolation. It is not clear why the insolation curves for each panel different because they were predicted to be the same. This illustrates the difficulty in using these sensors for comparison purposes since the sensors are representing battery charge operation, not unshunted panel current. The difference is likely due to one battery pack operating more efficiently than the other during charge, thus using less panel current to charge.



On April 9, 2001, the worse solar beta angle for which housekeeping data was available was observed. This case had no STS present, a XvvZnadir flight mode with a YPR of (–10,–10,0) degrees, gimbals tracking and a solar beta of 47 degrees. The range of solar beta angles traversed during the period of December 2000 to April 2001 was –75 to 57 degrees. Because the solar panels have the apex half angle of 45 degrees, a solar beta of 45 degrees should provide the best energy on one panel with a gradually cosine drop-off past 45 degrees. The other panel, because of its orientation would provide zero energy near 45 degrees solar beta and beyond. Shadowing should only begin to be noticeable beyond 60 degrees solar beta angle. Therefore, it is not clear why this is the maximum operational solar beta angle. Imax had to be reduced to 1.9A to get a good correlation. This may be due to sensor error or solar panel degradation. Another observation is that the discharge battery current is very different between batteries. This implies that the one battery pack was completely discharged, which is the case because one panel had been without incident energy for 11 days due to the high positive solar beta angles.



Near the end of the FPP operational period, April 21, 2001, data was obtained for a condition with no STS, a XvvZnadir flight mode with YPR of (0,0,0) degrees, gimbals sun-tracking and solar beta angle of –5 degrees. The solar panels seem to be producing close to the same amount of current, but the Imax used (1.9A) suggests either degradation of the panels or more sensor drift. This figure illustrates that the duration from beginning of eclipse to start of incident energy is much longer than the standard eclipse duration, due mainly to the solar panel orientations and the solar beta angle. Battery packs and charging must accommodate this kind of profile because discharge is occurring in insolation.



Discussion of Results

Generally, a good comparison between predicted and telemetry solar panel current was observed through the FPP period of operation. Although the cosine or pointing loss effects on the FPP solar panels were validated, the shadowing model effects could not be effectively validated due to lack of on-orbit data for shadowing intensive solar beta angles. Re-examination of ISS geometry showed no features that could cause shadowing that could cause intermittent FPP operation.

Also, predictions indicate ample incident energy (especially the later parts of the orbit which have no shadowing) for low to moderate negative solar beta angles when the FPP did not operate.

Assuming no current sensor drift, the requirement to reduce the maximum solar panel current (Imax) later in the operational period to match the predictions suggest degradation of the panels. Possible causes for observed reduced maximum current include structural deformation of solar panels or FPP support pole, solar panel temperature variation (unlikely because the cells are relatively temperature insensitive) or panel/cell/coating/ coverglass degradation (caused by mechanically or thermally induced cracking, orbital debris, micrometeorites, deposition of coatings from induced environment, ultraviolet radiation or atomic oxygen, ionizing radiation). Also, some unknown power system operational or design nuances could possibly reduce the operating point.

Finally, since the solar panels have their own battery pack to charge, a concern apparent from the data is the 'loss' of current due to shunting even when the other panel is getting less or no incident energy. The original predictions assumed all energy is utilized (no shunting). Therefore, either the FPP energy usage was lower than originally estimated, or the detailed operation of the power system is not reflected sufficiently in these sensors to address this issue or energy is lost, potentially affecting FPP operation.

Conclusion

The paper has illustrated the incident energy analyses that were performed to assist in the design and placement of the FPP on the ISS. Comparison of predicted values from these analyses with the on-orbit housekeeping telemetry for a variety of dates through the FPP operation show a good correlation that indicate the FPP was correctly deployed and oriented and that the geometry models and analysis techniques are valid.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE** January 2002	**3. REPORT TYPE AND DATES COVERED** Technical Memorandum

4. TITLE AND SUBTITLE

Incident Energy Focused Design and Validation for the Floating Potential Probe

5. FUNDING NUMBERS

WU–477–72–10–00

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–13166

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2002-211349
AIAA–2002–1037

11. SUPPLEMENTARY NOTES

Prepared for the 40th Aerospace Sciences Meeting and Exhibit sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 14–17, 2002. Responsible person, James Fincannon, organization code 6920, 216–433–5405.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 20 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov/GLTRS
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Utilizing the spacecraft shadowing and incident energy analysis capabilities of the NASA Glenn Research Center Power and Propulsion Office's SPACE (System Power Analysis for Capability Evaluation) computer code, this paper documents the analyses for various International Space Station (ISS) Floating Potential Probe (FPP) preliminary design options. These options include various solar panel orientations and configurations as well as deployment locations on the ISS. The incident energy for the final selected option is characterized. A good correlation between the predicted data and on-orbit operational telemetry is demonstrated. Minor deviations are postulated to be induced by degradation or sensor drift.

14. SUBJECT TERMS

Shadowing; Solar energy conversion; Solar arrays; Incident; Radiation; International Space Station; Probes; Geometry

15. NUMBER OF PAGES

17

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	