NASA Technical Memorandum 106994

IN-20
56596
p. 8

Analysis of Shadowing Effects on Spacecraft Power Systems

H.J. Fincannon
Lewis Research Center
Cleveland, Ohio

Prepared for the
Fourth European Space Power Conference
sponsored by the European Space Agency
Poitiers, France, September 4–8, 1995

National Aeronautics and
Space Administration

ANALYSIS OF SHADOWING EFFECTS ON SPACECRAFT POWER SYSTEMS

H.J.Fincannon

NASA Lewis Research Center

21000 Brookpark Road, MS 500-203, Cleveland, Ohio, USA 44135
Phone: (216) 433-5405, Fax: (216) 433-2995

ABSTRACT

This paper describes the Orbiting Spacecraft Shadowing Analysis (OSSA) computer program that was developed at NASA Lewis Research Center in order to assess the shadowing effects on various power systems. The algorithms, inputs and outputs are discussed. Examples of typical shadowing analyses that have been performed for the International Space Station Freedom, International Space Station Alpha and the joint United States/ Russia Mir Solar Dynamic Flight Experiment Project are covered. Effects of shadowing on power systems are demonstrated.

Keywords: Shadowing, shadow effects, spacecraft power systems.

1. BACKGROUND

Orbiting spacecraft are typically powered using solar energy collectors (e.g. photovoltaic arrays or solar dynamic mirrors) which under certain conditions may become shadowed by other parts of the vehicle or other approaching vehicles, resulting in power fluctuations and reducing the energy capabilities of the spacecraft. An assessment of the capabilities of the power system under these conditions is an important part in determining the design and operations of the spacecraft.

Contributing factors to the complexity of analyzing the shadowing effects on electrical power systems include the number of spacecraft hardware geometric configurations, yearly and daily orbital variations in the vehicle attitude due to drag area or environmental conditions, orbital maneuvers for reboost, collision avoidance, communications coverage contingency scenarios, payload pointing requirements and improved power production and rendezvous/docking with other vehicles which may require the reorientation of solar energy collectors to avoid maneuvering-jet plume impingement.

References in the literature show that a limited amount of shadowing analyses has been performed for past spacecraft. Gruber (1972) considered shadowing power effects of radial booms on a body-mounted solar cell-covered spinning cylinder and, similarly, Tsushima (1973) examined shadowing of antennas/probes on a solar array. Analyses of shadowing from solar array-to-solar array on the International Space Station Freedom has been done (Kumar, 1991). To a greater or lesser degree of applicability, some computer codes are available that can perform shadowing analysis; between solar arrays (Proeschel, 1992) or general thermal energy effects on Shuttle payloads (Skladany, 1993).

Difficulties and concerns regarding these codes included lack of speed, flexibility, availability, and integratability (i.e. into a NASA Lewis-developed general spacecraft power system tool). To overcome these problems and to assist is developing an in-depth understanding of the shadowing issue, the Orbiting Spacecraft Shadowing Analysis (OSSA) program was developed as a general purpose tool for quantifying shadowing for a wide variety of cases. It was integrated into the Station Power Analysis for Capability Evaluation (SPACE) (Hojnicki, 1993) (Kerslake, 1993) computer program which was used extensively in analyzing the International Space Station Alpha and Freedom power systems. Results from OSSA compares favorably with results generated by a recently-developed propriety Rocketdyne Division of Rockwell International shadowing program.

2. DESCRIPTION OF OSSA ALGORITHMS

In developing OSSA, several important code capabilities and features were devised in order to provide the necessary flexibility to efficiently handle many scenarios of evolving spacecraft. These include a flexible data interface, automatic reconfigurable and buildable geometric modeling within the computer program, detailed graphical output of data and models, automated animation post-processing and an efficient shadowing code.

The OSSA data interface section obtains data by reading input files and passing required data from other programs. An external program (i.e. the SPACE computer program) provides data describing, for each time step in the analysis, the pointing and tracking of the solar arrays, solar dynamic module and radiators, the attitude of the spacecraft and the location of the solar vector. Optionally, OSSA can be utilized as a stand-alone program.

Another input is the geometry model. This model is a collection of 4-vertex polygons given in terms of XYZ coordinates. These polygons describe a solid model of the orbiting spacecraft including any spacecraft that may dock with it. Non-solid models are acceptable, although this may increase run time because OSSA utilizes the surface normal information to eliminate unnecessary polygons from the analysis. The model also includes within it data that describes the rotation gimbals (i.e. which components are to rotate) and the rotation hierarchy. Up to three successive gimbal rotations are allowed, although two are typically the most required for typical power system tracking. Coding in the geometry model uniquely identifies each spacecraft structure so that it can be deactivated during an analysis profile.

Other required inputs are shadow analysis surfaces mesh size and resupply vehicles data. The mesh size is typically the minimum practical resolution limit for which the surface must be analyzed for shadowing. For solar arrays, this is the cell submodule level (e.g. ISS Alpha is 82 by 25 cell submodules, 8 solar cells in each submodule). This resolution is adequate based on the ISS solar arrays cell module interconnections and characteristics. For the solar dynamic power system, the required resolution on the mirror is represented circumferentially by each tube of the heat receiver and radially by an equally distributed typical mirror energy profile (e.g. for the Mir solar dynamic mirror; 27 by 23). For resupply spacecraft, it is necessary to know that vehicle's orientation, the distance when it is making a final approach or departure and its speed. OSSA will use this data to place the rendezvousing spacecraft correctly throughout the analysis profile.

The OSSA model manipulation section arranges the spacecraft components as they should appear at each time step in the orbit. This involves activating (assembly) or deactivating (disassembly) or relocating components, placing approaching or departing vehicles at the correct distances and orientations from the spacecraft, articulating gimbal joints for the photovoltaic blankets, solar dynamic power system, radiators and other structures. Finally, the vehicle is oriented based on the attitude for that time step.

The shadow analysis section handles the determination of the shadow pattern on specified surfaces. Usually, this surface is a solar array blanket. Figure 1 shows how the analysis is performed. Each blanket is oriented such that it is in the XY plane. This requires the rest of the coordinates and the solar vector to be rotated and sheared appropriately. For each point on the blanket, a ray is drawn in the positive X direction from that point. Each polygon is examined and the number of sides intersected by the ray is determined. If the total is an odd number then the point is in the polygon and, thus, shadowed. If the number is even then the point is not shadowed by the polygon.

To speed up the algorithm, all polygons behind the blanket surface, totally to one side or the other of the surface, or facing away from the Sun (for geometry models that are solid) are eliminated from the analysis. In addition, if no polygon sides are intersected for a particular ray after examining all 'valid' polygons, then all of the blanket analysis points along that ray are considered unshadowed (this only applies to analysis surfaces such as solar arrays with a rectilinear distribution of cells).

The algorithm stores the shadowing information regarding which cell submodule is shadowed and totals the number of submodules that are shadowed for each string of cell modules on the blanket. This string information is used outside of OSSA to determine the effects on the voltage and current of the solar array. The submodule shadowing information is used to determine the fraction of the surface that is shadowed and is used in generating graphics.

The graphical section of OSSA is used to create Postscript plots that depict the orientation of the spacecraft and shadow patterns on the various surfaces throughout the analysis period. A postprocessor is used to read these plots and construct animations. Other types of plots that are generated through graphical postprocessing show the shadowing effects and power capabilities for the range of solar beta angles. In order to characterize shadowing effects in general for a specific spacecraft configuration and attitude, it is useful to calculate the shadowing effects for a range of solar beta angles rather than for each orbit throughout the year. This is because the angle between the orbit plane and a line between the Sun and Earth (i.e. solar beta angle) is always changing through the year, but the values are repeatable through a certain range. Additional postprocessing converts this solar beta data into plots depicting a year-long analysis period without having to analyze thousands of orbits (typically over 5000 cases).

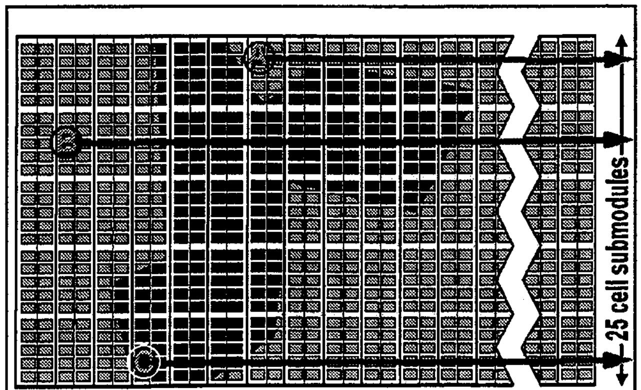

Figure 1: Shadow Analysis Method

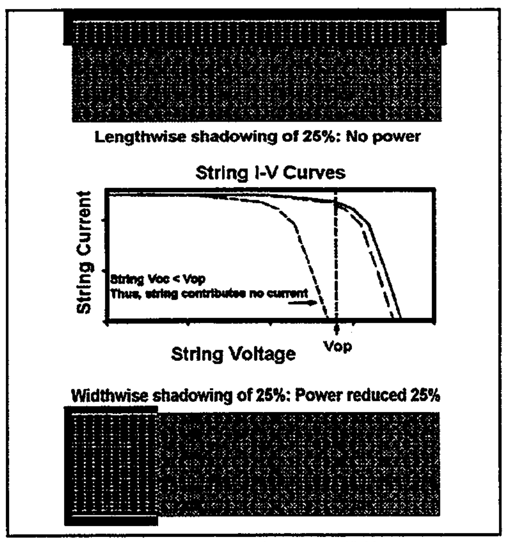

Figure 2: Typical String Shadow Effects

3. POWER SYSTEM EFFECTS

Shadowing effects on the power system are not simply the amount of incident energy being received by the solar array or solar dynamic mirror. An important factor in determining the impact of shadowing on power production is the shadow pattern itself. For the solar dynamic power system, a complex interplay of heat transfer flux in the thermal storage receiver can cause the same incident energy fraction being received by the mirror for two different cases to have different amounts of produced power. This is a result of certain axial or circumferential locations inside the receiver having improved energy transfer capability to the working gas or having more thermal capacity than others. It is therefore important to know the actual pattern of incident energy and map that onto the receiver interior surface. Because of the thermal storage nature of solar dynamic power systems, it is necessary to understand the shadow patterns throughout the insolation phase of the orbit to understand the power capability of the power system.

For solar arrays, the methodology used in connecting the solar cells affects how much of the incident energy is useable. A solar array string on ISSA consists of 50 cell submodules connected widthwise. Figure 2 shows that if the strings of solar cells run widthwise instead of lengthwise, then for shadows across the width of the solar blanket, the fall off in power is directly proportional to incident flux. However, a uniform shadow along the length of the solar array will shadow each string by the same amount. Because the power system is designed to maintain the string voltage at the solar array wing operating voltage (Vop), shadowing causes the remaining illuminated solar cells to operate at the higher voltage, lower current portion of their I-V curves to make up the voltage lost from the shadowed cells. However, as more of the string is shadowed, the operating voltage of the illuminated cells approach the open circuit conditions (Voc) and the string current falls to zero. This happens at around 25% lengthwise shadowing. This means that although a majority of the blanket is receiving incident energy, because of the method of string connection, the blanket is producing no power. Although normally most shadowing is transient on ISSA, the proximity of the solar array wings make it possible to have wings shadowing other wings such as at the top of the figure. This happens at high solar beta angles or at some spacecraft attitudes. Operational workarounds such as adjusting the spacecraft attitude or off-pointing the wings along their beta axis enough to eliminate adjacent shadowing are utilized to eliminate this problem.

In addition to the number of cell modules shadowed and the number of strings deactivated, shadowing has an impact on the ability to operate the batteries normally used in photovoltaic power systems. For typical orbits, solar arrays are sized to provide sufficient power not only for use by the spacecraft for experiments or housekeeping, but also for recharging the batteries for eclipse power production. Standard recharging profiles are used which limit the level to which the batteries are discharged. When shadowing is considered, standard operation of the batteries may result in the batteries being unable to either fully recharge, discharge in insolation or even cause sizable drops in available power during certain parts of the orbit.

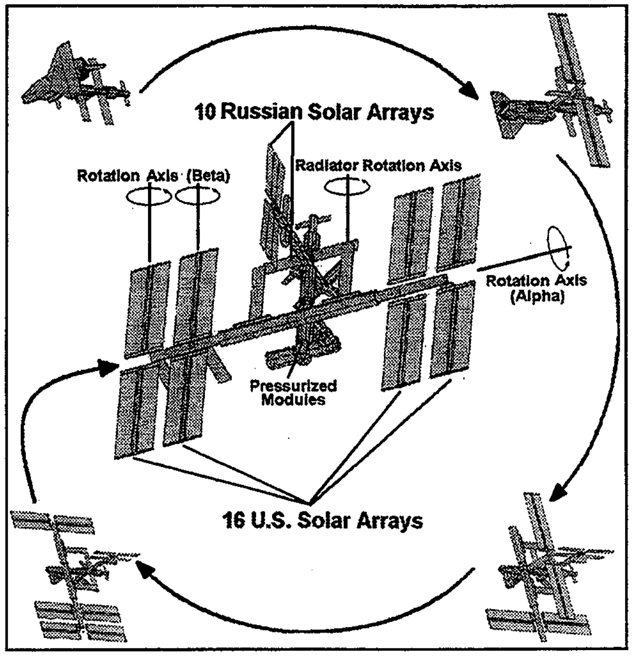

Figure 3: International Space Station Geometry Models

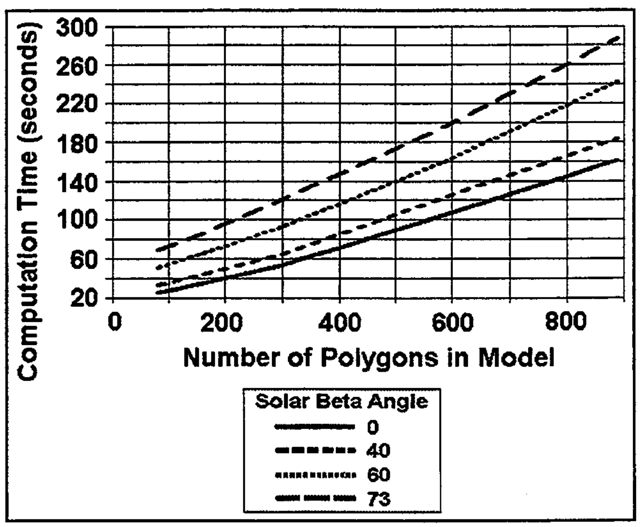

Figure 4: Polygon Quantity Effects on CPU time

4. TYPICAL GEOMETRIC MODELS

International Space Station Alpha (ISSA) and Freedom geometry models were composed of approximately 1200 polygons. The two models were similar in many respects. Figure 3 shows one version of the ISSA geometry model and only a few of the over 30 ISSA assembly steps. There are about 40 activatable structures in this model. These include the solar array wings, solar dynamic modules, integrated truss segments, US laboratory, ESA laboratory, NASDA laboratory, habitation module and Russian service module. These objects have been designed to minimize the number of polygons yet still obtain valid results. Component structures for OSSA geometry models include cylinders, planes, boxes and spheres. Figure 4 shows the effect of polygon quantity on computation time. A higher solar beta angle increases the amount of shadowing and thus computer time. Although the plot is linear, models with different numbers of polygons which have greatly different spacecraft configurations with numerous rotating structures would result in a nonlinear effect.

The Mir space station with a solar dynamic power unit geometry module was composed of about 900 polygons with about 30 activatable structures. Figure 5 shows one version of this module. Because of the proximity of the shadow analysis surfaces (i.e. solar arrays, solar dynamic mirror) to the rest of the spacecraft, it is important to have sufficient detail in the structure to adequately depict the shadowing. A trade study was performed to examine the effect of cylinder number of sides on the accuracy of the analysis results. The cylinder structure was chosen because it is the most common after the rectangular box structure and the most likely to suffer in fidelity after the sphere. A simple model was analyzed (i.e. Service Module and FGB with articulating solar array wings) for a range of solar beta angles for a flight attitude with the cylinder axes being coincident with the velocity vector and the solar array rotation axes perpendicular to the orbit plane. Figure 6 shows that ten sided cylinders provide an adequate trade-off in accuracy versus model fidelity (which is proportional to computation time).

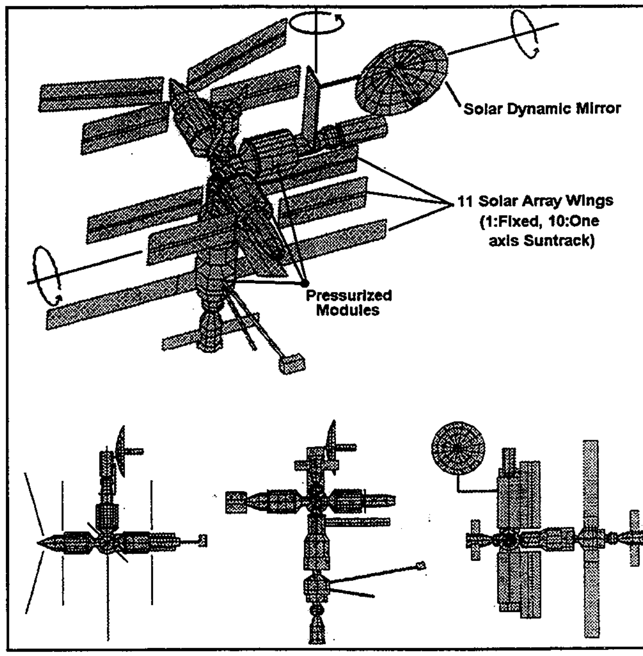

Figure 5: Russian Mir/Solar Dynamic Geometry Model

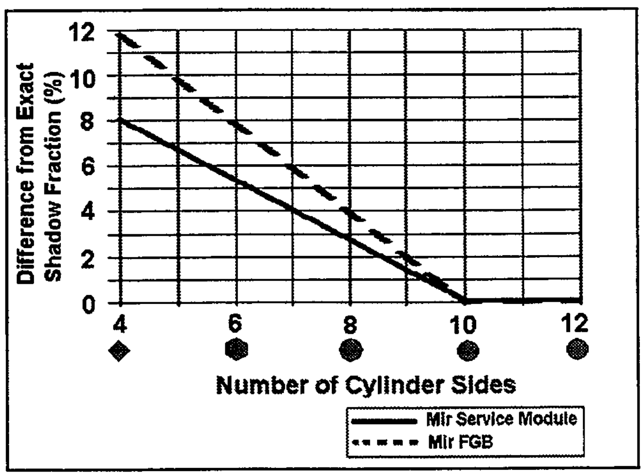

Figure 6: Model Fidelity Trade

5. INTERNATIONAL SPACE STATION ANALYSES

Figure 7 shows a typical shadowing profile for the ISS Alpha. The data shown is for a solar beta angle of 40 degrees. The shadow fraction (i.e. the fraction of the total number of solar array cell submodules shadowed for that time step) during the insolation phase of the orbit for four US solar arrays that have significant shadowing is shown. Two solar array analysis surfaces or 'blankets' make up one solar array wing. Also depicted are a small sample of the shadow patterns on the solar arrays and spacecraft orientation for various points in the orbit. The vehicle orientation is such that an orbit plane of solar beta 0 degrees is a horizontal plane. For the same case, plots of battery depth-of-discharge (DOD), battery power and solar array power are presented in Figure 8. Solar array wings 1 (composed of blankets 3 and 4), 2 (composed of blankets 1 and 2), 5 and 6 have significant shadowing while solar array wings 3, 4, 7 and 8 have no shadowing. Although each wing has different characteristics and is operated slightly differently, the unshadowed wings provide a good baseline from which to gain an understanding of shadowing effects.

Figure 9 depicts the effects on received incident energy of two parameters for a Space Shuttle-docked scenario; attitude variation and solar beta angle. The spacecraft was parametrically varied from its nominal attitude by plus and minus 15 degrees about each rotation axis. The worse and best cases of all of these combinations were determined and plotted for a variety of solar beta angles. The solar arrays considered were on the Russian part of ISSA (i.e. Service Module and FGB). Because the Russian solar arrays cannot articulate for full Sun-tracking, for higher solar beta angles, the drop-off is mainly due to off-pointing. The incident energy fraction is the insolation-period incident energy normalized by the maximum possible value (no eclipse, perfect Sun-pointing).

Other analyses have been performed which represent Space Shuttle approach and docking, departure, and feathering (i.e. locking the solar array angle to face edge-on to the Space Shuttle) of solar arrays to prepare for these events. These have been included in ISS Design Analysis Cycle timelines intended to depict week-long periods in the life of the space station. Feathering occurs infrequently and although feathering exaggerates shadowing on solar arrays, power is reduced much more by simply not completely tracking the Sun. The transient shadowing effect due to the Space Shuttle is fairly small due to the short period of time it occurs over during its approach or departure. Even after docking, the Space Shuttle is usually not the major contributor to shadowing, because of its docking location. This is not so if considering non-US solar arrays.

6. MIR SOLAR DYNAMIC ANALYSES

Figure 10 shows the shadow fraction of the solar dynamic power system mirror on Mir during the insolation portion of the orbit for a solar beta angle of 30 degrees and for two mirror diameters. Also shown are the spacecraft configuration and mirror shadow patterns at several times during this period. The figure is for an Earth-inertial attitude where the solar array gimbal axes are perpendicular to the velocity vector, with the solar dynamic unit at nadir, and the booms pointing opposite the vehicle velocity vector. Sun-tracking is assumed for the solar arrays and the solar dynamic power module. Although the cases in this figure have shadow fractions that do not exceed .9 during the orbit, other solar beta angles can cause complete shadowing or eliminate shadowing during the orbit.

For a range of solar beta angles that adequately characterizes the Mir orbit through the year, Figure 11 shows the average incident energy fraction and the shadow fraction for a variety of flight attitudes likely to be flown. The incident energy fraction in this figure is the energy that the solar dynamic mirror receives, after considering shadowing effects, normalized based on the maximum possible incident energy with no shade time, perfect pointing and no shadowing. Even though high moment-by-moment shadowing occurs through the orbit for some high solar beta angle cases, because the insolation period is longer at higher solar beta angles, more cumulative incident energy is available resulting in a higher incident energy fraction. The setting at which the solar dynamic beta gimbal is locked for an orbit also plays an important role in how much shadowing is experienced. A range of cases with various solar beta angles and spacecraft attitudes were analyzed, some of which resulted in solar dynamic module pointing with multiple solutions, each solution having greatly varying amounts of shadowing. When identifying the worse case, it was assumed that there were two types. One (i.e. Worse Case: Best solar dynamic beta setting) has the beta gimbal setting based whether it is a valid pointing solution and whether it minimizes solar dynamic mirror shadowing; all other beta gimbal settings are not valid. The other case (i.e. Worse Case: Worse solar dynamic beta setting) considers the entire range of valid beta gimbal settings on the basis that beta gimbal setting may not be based on shadowing criteria alone.

7. CONCLUSION

The Orbiting Spacecraft Shadowing Analysis computer program together with the Station Power Analysis for Capability Evaluation computer program provide power systems engineers at NASA Lewis Research Center with powerful and flexible tools for analyzing International Space Station, Mir and a variety of future photovoltaic and solar dynamic power systems. Calculation of shadowing effects and directly accounting for those effects in detail in power analyses has played an important role in designing and evaluating the ISS through several redesigns. For the joint Mir Russia/US Solar Dynamic Project, determination of detailed shadowing information for the wide variety of flight modes has proven very valuable in the design process. An important spin-off of OSSA has been the graphical depiction of vehicle orientations and shadow patterns. Visualizations of this kind are extremely useful in helping analysts and lay-people understand a complex integration of information.

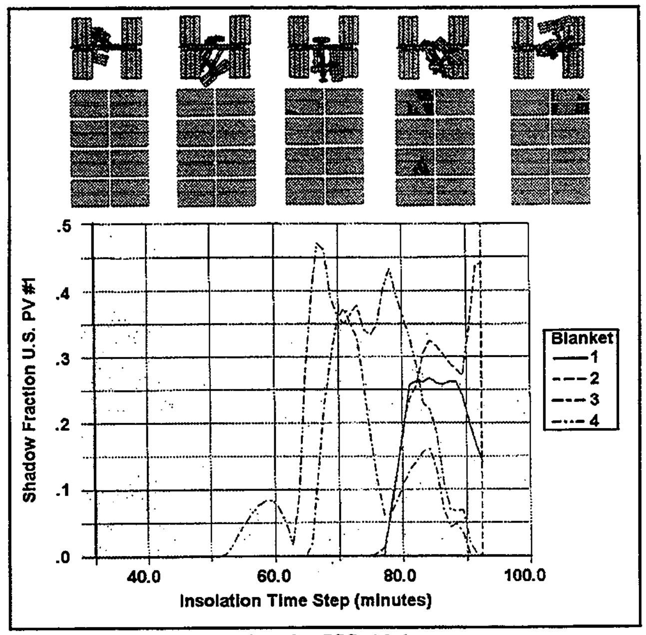

Figure 7: Shadow Fraction for ISS Alpha

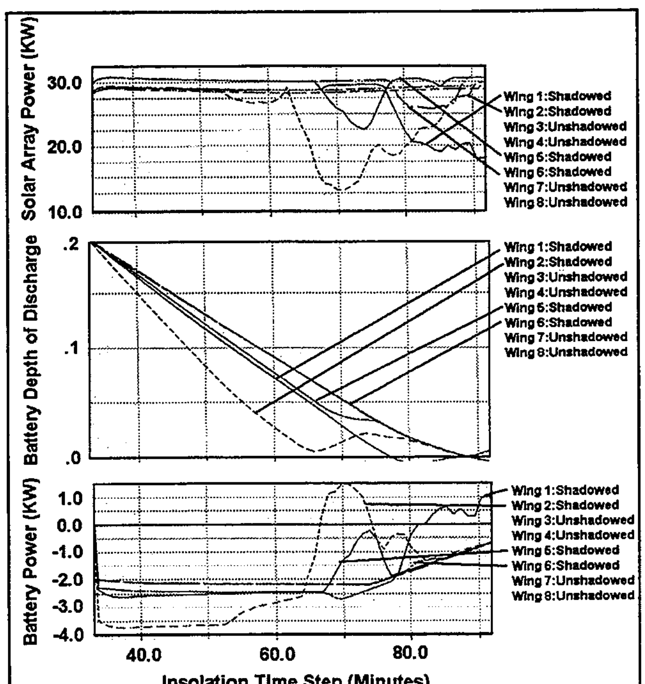

Figure 8: Shadow Effects: ISSA Arrays and Batteries

REFERENCES

1. Fincannon, James, 1993, "Orbiting Vehicle Shadowing and Power Analysis Computer Programs Integrated", *Research and Technology 1993*, NASA TM-106376, NASA Lewis Research Center, p.120-121.

2. Gruber, O. H., 1972, "Variations of electrical input parameters in a single battery unregulated bus concept", *ESRO Spacecraft Power Conditioning Electronics*, European Space Agency, European Space Research and Technology Center, ESTEC, Noordwijk (Netherlands), p 223-237.

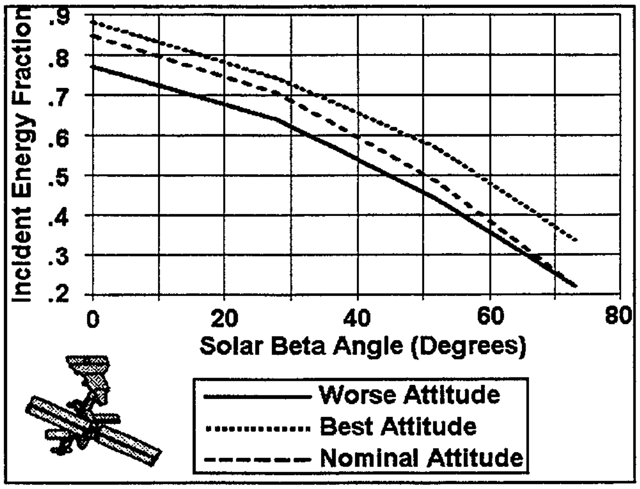

Figure 9: ISSA Attitude, Solar Beta Shadow Effect

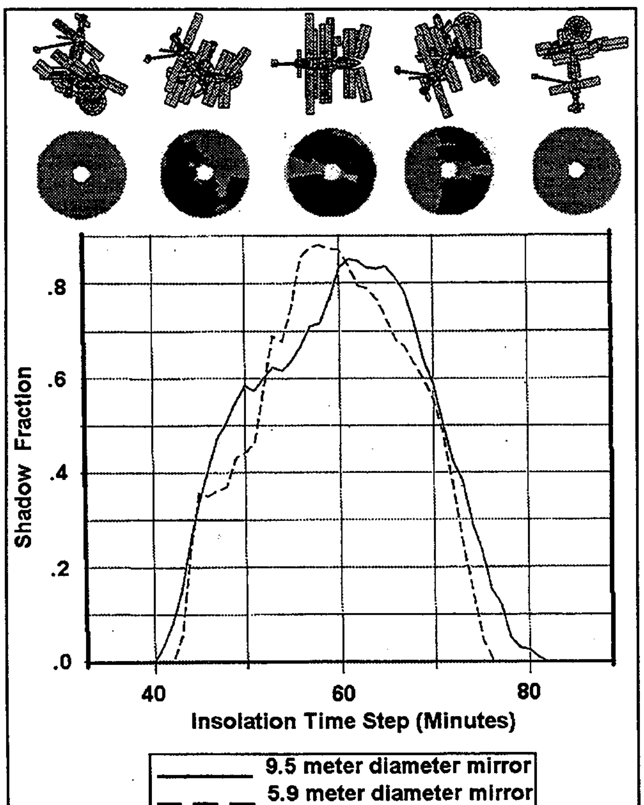

Figure 10: Mir/Solar Dynamic Shadow Fraction

3. Hojnicki, Jeffrey S., 1991, "Computer Code Analyzes Electric Power System Performance", *Research and Technology 1991*, NASA TM-105320, NASA Lewis Research Center, p. 130-131.
4. Hojnicki, Jeffrey S., Green, Robert. D., Kerslake, Thomas W., McKissock, David B., and Trudell, Jeffrey J., 1993, "Space Station Freedom Electrical Performance Model", NASA TM-106395, *Proceedings, 28th Intersociety Energy Conversion Engineering Conference*, Atlanta, Georgia.
5. Kerslake, Thomas W., Hojnicki, Jeffrey S., Green, Robert D., and Follo, Jeffrey C., 1993, "*System Performance Predictions For*

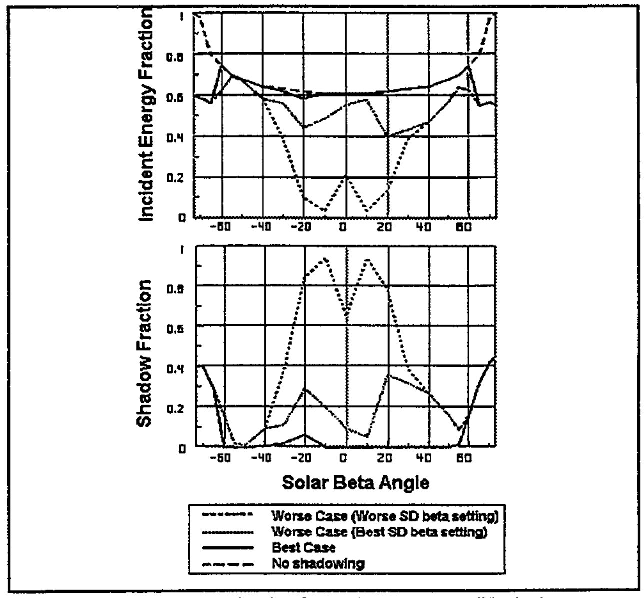

Figure 11: Mir/SD Attitude+Solar Beta Angle Variation

*Space Station Freedom's Electrical Power System", NASA TM-106396, Proceedings, 28th Intersociety Energy Conversion*Engineering Conference, Atlanta, Georgia.
6. Kumar, Renjith R., Heck, Michael L., 1991, "Power optimal single-axis articulating strategies", NASA-CR-187510, REPT-91-1, NAS 1.26:187510, Analytical Mechanics Associates, Inc., Hampton, VA.
7. Proeschel, R.A., 1992, "Orbiting Solar Array Simulation Model", *COSMIC* Computer Program Number: MSC-18558, Rockwell International Corp.
8. Skladany, J.T., 1993, "SSPTA- Simplified Shuttle Payload Thermal Analyzer", *COSMIC* Computer Program Number: GSC-12698, NASA Goddard Space Flight Center.
9. Tsushima, S., Orii, T., Mizushima, M., and Hara, H., 1973, "Shadow effect analysis of solar array", Nippon Electric Co., Ltd., Yokohama, Japan, *Proceedings, 10th International Symposium on Space Technology and Science*, Tokyo, Japan, September 3-8, 1973, AGNE Publishing, p. 719-727.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1995	Technical Memorandum

4. TITLE AND SUBTITLE

Analysis of Shadowing Effects on Spacecraft Power Systems

5. FUNDING NUMBERS

WU–478–12–10

6. AUTHOR(S)

H.J. Fincannon

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

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–9770

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

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106994

11. SUPPLEMENTARY NOTES

Prepared for the Fourth European Space Power Conference sponsored by the European Space Agency, Poitiers, France, September 4–8, 1995. Responsible person, H.J. Fincannon, organization code 6920, (216) 433–5405.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories 18 and 20

This publication is available from the NASA Center for Aerospace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This paper describes the Orbiting Spacecraft Shadowing Analysis (OSSA) computer program that was developed at NASA Lewis Research Center in order to assess the shadowing effects on various power systems. The algorithms, inputs and outputs are discussed. Examples of typical shadowing analyses that have been performed for the International Space Station Freedom, International Space Station Alpha and the joint United States/Russia Mir Solar Dynamic Flight Experiment Project are covered. Effects of shadowing on power systems are demonstrated.

14. SUBJECT TERMS

Space stations; Space vehicles; Satellites; Electric power, Power modules; Shadowing; Shadowing effects; Simulation; Modeling

15. NUMBER OF PAGES

8

16. PRICE CODE

A02

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