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Analysis of Shadowing Effects on MIR Photovoltaic and Solar Dynamic Power Systems

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ANALYSIS OF SHADOWING EFFECTS ON MIR PHOTOVOLTAIC AND SOLAR DYNAMIC POWER SYSTEMS

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ABSTRACT

The NASA Lewis Research Center is currently working with RSC-Energia, the Russian Space Agency, and Allied Signal in developing a flight demonstration solar dynamic power system. This type of power system is dependent upon solar flux that is reflected and concentrated into a thermal storage system to provide the thermal energy input to a closed-cycle Brayton heat engine. The solar dynamic unit will be flown on the Russian Mir space station in anticipation of use on the International Space Station Alpha. By the time the power system is launched, the Mir will be a spatially complex configuration which will have, in addition to the three-gimbaled solar dynamic unit, eleven solar array wings that are either fixed or track the Sun along one axis and a variety of repositionable habitation and experiment modules. The proximity of arrays to modules creates a situation which makes it highly probable that there will be varying solar flux due to shadowing on the solar dynamic unit and some of the arrays throughout the orbit. Shadowing causes fluctuations in the power output from the arrays and the solar dynamic power system, thus, reducing the energy capabilities of the spacecraft. An assessment of the capabilities of the power system under these conditions is an important part in influencing the design and operations of the spacecraft and predicting its energy performance.

This paper describes the results obtained from using the Orbiting Spacecraft Shadowing Analysis (OSSA) program that was integrated into the Station Power Analysis for Capability Evaluation (SPACE) electrical power system computer program. OSSA allows one to consider the numerous complex factors for analyzing the shadowing effects on the electrical power system including the variety of spacecraft hardware geometric configurations, yearly and daily orbital variations in the vehicle attitude and orbital maneuvers (for communications coverage, payload pointing requirements and rendezvous/docking with other vehicles).

The geometric models of the MIR with a solar dynamic power unit that were used in performing shadowing analyses are described. Also presented in this paper are results for individual orbits for several flight attitude cases which include assessments of the shadowing impacts upon the solar dynamic unit and the solar arrays. These cases depict typical MIR flight attitudes likely to have shadowing impact. Because of the time varying nature of the Mir orientation with respect to the Sun and the lack of knowledge of the precise timing of the attitude changes, strategies must be devised to assess and depict the shadowing impacts on power generation throughout the year. To address this, the best, nominal and worst impact of shadowing considering a wide possible range of parameter changes for typical mission operation period is shown.

BACKGROUND

Since 1993, NASA Lewis Research Center has been participating in the development of Solar Dynamic Flight Demonstration Project in conjunction with the AlliedSignal, Russian Space Agency and RSC-Energia. The purpose of this project was to jointly build in Russia and the United States a solar dynamic power system minimizing cost by using pre-existing component designs as much as possible, deploy from the Space Shuttle the assembled solar dynamic unit onto the Mir space station and operate the solar dynamic unit for a period of time to obtain flight experience in this new type of space power system.

A solar dynamic power system relies upon a reflective surface to concentrate light into a heat-storage receiver from which an engine draws thermal energy to turn an alternator, thus providing electric power. One of the main benefits of this type of power source is the reduced projected surface area in the direction of flight because, for the orbit altitudes of typical space stations, this area is proportional to amount of fuel needed to maintain the vehicle orbit altitude. Conversely, because of its smaller projected area in the direction of the Sun, shadowing of the SD mirror from other parts of the vehicle can potentially cause a more dramatic decrease in the power of the unit than a solar array power system of comparable power level. Since the amount of power decrease depends upon the location of the shadowing on the mirror, positions of components, and solar vector location, it becomes necessary to perform shadowing analysis to quantify the shadowing effects. Power effects of shadowing can either cause shutdowns in the power system due to insufficient incident energy or receiver overheating due to asymmetric continuous incident flux. This overheating can also result in an increase in receiver stresses due to differential thermal expansion.

Examination of the literature indicates that shadowing has been considered in the design of past spacecraft; namely, of radial booms on a body-mounted solar cell-covered spinning cylinder (Gruber, 1972) and of antennas/probes on an array (Tsushima, 1973). Some solar array-to-solar array analysis on the International Space Station Freedom has been done (Kumar, 1991). In addition, some computer codes are available that perform shadowing analysis between solar arrays (Proeschel, 1992), general thermal energy effects on Shuttle payloads (Skladany, 1993) or general energy absorption on orbiting spacecraft (Skladany, 1969). Drawbacks of these codes include speed, flexibility, complexity and availability.

ALGORITHMS

Two computer programs developed at NASA for the analysis of the Space Station Freedom power system were used to quantify the shadowing effects of the Mir Space Station on the solar dynamic concentrator.

OSSA (Orbiting Spacecraft Shadowing Analysis) is a computer program which is used to perform shadowing analysis on selected surfaces of a spacecraft given a solid geometry model, articulating surface rotation angles (i.e. tracking data), Sun pointing angle and spacecraft attitude orientation (Fincannon, 1993) (Hojnicki, 1992).

To provide the tracking data and pointing data, OSSA was completely integrated into SPACE (Station Power Analysis for Capability Evaluation). SPACE is a computer program which is used to predict the power produced by solar arrays with batteries and a distributed power system for an orbiting spacecraft (Hojnicki, 1991) (Hojnicki, 1993). Various programs within SPACE perform power system optimization, orbital mechanics, pointing and tracking, and battery/solar array/power distribution simulation. SPACE has been used to predict power system performance on the International Space Station Freedom (Kerslake, 1993).

For the articulating Mir solar arrays, the tracking algorithms ratcheted the array gimbals in 12.5 degree increments based on the solar vector. For the solar dynamic unit, the gamma and alpha gimbals were adjusted to provide a sun tracking solution such that both gimbals were maintained within their allowable limits for each time step during an orbit. The beta gimbal was fixed at one of five allowable gimbal positions (-90,-45,0,45,90) for each orbit depending on whether that beta gimbal setting permitted the other gimbals to obtain sun-tracking solutions throughout the insolation part of the orbit. The algorithms to accomplish the solar dynamic unit pointing were based on iteration of the beta gimbal settings with a linear optimization of the alpha gimbal and then the gamma gimbal to provide optimum solar tracking.

MODEL

The OSSA computer program requires a solid model data file of the spacecraft to be analyzed. This file contains coding to identify the shadowed surface to be analyzed, the articulating elements and the pivot points and rotation axes for each articulating element.

The Mir Space Station is composed of four primary elements, the Base module, the Kvant-1 module, the Krystal module, the Kvant-2 module and the Spectre module (Figure 1). There are also two Soyuz modules. Each of the modules have solar arrays which may be articulating. The Base module has two solar array wings that articulate about one axis and one wing that is stationary, the Soyuz modules each have two small non-articulating solar array wings, and the Kvant-2, Kvant-1 and Spectre modules each have two one-axis articulating solar array wings.

The solar dynamic unit has a parabolic dish mirror, gimbal/support structure, receiver/PCU and three articulation joints: a 'beta' gimbal for coarse pointing to compensate for solar beta angle variation, an 'alpha' gimbal for daily sun tracking, and a 'gamma' gimbal for fine pointing (Figure 2).

Typically, the OSSA geometry models are composed of cylinders, planes, boxes and spheres. The model used in the analysis contained 1000 polygons. There were 621 points on the mirror that were analyzed for shadowing (23 radially by 27 axially, non-equidistant).

MIR FLIGHT ATTITUDES

In actual operation, the attitude of the Mir spacecraft is always varying such that it is difficult to characterize the 'on-average' shadowing effects. It is possible to perform statistical analyses by randomly selecting attitudes for which to analyze shadowing effects (Figure 3). In this figure, an orbit with a zero degree solar beta angle was selected to characterize the solar vector and each rotation about each vehicle axes was randomly selected with equal probability for over 5000 cases. The average incident energy fraction for the insolation period of the orbit is the amount of energy the solar dynamic mirror receives if shadowing effects are considered normalized by the energy received if there were no shadowing. The most frequently seen incident energy fraction was about .63, which translates into 37% average shadowing for the insolation part of the orbit. This approach is satisfactory only if the flight attitude frequency is completely unknown.

In order to realistically bound the fluctuation of shadowing on the solar dynamic unit and the Mir solar arrays, it is necessary to understand the range of valid flight attitudes the Mir experiences.

These have been broken down into four classes; Earth-inertial, Solar-inertial, inverted Earth-inertial and inverted solar-inertial.

The Earth-inertial attitudes constantly maintain the orientation of the Mir spacecraft with respect to the Earth, while the solar-inertial has the Mir oriented with respect to the Sun. These typical attitudes are for analysis only and do not represent exact planned orientations (e.g. vehicle attitude is usually kept within a specified band of +-5 degrees and transient flight attitudes are needed for Soyuz or Space Shuttle docking or altitude station-keeping).

The Earth-inertial attitudes are of three types; 1) with the solar array gimbal axes perpendicular to the orbit plane, the booms pointing opposite the vehicle velocity vector (Figure 4), 2) with the solar array gimbal axes along the velocity vector (Figure 5) and 3) rotates about the Mir main body axis through each orbit to optimize on solar array pointing. Earth inertial cases have the solar dynamic unit at nadir. This is considered a nominal or most frequently seen type of orbit for the anticipated time frame of the Solar Dynamic Flight Experiment. Selection of either case 1 or 2 is based on which orientation is best able to allow the solar array gimbals to track the Sun and save on attitude control resource usage. Case 3 is anticipated to be used when there are high power needs and attitude control resources may be expended. The solar-inertial attitudes resemble the Earth-inertial attitude at noon. Solar-inertial attitudes are best for charging the space vehicle batteries or performing astronomical or Earth viewing, but cannot be maintained for long periods because of attitude control fuel usage.

The inverted attitude classes simply have the vehicle rotated about one axis to obtain the solar dynamic unit at zenith instead of nadir. The inverted classes will not be frequently used because they are not stable and require too much fuel to maintain. They will be used mainly during the initial setup and operation of the solar dynamic unit because they place the unit in a very favorable 'Sun-seeing' orientation.

ANALYSIS RESULTS: SOLAR DYNAMIC UNIT

Figures 4 and 5 show the percentage of the solar dynamic unit mirror that is shadowed and the incident energy fraction during the insolation portion of the orbit for a solar beta angle of -20 degrees. This figure also provides a pictorial description of the vehicle and calculated shadow pattern at several times during insolation. The vehicle orientation is such that an orbit plane of solar beta 0 degrees is a horizontal plane. Solar beta angle, the angle between the orbit plane and a line from the Earth to the Sun, is a useful parameter in analyzing power-systems of orbiting spacecraft because rather than having to perform analyses for each day of the year, it is necessary only to perform analyses for the small range of solar beta angles which occur during that year or time period. Although the cases in figures 4 and 5 have shadow fractions that do not exceed .7 during the orbit, other solar beta angles can cause complete shadowing to no shadowing during the orbit.

For a range of solar beta angles that adequately characterizes the Mir orbit through the year, Figure 6 shows the average incident energy fraction and the shadow fraction for each flight mode. The crossover point in solar beta angles from Earth-inertial flight attitude 1 to 2 is at plus or minus 20 degrees. The incident energy fraction in this figure is the incident 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 a high moment-by-moment shadowing occurs through the orbit for high solar beta angle cases, because the insolation period is longer at higher absolute solar beta angles, more cumulative incident energy is available resulting in a higher incident energy fraction. The solar inertial flight attitudes have potentially the worst shadowing because the vehicle maintains the same attitude throughout the orbit. The setting which the beta gimbal is locked to for an orbit also plays an important role in how much shadowing is experienced. For the earth-inertial flight mode with gamma and beta gimbals resulting in the alpha gimbal being parallel to the velocity vector, variation of setting can increase the possible incident energy significantly. Another way to visualize the variation of energy that the solar dynamic unit receives is to translate the solar beta angle data into the yearly plot (Figure 7). The figure shows the shadow fraction during the entire year. Valid flight attitudes and solar dynamic gimbal tracking solutions were assessed to find the 'minimum' and 'maximum' shadowing. For the 'typical' shadowing, it was assumed the only valid gimbal positions were those that minimized shadowing, however, the flight attitude selection was based on worse shadowing. The inverted attitude classes have minimal shadowing.

ANALYSIS RESULTS: MIR SOLAR ARRAYS

The shadowing effects on the Mir solar arrays is shown in Figure 8. This figure shows the average incident energy fraction on the Mir solar arrays for the two Earth inertial flight attitudes. The data for both wings of each Mir module is combined. Incident energy provides only a first order idea of how the photovoltaic power system is affected by shadowing. A better approximation of shadowing effects requires detailed knowledge of the solar cell connections, present solar array power capability and battery operation which is unavailable at this time.

CONCLUSIONS

Analyses have been performed at NASA Lewis Research Center using the Orbiting Spacecraft Shadowing Analysis tool and the Station Power Analysis for Capability Evaluation computer program as part of the joint Russian/United States Solar Dynamic Flight Demonstration Project design and capability assessment process. Additional analyses will be performed to assess revised or additional Mir flight attitudes, new solar dynamic gimbal tracking and pointing strategies and updated Mir configurations up to the launch (and afterwards for purposes of operational recommendations and confirmation of shadowing predictions).

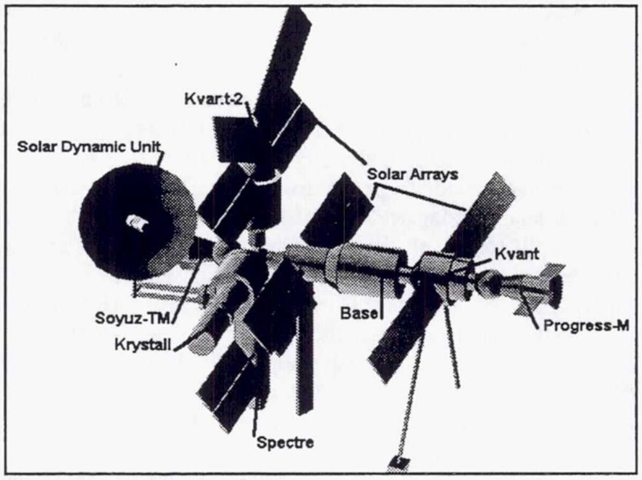

Figure 1: Mir Space Station

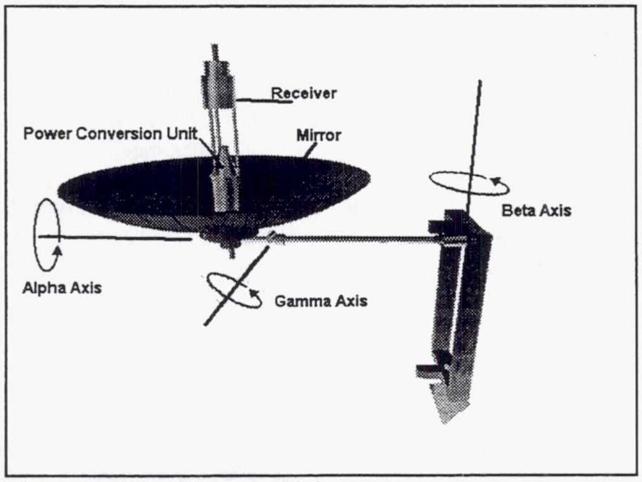

Figure 2: Solar Dynamic Unit

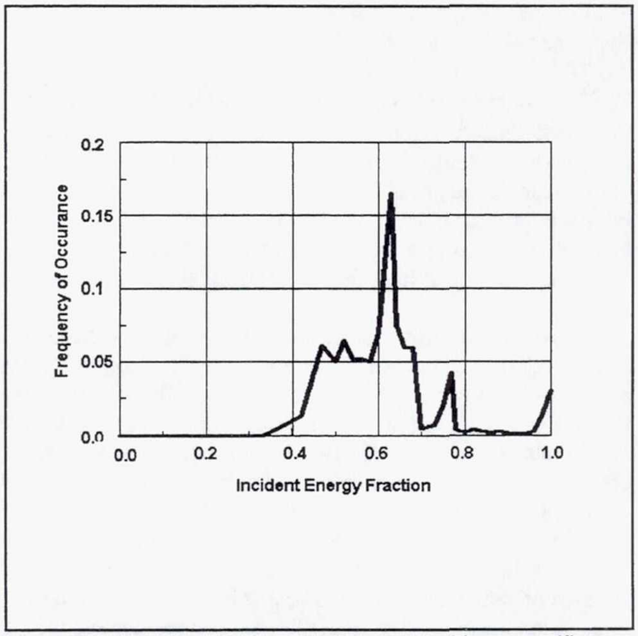

Figure 3: Frequency of having an orbit with a specific incident energy fraction (5632 cases)

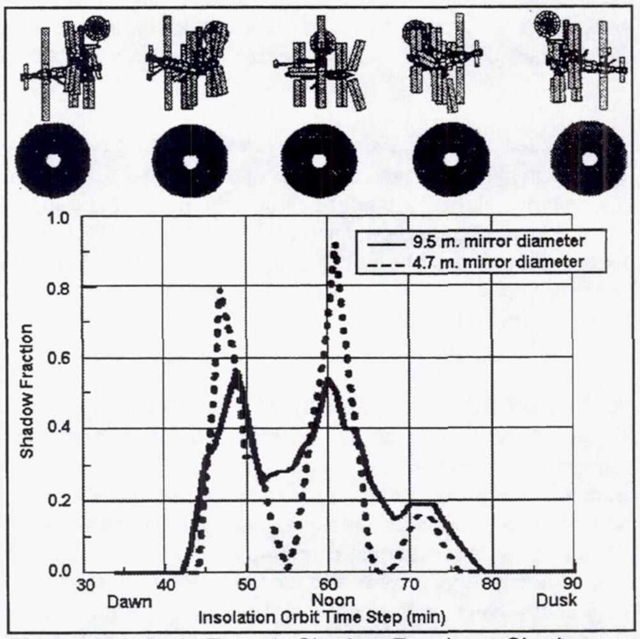

Figure 4: Attitude Type 1; Shadow Fractions, Shadow Patterns and Vehicle Orientation

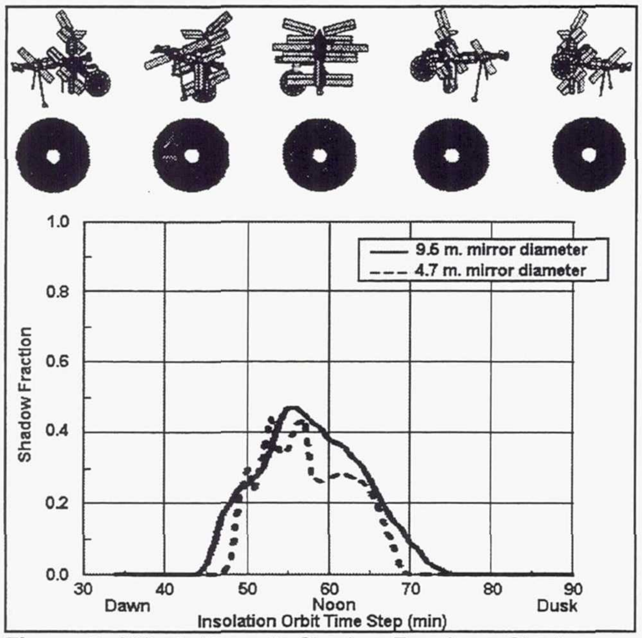

Figure 5: Attitude Type 2; Shadow Fractions, Shadow Patterns, Vehicle Orientations

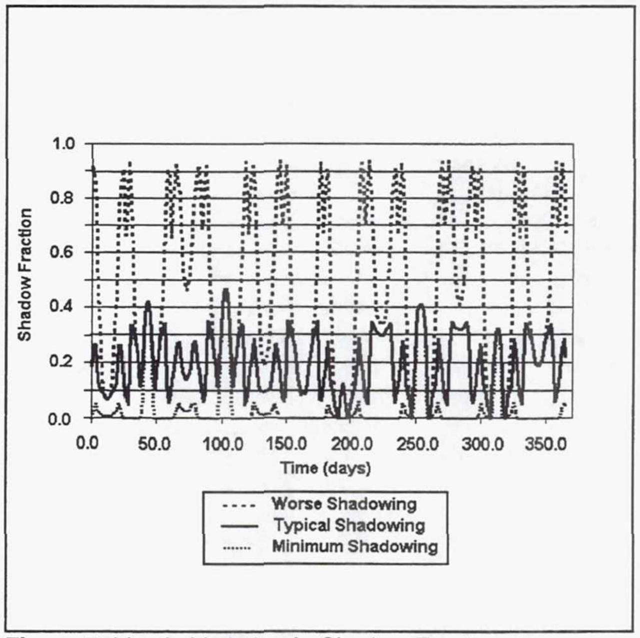

Figure 7: Yearly Variation in Shadow Fraction

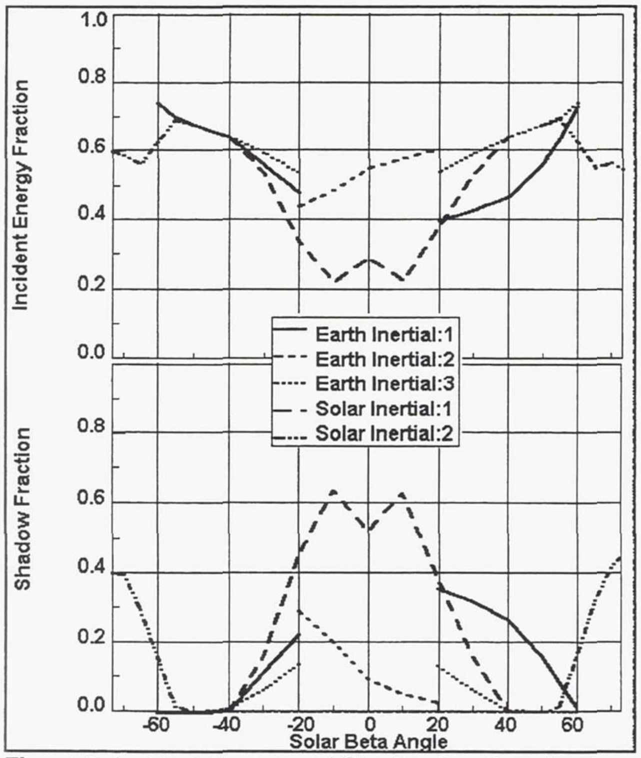

Figure 6: Incident Energy and Shadow Fractions for a Range of Flight Attitudes

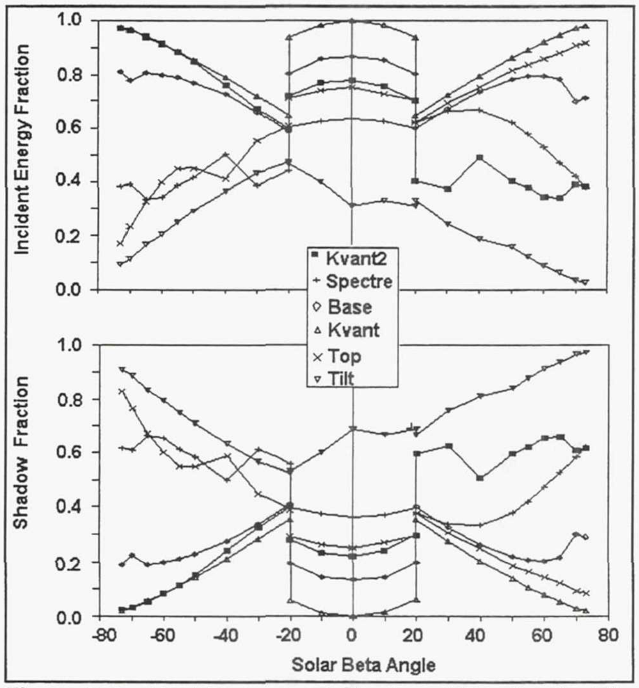

Figure 8: Incident Energy and Shadowed Fraction for Mir Solar Arrays

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13. ABSTRACT *(Maximum 200 words)*

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