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Contamination Effects of GPS Navstar Solar Array Performance

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Summary

The solar arrays on Navstars 1–6 have been limiting the electrical power capabilities in the extended life (beyond the 5 year design life). The departure from predicted performance consists of an extra 2.5% per year degradation beyond the radiation model estimates. This degradation is unusual in showing a linear rather than exponential decay with time. The performance of the arrays on these satellites has been examined in order to predict future behavior and to make refined projections on the Navstar 7-11 solar arrays. Evidence obtained from flight experiments on Navstar 5 and 6, and from laboratory experiments, suggests that contamination of the solar arrays while on orbit may be responsible. In this paper the evidence for photo-induced contamination of spacecraft surfaces is presented, and the effect on solar array output in the case of the GPS satellites is shown to be consistent with the observed anomalies.

Background

The Block I Navstar satellites have a design life of 5 years, and utilize silicon solar cells which are essentially the K4 1/2 type. For several of these satellites there is now 9 years of flight data, from which the solar panel output may be estimated. These data contrast sharply with the predicted output calculated from radiation models. In particular the degradation is more rapid than expected and is nearly linear with time rather than exponential. The data from five spacecraft are plotted in Figure 1 along with the predicted degradation. All of the spacecraft in this group show the same trend, with power losses of 23% and 37% at 5 and 10 years, respectively. The predicted losses are 18% and 21% for these same times. A discrepancy of this magnitude has strong implications for the end of life of the spacecraft and subsequent generations of satellites of similar design.

Approach to the Problem

Initial attempts to explain the flight data included consideration of several scenarios. One of these was the possibility that the radiation environment used to predict performance was inadequate. The GPS orbit is half-synchronous and no published data are available for solar cell performance on other vehicles in this orbit. The JPL Solar Cell Radiation Handbook [ref. 1] shows that for cells of this type, the radiation fluence would have to be in error by more than an order of magnitude to account for the observed degradation at the 10 year point. Therefore the knowledge of the environment was assumed to be accurate. The possibility was also considered that the solar cells

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were substandard. However, the cells used on these vehicles were manufactured by several vendors over a 5 year period, and it is highly improbable that they would all be flawed in the same way.

The possibility of physical damage to the cells was also considered. Micrometeoroid impacts on the coverglasses could roughen the surface and lead to a small reduction in short circuit current, but not a reduction of the observed magnitude. Actual mechanical failures such as interconnect detachments or cell breakage were also considered, however these would have led to abrupt changes in power output rather than the smooth decrease which was observed. Also it would be unlikely that all 5 spacecraft in this study would be affected in the identical fashion that has been observed.

Attention was then turned to the possibility that the solar cells themselves were not degrading, but that less light was reaching them. Recent work [ref. 2] on photo-enhanced contamination of spacecraft thermal control surfaces was examined. Observation of thermal radiator properties on a number of spacecraft (DSCS, FLTSATCOM, INTELSAT, DSP, SCATHA) had shown that contamination of these surfaces occurs over time. This contamination leads to increases in the solar absorbtance, which in turn results in higher radiator temperatures. Figure 2 shows the increase with time on orbit of the radiator solar absorptance for a variety of spacecraft, as inferred from observed temperature increase [ref. 2]. The absorptance is defined as

$$\Delta\alpha = (I_0 - I_r)/I_0 - \alpha_0$$

where I_0 is the incident solar intensity, I_r is the reflected intensity, and α_0 is the absorptance of the radiator in the absence of any contaminant film. The curve labeled GPS Navstar refers to data taken from a second surface mirror mounted on the solar array of Navstar 5. This sensor was therefore exposed to the same environment as the solar panels.

Two curves from the DSP program provide direct evidence that contamination emanating from the spacecraft body is redepositing on the thermal control surfaces. The "DSP AVG" data are averages over several early vehicles, on which the sensitive surfaces had a direct field of view of spacecraft body vents. DSP "FLT-10" is a later vehicle in which the vents were relocated to eliminate the field of view. The improvement is obvious, and lends support to the contamination scenario.

Additional flight and laboratory experiments [refs. 2,3] have determined that the contamination of thermal control surfaces is a photo-assisted deposition process. The essence of the process is that organic films which condense on, and evaporate from surfaces become polymerized on UV exposed surfaces and cannot re-evaporate. Under illuminated conditions the temperature of the surface becomes relatively unimportant (up to at least 60°C), as demonstrated by a SCATHA flight experiment which utilized a temperature controlled quartz crystal microbalance. This experiment also showed that the net contaminant deposition rate is approximately an order of magnitude higher on a sunlit surface than on a dark one. Polymerized films produced by this process on fused silica second surface mirrors and silverized teflon have been characterized [ref. 3]. In particular the wavelength dependence of the film absorption coefficient $\epsilon(\lambda)$ has been estimated from 3 sets of data, and using this information and the measured $\Delta\alpha$ for Navstar 5, the expected degradation of solar array output power can be computed.

Contaminated Solar Array Calculation

The procedure for calculating the loss in solar array power is straightforward once the necessary input data is available. The measured value of $\Delta\alpha$ vs. time from Figure 2 is combined with the estimated $\Delta\alpha$ per unit film thickness from reference 3, equation 8 to obtain the film deposition rate. The wavelength dependent absorption of this film is convolved with the spectral response characteristic of the silicon solar cell and the AM0 solar spectrum to estimate the power loss as a function of time.

From the Navstar 5 calorimeter flight experiment, the measured $\Delta\alpha$ is 0.06/year. The dependence of $\Delta\alpha$ on film thickness is obtained from equation 8 of reference 3 as $\Delta\alpha = 0.0034/100$ A. Combining these parameters gives a deposition rate $L(t) = 0.176\ \mu m/year$. The spectral absorption $\epsilon(\lambda)$ for contaminant films on silica surfaces was obtained from reference 3. The spectral response of the silicon solar cells $S(\lambda)$ is taken from Figure 4.7 of reference 4. The degradation factor for output current of the solar cell is thus

$$F(t) = \int \exp(-\epsilon(\lambda)\ L(t))\ S(\lambda)\ I_0(\lambda)\ d\lambda \Big/ \int S(\lambda)\ I_0(\lambda)\ d\lambda$$

where $I_0(\lambda)$ is the AM0 solar spectrum.

Figure 3 shows the power system output for Navstar 4 (squares), the original radiation induced degradation predictions (solid line) and a new prediction based on the product of this original model and the F(t) term just evaluated. Although the uncertainty in the contamination contribution is substantial, the shape of the flight data curve is well represented by the combined effects, and the magnitude of the total degradation is much closer to that actually observed on the five Block I vehicles.

Conclusion

Evidence for the effects of contaminant films on spacecraft radiator surfaces have been applied in a study of anomalous solar array degradation on the GPS Navstar satellites. Data from flight experiments on Navstar 5 have been used to demonstrate that this degradation is consistent with photo induced contaminant deposition on the solar array surface.

References

[1] *JPL Solar Cell Radiaton Handbook*, publication 82-69.

[2] D. F. Hall and T. S. Stewart, AIAA-85-0953.

[3] D. F. Hall, *Intl. Symposium on Spacecraft Materials in Space Environment*, ESA SP-178, June 1982, Toulouse, France.

[4] Fahrenbruch and Bube, "Fundamentals of Solar Cells", Academic Press, 1983.

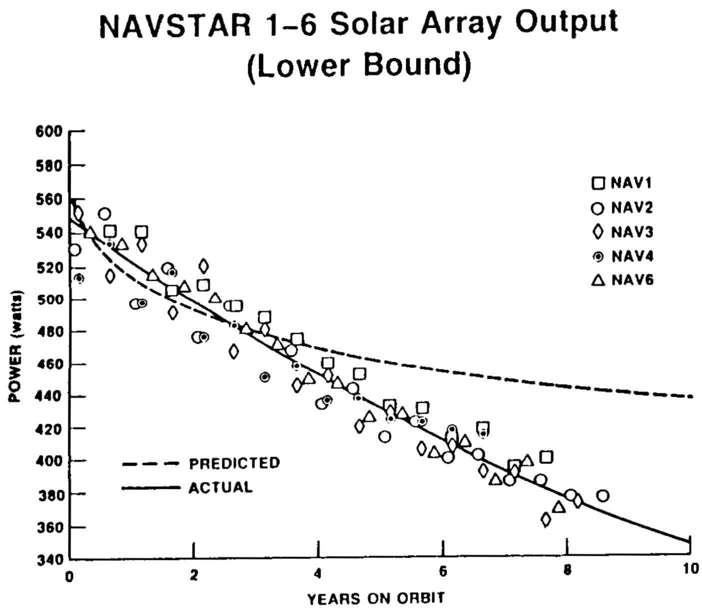
NAVSTAR 1-6 Solar Array Output
(Lower Bound)
POWER (watts)
600
580
560
540
520
500
480
460
440
420
400
380
360
340
0
2
4
6
8
10
YEARS ON ORBIT
NAV1
NAV2
NAV3
NAV4
NAV6
PREDICTED
ACTUAL

Figure 1

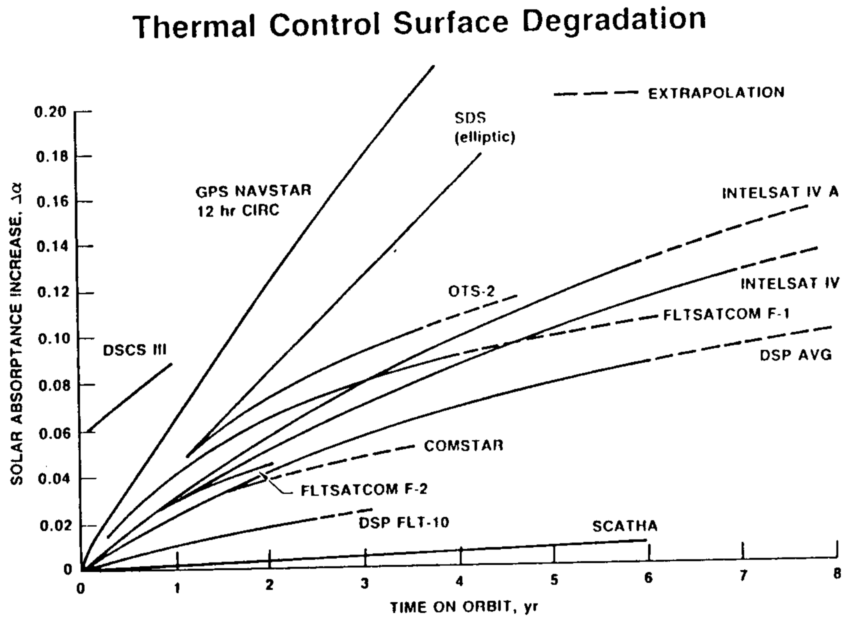

Figure 2

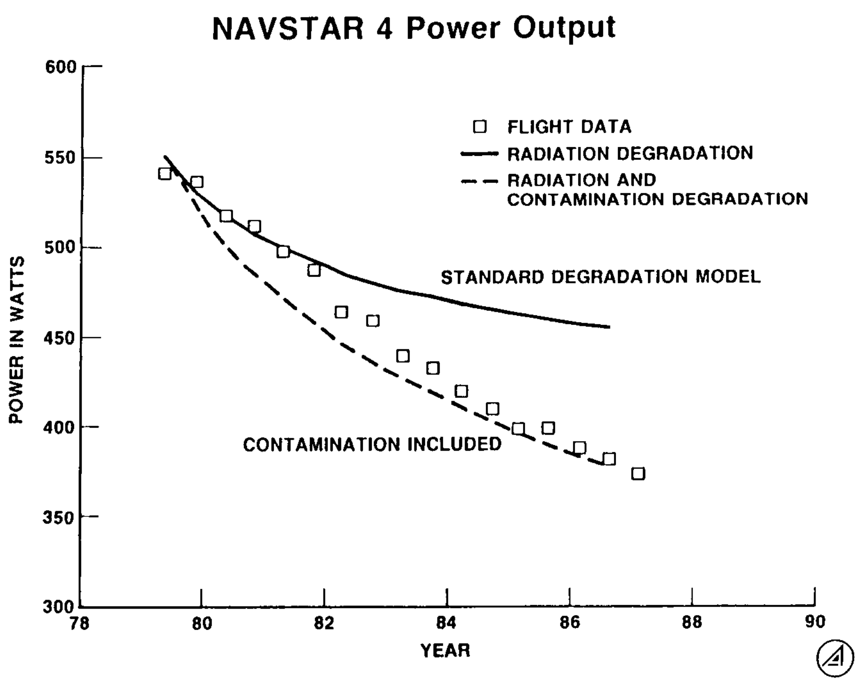

Figure 3