DESIGN AND ANALYSIS CONSIDERATIONS FOR DEPLOYMENT MECHANISMS IN A SPACE ENVIRONMENT

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ABSTRACT

On the second flight of Ford Aerospace and Communication Corporation's INTELSAT V spacecraft the time required for successful deployment of the north solar array was longer than originally predicted. The south solar array deployed as predicted. As a result of the difference in deployment times a series of experiments was conducted to locate the cause of the difference. Specifically, deployment rate sensitivity to hinge friction and temperature levels was investigated. In conjunction with these experiments a digital computer simulation of the deployment was created to evaluate the effects of parameter changes on deployment. As a result of the experiments and simulation, hinge design was optimized for nominal solar array deployment time for future INTELSAT V satellites. The nominal deployment times of both solar arrays on the third flight of INTELSAT V confirms the validity of the simulation and design optimization.

INTRODUCTION

As satellites grow in size, the need for stowing the satellite within the dimensions of the launch vehicle fairing becomes a serious design constraint. For this reason spacecraft are being built which are stowed in one configuration and then deployed into another configuration once in orbit. An example of such a satellite is the successful Ford Aerospace and Communications Corporation (FACC) INTELSAT V spacecraft. INTELSAT V is powered by two solar arrays that deploy once the satellite reaches geosynchronous orbit.

On the second flight of INTELSAT V the time required for successful deployment of the north solar array was longer than predicted. As a result of this, a series of ground-based experiments was conducted in order to locate the cause. Results of the experiments showed much higher friction levels on the flight hinge assemblies than had been originally predicted. In addition, friction levels increased significantly at the low temperatures expected in orbit. Additional experiments and computer simulations gave additional insight into the solar array deployment mechanisms.

As a result of the experiments and simulations, hinge design was optimized for nominal solar array deployment time for subsequent INTELSAT V satellites. The successful deployment of both solar arrays on the third flight of INTELSAT V confirms the validity of the simulation and design optimization. This paper will present a case study of the analysis and design changes that resulted from the deployment described above. Problems encountered in the analysis of the solar array deployment will be discussed. This is intended to give some insight and guidelines for designers and analysts for use in design of similar mechanisms.

THE SYSTEM

The Spacecraft

The FACC INTELSAT V spacecraft is a communications satellite capable of transmitting 12,000 voice channels and 2 television channels. FACC has been contracted to build 15 INTELSAT V's. INTELSAT V FM-2 was launched December 6, 1980 and is currently operational over the Atlantic Ocean, supplying voice channels between North America and Europe. FM-1, launched May 21, 1981, is also operational over the Atlantic Ocean. The third INTELSAT V, FM-3, was successfully launched December 15, 1981 and is currently undergoing pre-operational testing. Figure 1 is an artist's rendition of the spacecraft.

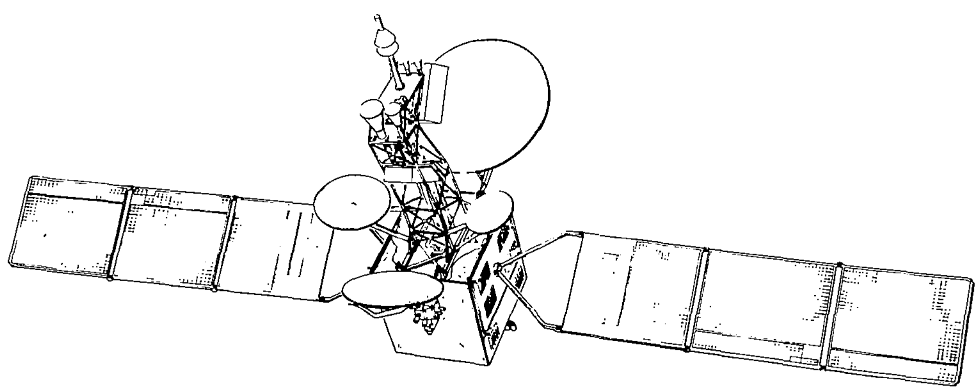

Figure 1. The INTELSAT V Spacecraft

The Solar Array

The solar arrays on INTELSAT V consist of a yoke and three solar panels that deploy in an accordion-type manner (see Figure 2). The array has two deployment mechanisms: (1) torsion springs and (2) closed cable loops. The torsion springs provide the energy to deploy the array. The closed cable loops restrain the deployment of transferring torques between the hinges, synchronizing the hinge deployment angles, and controlling the deployment rate to a point within the structural capability. Springs placed on the closed-cable-loop cables compensate for changes in cable length due to temperature variation. The springs also allow the hinge lines to be at somewhat different angles during deployment and add considerable complexity to the mathematical model of the solar array deployment. See Figure 2 for a description of the deployment mechanism and solar array parameters. Figure 2 also contains drawings of the hinge assemblies.

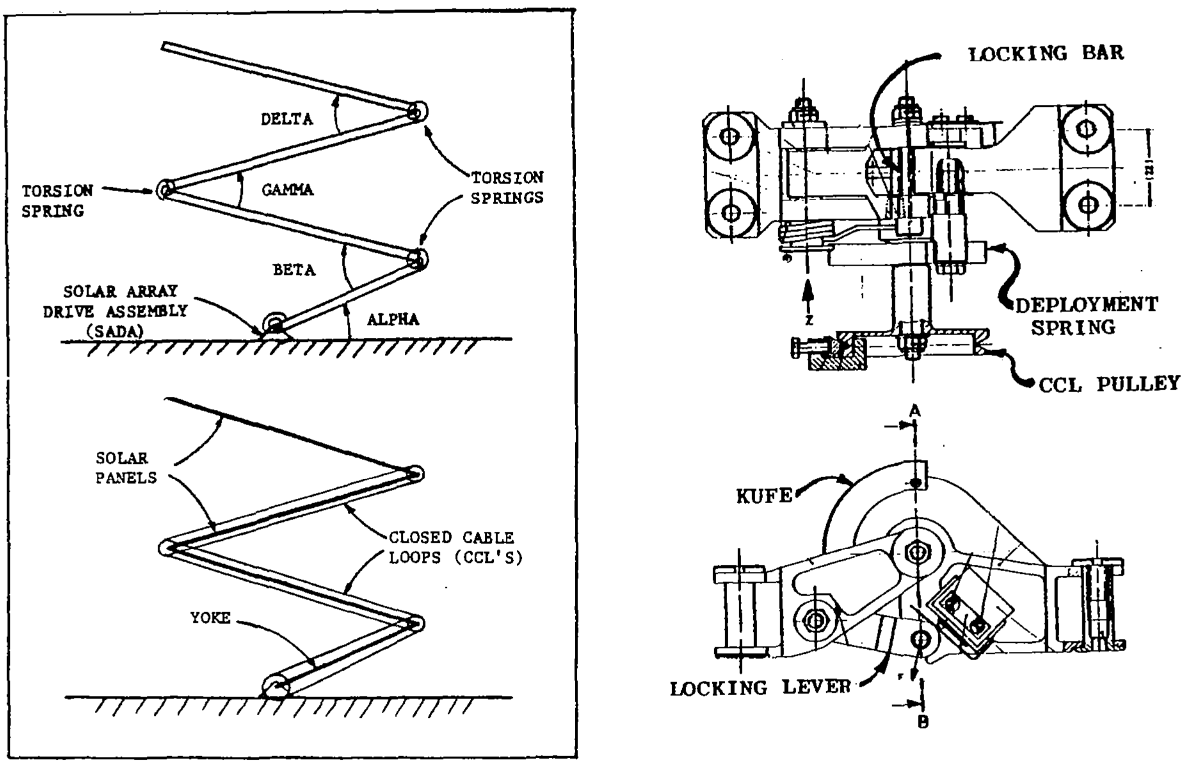

Figure 2. The Deployment Mechanisms and Hinges

THE SOLAR ARRAY DEPLOYMENT

On the second flight the south solar array deployment time was 22 seconds. The north solar array almost completely deployed in 22 seconds, but spacecraft roll rate data indicate the array was still moving until 32 seconds after release. Original predictions were for both solar arrays to deploy in approximately 13.5 seconds.

Figure 3 shows the roll rate of the spacecraft during the deployment of both the north and south solar arrays on the second flight. As the arrays are deploying, the roll inertia of the spacecraft increases, which results in a decrease in the spacecraft roll rate. From 0 to 22 seconds the spacecraft roll rate steadily decreases from .34 deg./sec. to .12 deg./sec. Accelerometer data indicated the south solar array locked into the deployed position at around 22 seconds.

Further analysis of the data indicates there is a slow decrease in the roll rate from 22 to 32 seconds, which implies the north solar array was continuing to slowly deploy. The oscillation of the roll rate occurring after 22 seconds is caused by the first bending mode vibration of the south array after it has locked up. This damped oscillation appears to be vibrating around a slowly decreasing roll rate, but due to the quantized nature of the roll rate data, no change in the roll rate is directly measured after the oscillation has damped out.

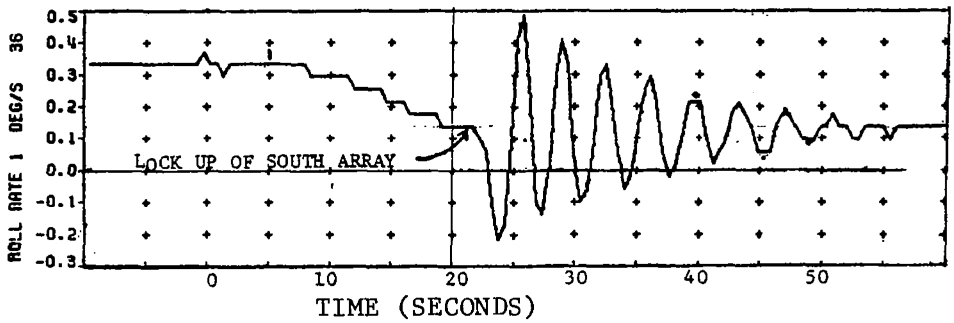

Figure 3. Spacecraft Roll Rate Data From FM-1

EXPERIMENTS

Two sets of ground-based experiments were conducted using an engineering model and flight hinge assemblies in order to locate the cause of the deployment time difference. A series of deployment tests was made with an engineering model of the solar array at FACC. These tests were intended to duplicate the flight experience, or to give insight into the possible causes. The second series of experiments was the measurement of resisting (friction) torques on flight hinge assemblies. These tests were intended to provide better values of the resisting torques in thermal vacuum environments, representative of expected orbital conditions.

Tests on Engineering Model

The deployment tests on the engineering model were divided into two groups:

1. Attempts to duplicate the flight data
2. Deployment tests with simulated hot and cold closed cable loops and hinges, duplicating on-orbit conditions.

A photograph of the test setup is seen in Figure 4. The array deploys horizontally and is supported at the panel centers by a sliding bar support device. The support rig was slightly inclined (2 mm/m) to counteract for the friction of the support device and air drag. At this inclination the array deployed in 22 seconds, the same as the south solar array on the second flight.

The attempts to duplicate the on-orbit results proved unsuccessful. Several test runs were made, varying the inclination of the support rig. No cases were recorded with the type of flight data experienced on-orbit. Additional tests were conducted in which the closed cable loop (CCL) was slipped off of the hinge pulleys. Again, no insight into the deployment time difference was gained.

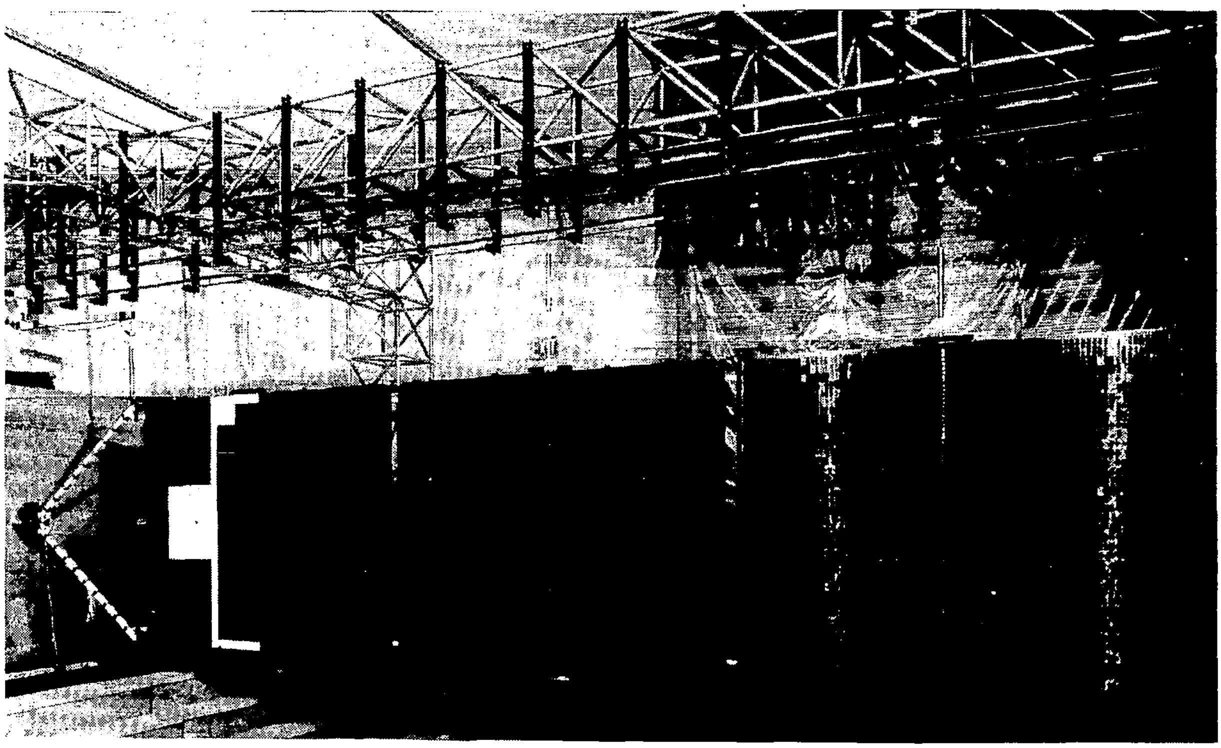

Figure 4. The Experimental Model Test Setup

The second series of tests on the engineering model was conducted to simulate the on-orbit temperature conditions. The orbital configuration of the solar arrays during deployment is edge-on to the sun. This position results in a temperature difference between the sunward and shaded hinges. To evaluate the effects of hot and cold conditions a test was constructed where the upper hinges were heated to 85°C with lamps, and the lower hinges were cooled with gaseous nitrogen to -100°C. The deployment time in this configuration increased to 24.7 seconds. These tests indicated an increasing resistance torque level with decreasing hinge temperature.

Additional tests were conducted to examine the effect of the closed cable loop (CCL) temperatures on deployment times. Temperature changes on the CCL's affect the length of the cables, which will change the point at which the cable will go slack. When the effects of temperature on the CCL's were tested, significant variations in deployment time resulted. Under nominal on-orbit conditions the south array deployment time was three seconds faster than the north array during the tests on the experimental model. On the first flight the south solar array deployed 6.5 seconds faster than the north array. Evidently the temperature of the CCL's contributed to this difference.

Beyond increasing the deployment time, the effect of the CCL temperature on the deployment did not reveal any insight into the deployment experienced on-orbit. Table 1 summarizes the four test runs described above.

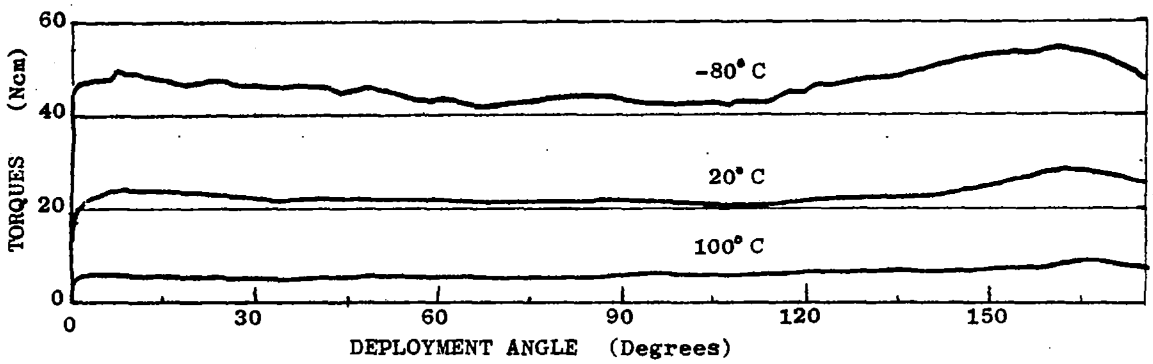

Figure 5. Hinge-Resisting Torque for Original Inter-Panel Hinges

Table 1. Test Runs on Engineering Model

Test Number	Deployment Times (sec.) 1st Hinge Lockup	Last Hinge Lockup	Comments
1	21.7	22.0	Rig inclination 2mm/m. Room temperature, baseline deployment
2	24.0	24.7	Rig inclination 2mm/m. Nominal north panel on-orbit conditions. Upper hinges 85°C. Lower hinges -100°C.
3	21.7	22.9	Rig inclination 2mm/m. Nominal north panel taking into account CCL temp. effect.
4	19.0	19.7	Rig inclination 2mm/m. Nominal south panel taking into account CCL temp. effect.

Tests on Hinge Friction Levels

The most important findings of the investigations were the measurements of the resisting torques on flight hinge assemblies. These measurements revealed that the resisting torques at low temperatures in vacuum were much larger than values obtained from measurements obtained on development model assemblies, and much larger than the values obtained in ambient conditions.

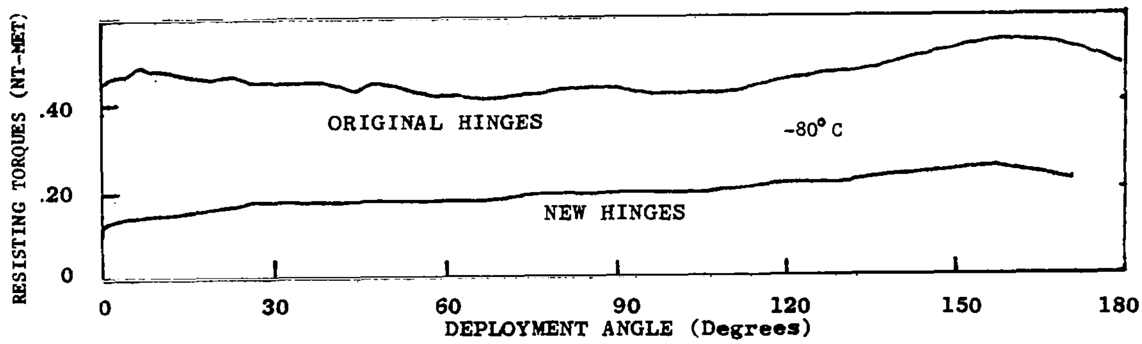

Figure 6. Hinge-Resisting Torques for Modified Inter-Panel Hinges

Figure 5 shows the resisting torque level variation with deployment angle at various temperature levels. The resisting torque does not include the torsion spring torques. The resisting torques at low temperatures are higher than initially estimated. The values are such that beyond a 100° deployment angle of the inter-panel hinges, inertia forces of the moving array are needed to assist the torsion spring torque in the deployment of the array.

As a result of these findings all the hinges were given special lubrication. In addition, the bearing tolerences were increased to allow for greater temperature variations. Results of the hinge friction measurements on the modified hinges are shown in Figure 6. The resisting torque level has been greatly reduced at low temperatures. Further tests showed that the friction level on the modified hinges is not as sensitive to temperature variation as the original hinges.

THEORETICAL ANALYSIS

In conjunction with the laboratory experiments, a theoretical model and digital computer simulation of the solar array deployment was developed. The purpose of the model was to: (1) recreate the on-orbit deployment results, (2) give additional insight into the deployment mechanism dynamics, and (3) provide a tool whereby the data from the friction tests could be evaluated in respect to deployment dynamics. In the simulation the panels and yoke are modeled as rigid elements interconnected with flexible hinges and extendible closed cable loops with accurately modeled temperature compensating springs. The torques acting on the hinges in the simulation include:

1. The torsion springs at the hinges
2. Torques from the closed cable loops
3. Stick-slip coulomb friction torques (stiction).

Stiction is a resisting force that always opposes velocity and accounts for the fact that a finite force is needed to start a body moving. Accurate simulation of stiction is important for both the designer and analyst to consider, as this was eventually found to account for the differences in the north and south panel deployment times.

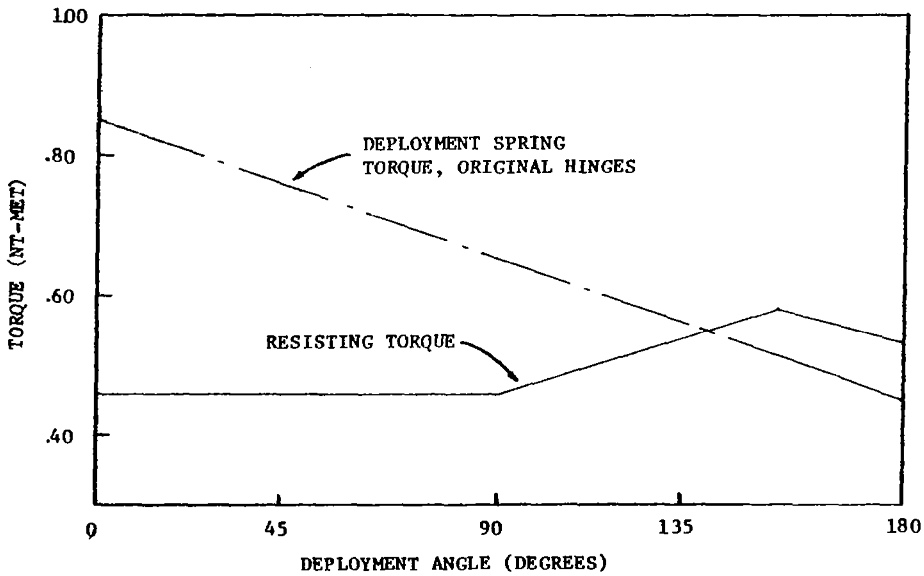

Figure 7. Spring and Resisting Torques Used in the Simulation on the Inter-Panel Hinges

Examination of the results of the hinge friction tests shows the resisting torque to be angle dependent. Since the stiction torque is angle dependent, the torque was represented in the simulation as shown in Figure 7. Figure 7 shows the torsion spring torques and the nominal resisting torques used for the inter-panel hinges in the nominal-case computer simulation.

Several simulation runs were made, varying the driving torques and stiction level at each of the hinges. Results of the simulation are the deployment angles plotted against time. From these curves the deployment time of the panel can be determined. See Figure 1 for a definition of the deployment angles. Figure 8 is the result of a simulation of the deployment of the north solar array with the nominally measured friction levels shown in Figure 7. The deployment time is approximately 18.5 seconds.

Additional runs were made attempting to duplicate a deployment similar to that experienced on orbit. The runs showed that the deployment rate was most sensitive to the friction level on the yoke/solar-array-drive-assembly (SADA) hinge. Raising the stiction on the yoke/SADA hinge 50% and the yoke/inboard-panel hinge 50% yielded a deployment similar to that experienced on orbit. Figure 9 shows these results. The array deploys for approximately 26 seconds at which point it nearly stops, but velocity data indicate the array slowly moves for another 8 seconds, at which point the deployment stops with the array in a partially deployed position.

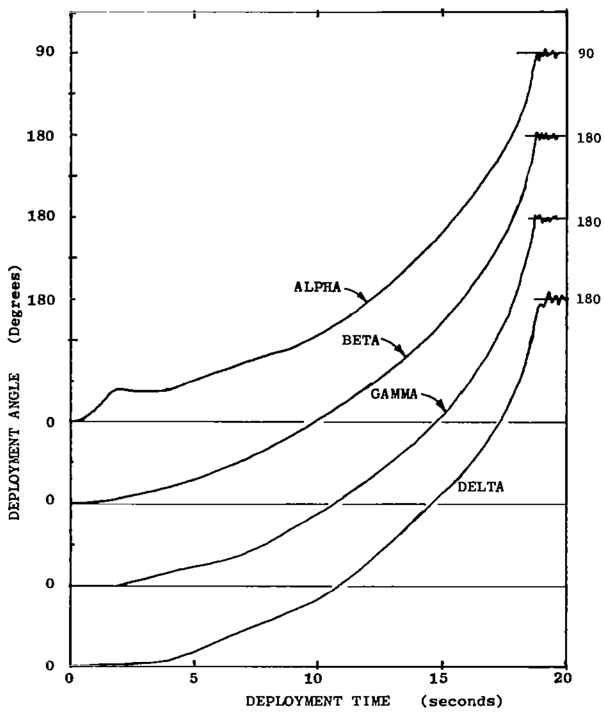

Figure 8. Simulation Results of the Deployment of the North Solar Array Under Nominal Conditions

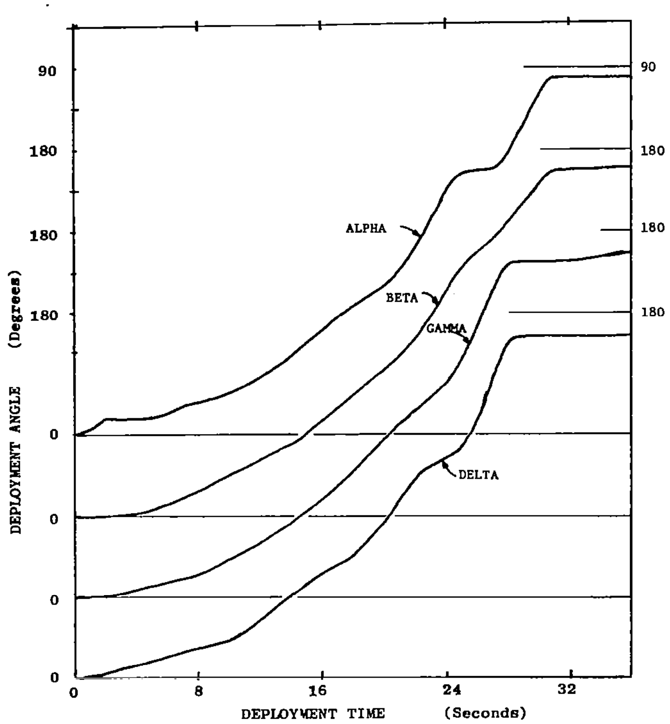

Figure 9. Deployment Similar to That Experienced on Orbit for the North Solar Array

CHANGES TO THE HINGES

As a result of the findings of the simulation runs and the experiments, several changes to the hinges were made. Among the changes are:

1. Special application of lubricant to all moving parts in the hinges
2. Increased bearing tolerances to allow greater variation in temperature
3. Increased polish on locking bars (see Figure 2)
4. Increased torsion spring pretorque level (see Figure 7).

Using the stiction torque level on the modified hinges as given in Figure 5, the predicted deployment time decreased to about 12 to 14 seconds for the south and north solar arrays respectively. Figure 10 shows the simulation results with the modified hinges on the north solar array.

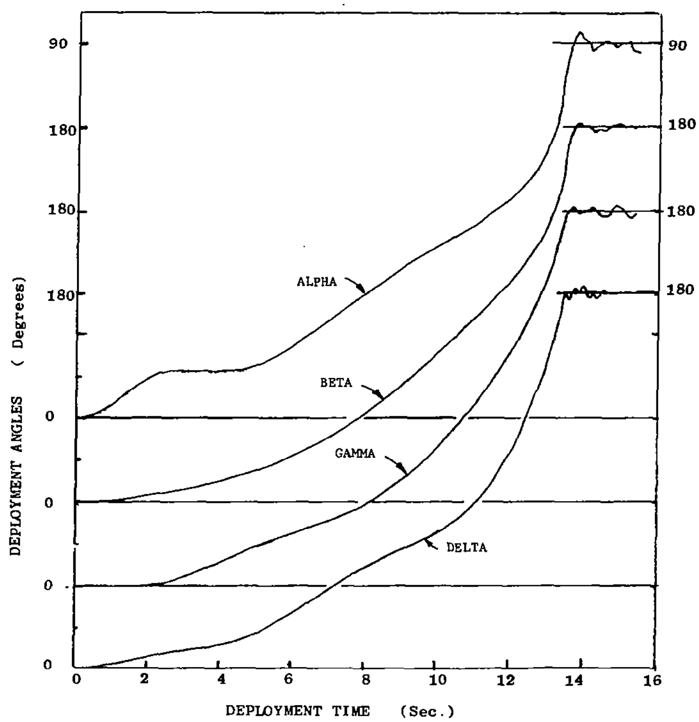

Figure 10. Deployment Simulation With the Modified Hinges on the North Solar Array

RESULTS

The hinge assemblies on the third flight of INTELSAT V incorporated the modifications previously described. The satellite was successfully launched December 15, 1981. Data from the onboard accelerometer, shown in Figure 11, indicate that the first hinge of the south array locked up at 11.8 seconds, and the first hinge of the north solar array began lock up at about 13.8 seconds.

The accelerometer is located on the spacecraft body, near the north solar array. The proximity of the accelerometer to the north solar array makes it more sensitive to accelerations of the north solar array. Therefore, the small initial acceleration disturbance occurring at 11.76 seconds is assumed to be the south solar array locking up, and the larger disturbance at 13.64 seconds is assumed to be the north solar array locking into position. These results are in excellent agreement with the simulation results mentioned in the previous section.

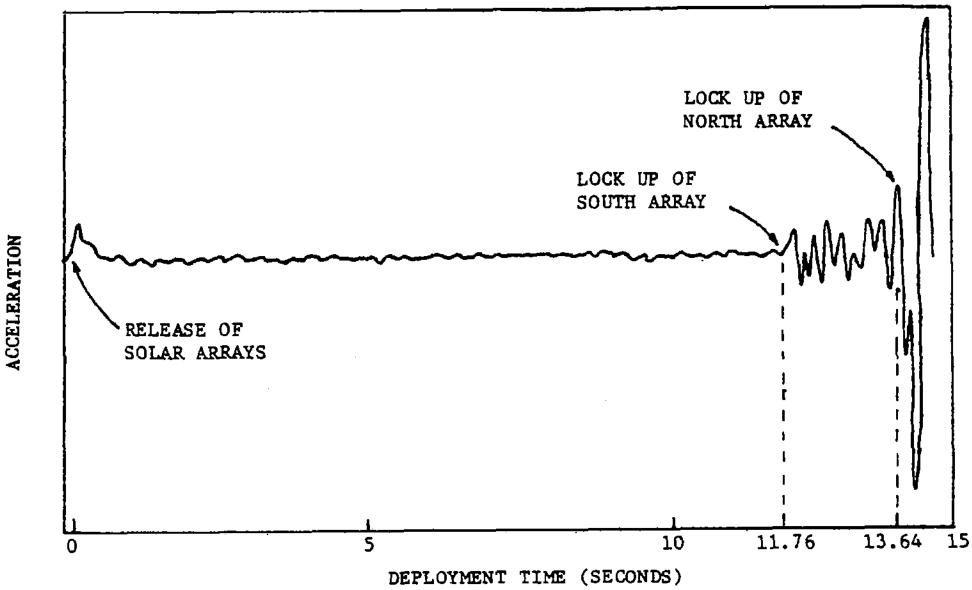

Figure 11. Accelerometer Data From FM-3

CONCLUSIONS

The most probable cause of the deployment time difference has been identified as the variation in the friction level in the hinge assemblies at low temperatures. Some of the changes to the hinges included special lubrication of the guides and bearings and additional polishing of the locking bars. Experiments on the modified hinges showed a reduction of the resisting torque on the hinges by about 50% at low temperatures. When the new friction values were put into the computer simulation, the deployment times of the south and north solar arrays decreased to 11.9 and 13.7 seconds, respectively. The deployment times of the south and north solar arrays on the third flight of INTELSAT V were 11.8 and 13.6 seconds, respectively, in excellent agreement with the theoretical results. These data validate the analysis used in the simulation technique described in this paper. Using techniques similar to those described herein will provide analysts and designers with more accurate simulations and a better basis to evaluate potential problems associated with deployment mechanisms. Points to be stressed are: (1) adequate theoretical analysis of a mechanism should be undertaken, (2) mechanisms should be tested under conditions which duplicate the range of expected orbital environments in order to identify sensitive conditions, and (3) during the ground testing of very large complete assemblies it is very difficult if not impossible to adequately duplicate the orbital conditions.

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