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G. Tsuyuki and R. Reeve
Jet Propulsion Laboratory
Pasadena, CA

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G. Tsuyuki* and R. Reeve**
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

Abstract

In April of 1991, the Galilee) spacecraft executed a sequence of commands to unfurl its umbrella-like high gain antenna. After analysis of flight telemetry and ground testing of the spare antenna, indications were that three or four of the eighteen antenna ribs were stuck in their stowed position. The primary theory was that a wry high coefficient of friction existed between the mid-rib restraint pins and their receptacles along the antenna's central tower. The course of recovery actions included: extreme cooling of the antenna by turning the spacecraft to shade the antenna from the Suit, cyclic warming and cooling of the antenna, and pulsing the deployment motors to act as a mechanical hammer. The thermal analysis support to the recovery effort was integral in terms of quantify ing the potential effectiveness of thermally-induced actions. This paper will summarize the thermal analysis support to the efforts associated with the repeated pulsing of the deployment motors anti warming and cooling of the antenna to enhance thermally-induced forces. The focus will be on the antcma-relate.d elements, therefore no in-depth discussion] is presented for the analysis of the other spacecraft components.

Nomenclature

AU	Astronomical unit
CRM	Central release mechanism
Gr/Ep	Graphite/epoxy
HGA	High gain antenna
JPL	Jet Propulsion Laboratory
LGA	Low gain antenna
MLI	Multilayer insulation
NA	Not applicable
PWS	Plasma wave science
RF	Radio frequency
S/C	Spacecraft
SCP	Search coil pre-amp
STV	Solar thermal vacuum
TDRS	Tracking and Data Relay Satellite
ZOT	Zinc orthotitanate

Hardware Description

The HGA was fabricated by the Harris Corporation and it is based on the TDRS antenna. The antenna is a Cassigranian system with a gold-plated molybdenum wire mesh stretched across its eighteen Gr/Ep ribs representing the parabolic primary reflector as shown in Fig. 1. A schematic of the stowed antenna cross-section is depicted in

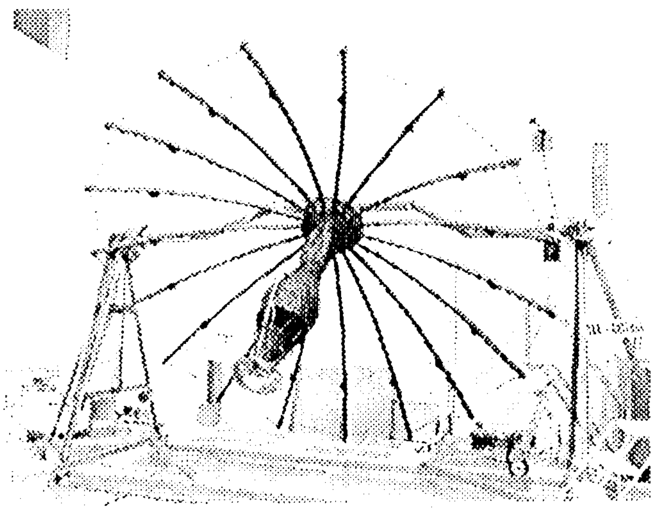

Figure 1 - Fully deployed antenna on a test fixture

* Technical Group Leader, Member AIAA

** Technical Group Supervisor

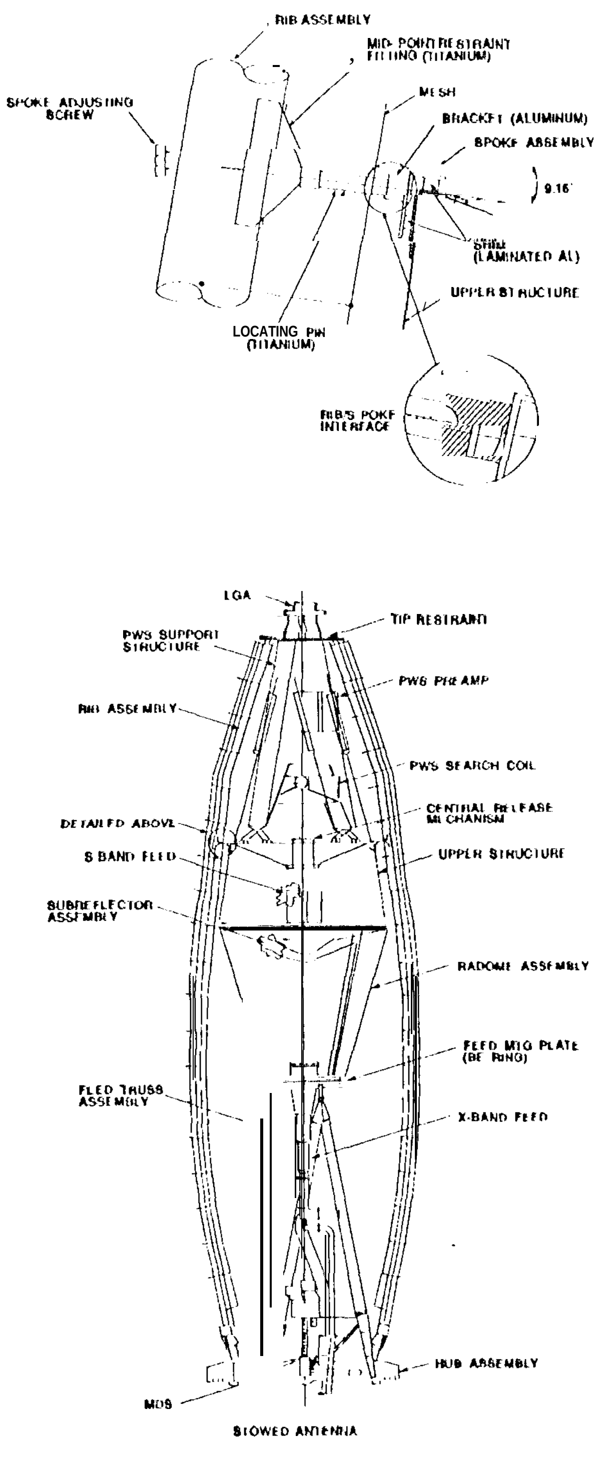

Figure 2- Schematic of stowed antenna

Fig. 2. The radome assembly which includes the antenna subreflector, is positioned atop a beryllium feed [111SS assembly. The PWS support structure and the LGA are sequentially stacked above the radome. Each of the ribs pivots about its base. A ballscrew on the centerline is driven by redundant motors, and it raises a carrier ring attached to the ballnut. Each rib is connected to the carrier ring via a pushrod. As the carrier raises, the ribs are nominally rotated into their fully deployed position. Each rib is firmly supported during launch at its mid-span and tip.

Thermal Design Description

The general approach employed passive techniques in order to meet the temperature limits listed in Table 1. Galileo was launched in October 1989 and would take a circuitous route to Jupiter, its ultimate destination. The cruise trajectory to Jupiter is illustrated in Fig. 3. Shortly after launch, the S/C was headed toward Venus for the first of three planetary gravity assists since the launch energy alone would not be sufficient to reach Jupiter. In order to protect the parabolic reflector from the intense solar irradiance at Venus (-2.2 equivalent Suns), the antenna had remained stowed and had been protected from direct insolation by a tip shade located at the base of the LGA while the S/C remained pointing the antenna boresight at the Sun. Each of the Gr/Ep ribs was wrapped with MLI blankets as well as the feed truss assembly. Since the radome housed the subreflector, MLI blanketing was not permitted since it would significantly attenuate RF signals. The PWS support structure was covered by a single layer of black Kapton. The tip shade consisted of an aluminum honeycomb structure with spokes to support the carbon-filled Kapton shade itself. The backside of the honeycomb structure was covered with ZOT white paint and acted as a radiator for the attached LGA. The LGA was also painted with ZOT white paint since it could not be shaded from the Sun. However, the LGA base could be blanketed, and this blanketing was attached to the tip shade honeycomb structure. Behind the parabolic reflector, a large conical bus shade protected the remainder of the S/C from insolation (see Fig. 4). The deployment motors were conductively coupled with the S/C bus through the attachment structure. Through mission planning, sufficient opportunities were identified to deploy the antenna ribs

Table 1 - Antenna flight allowable temperatures in °C

Item	Oper	Non Op
Reflector Ribs		
Stowed	-168/113	-168/113
Deployed	-168/100	-16W1OO
Low Gain Antenna	-?00/ 104	-?00/104
X-Band Feed	-92/65	-92/65
S-Band Feed	-156/8?	-1 S6/82
Deployment Motor	-35/44	-57/55
CRM	-101/93	NA
Ballscrew, Nut, & Bearing	-29/6S	-120/NA

when the motors were within flight allowable temperatures without the use of an electrical heater.

Deployment Anomaly

The anomaly has been well chronicled by O'Neil et. al.[1, 2] On April 11, 1991, the Galileo S/C executed a sequence of commands to unfurl its umbrella-like HGA. The initial deployment opportunity occurred at a solar distance of 1.32 AU, eight months prior to an aphelion of 2.27 AU and approximately twenty months prior to a gravity-assist from the Earth which would hurl the S/C toward Jupiter. Confirmation of deployment was not received. An investigation team was assembled to determine likely failure scenarios and to recommend courses of recovery actions. After intensive analysis of flight telemetry (attitude control wobble, Sun gate obscuration, and deployment motor current), the team postulated that a number of the antenna's eighteen ribs were stuck in the fully stowed position.

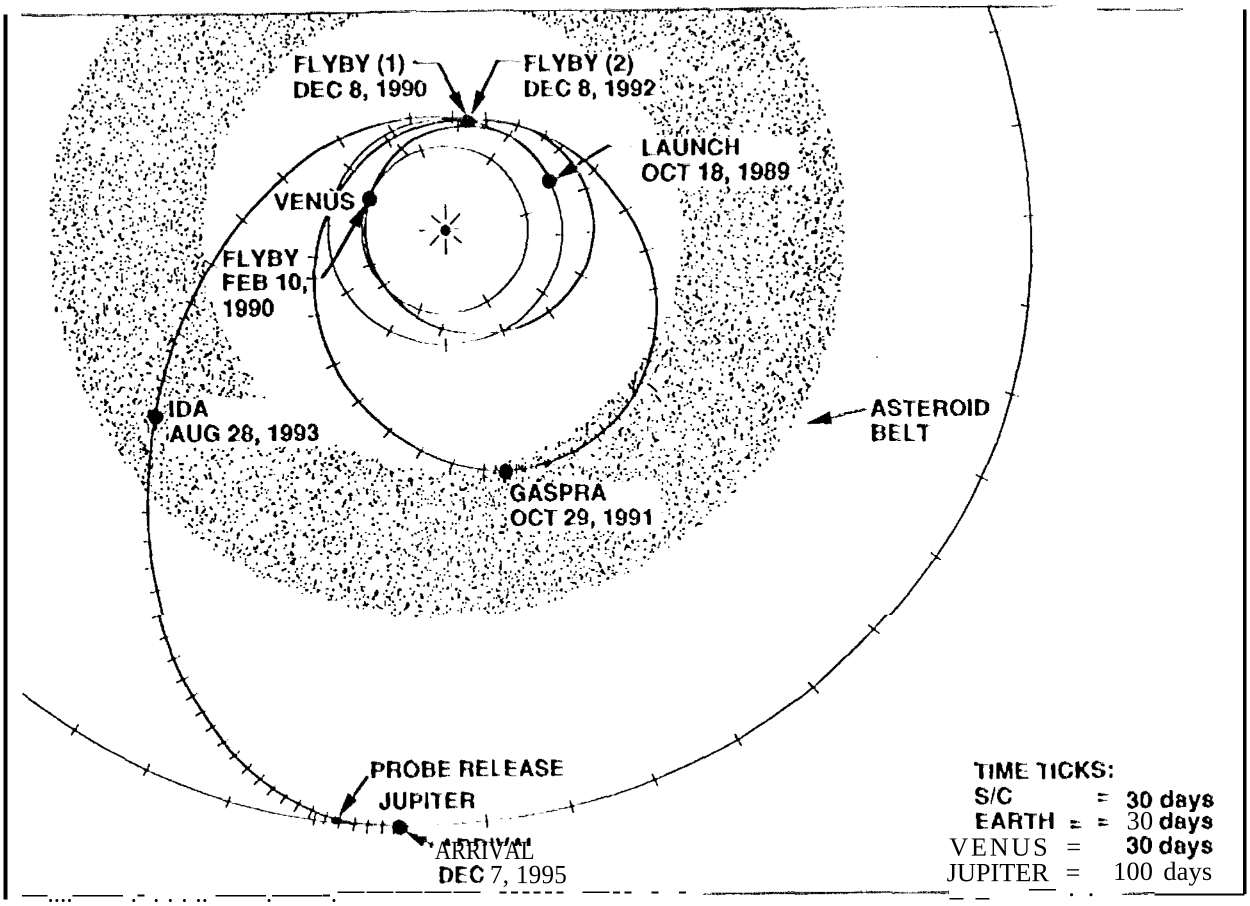

Figure 3 - Galileo trajectory to Jupiter

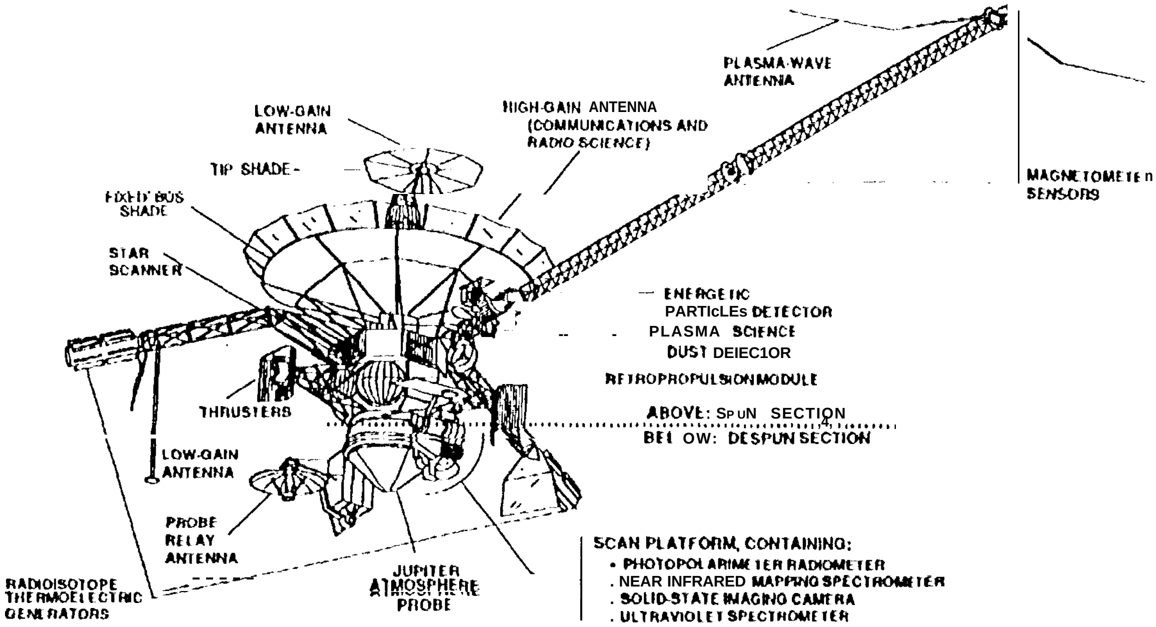

Figure 4- Galileo S/C configuration

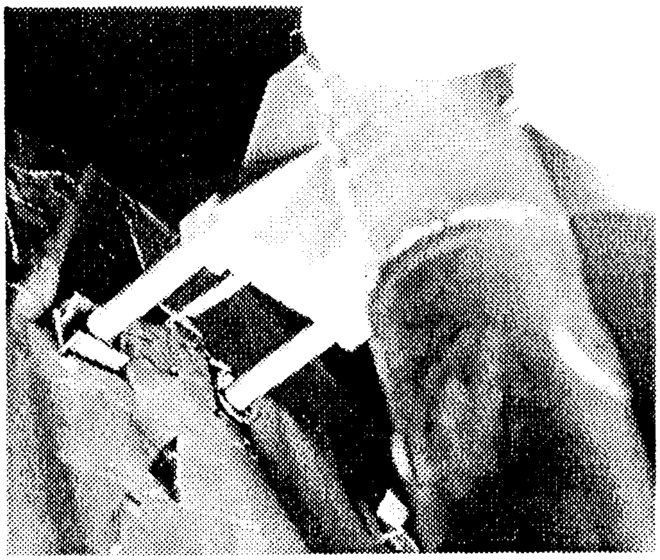

Figure 5 - **Mid-rib** locating pins

Subsequent ground testing of the spare antenna was correlated to the flight telemetry, and the team concluded that probably three or four ribs were stuck in their stowed position. Investigation of the S/C design revealed that the forces that could be applied to the antenna were limited to: 1) spinning the S/C faster to increase centripetal forces, 2) stowing and redeploying a boom, 3) repeated pulsing of the deployment motors to induce impulsive forces, 4) inducing S/C wobble, 5) firing thrusters, or 6) changing the S/C attitude relative to the Sun to promote. thermally-induced forces. Efforts to free the antenna ribs solely employed actions #1, #2, #3, and #6.

The leading theory that emerged centered on the mid-rib rest raints which act as braces when the ribs are stowed. Each rib is braced by a pair of "locating pins" that fit into receptacles along the tower (see Fig. 5). A spoke that is located between the pins was tensioned to 85 lbs to firmly hold each rib to the tower. During ground transportation, the antenna was horizontally cantilevered from its base, and the presently stuck ribs, which were nearest the vertical plane, received the greatest vibration. In turn, this caused a loss of the dry lubricant and subsequent galling of the pin

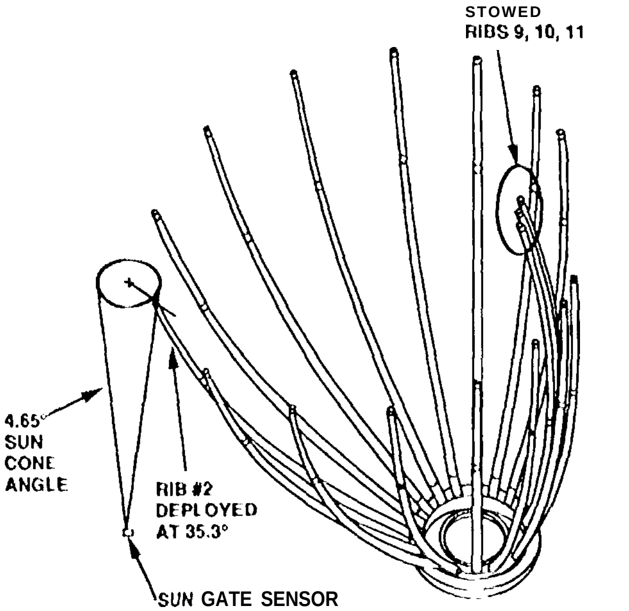

Figure 6 - Postulated HGA configuration with three stuck ribs immediately after deployment attempt

and receptacle surfaces. When the S/C achieved the hard vacuum of space, a very large effective coefficient of friction (~ 1.25) developed at the contact stress points. As the ballscrew rotation initiated during the initial deployment opportunity, flight telemetry suggests that some neighboring and some opposite ribs were held to the tower by the friction force, thus preventing their pins from sliding off the contact stress points. Deployment forces became more concentrated in the stuck ribs as deployment continued. After one ballscrew turn, the opposite stuck ribs popped free and after three ballscrew turns, the. neighboring ribs had been released (leaving three ribs stuck as shown in Fig. 6). Further ballscrew rotation caused the stuck ribs tobc bowed by the bending moment applied at their base by the pushrods. This caused the pins to rotate downward, thus increasing contact stress on the lower surface of the receptacles. When the deployment motors reached a full stall condition, at least one pin of each pair had driven itself into the lower surface of its receptacle. The stall occurred duc to the bending moment on the ballscrew resulting from the asymmetric loading of the carrier.

Extreme Antenna Cooling

Extreme cooling of the antenna was proposed to reduce the bending moment-induced stress on the receptacle lower surfaces and to transfer pre-load stress to the easier-sliding upper surfaces. If the cooling produced sufficient tower contraction with respect to the room temperature assembly condition, the stored strain energy in the stuck ribs would free them. The cooling was accomplished by turning the S/C 165° so that the antenna points to deep space, and the bus shade obstructs the Sun from directly illuminating the antenna. The first cooling turn was performed on July 10, 1991 at a heliocentric distance of 1.84 AU. Prior to the turn, analytical predictions were performed with a simplified version of HGA thermal math model which was developed by the Harris Corporation. Originally, this mode] was intended to support the Venus trajectory redesign effort', and its usc for other purposes had to be carefully considered. Extensive revisions of the model were not undertaken so that responses would be timely. Instead, a bounding analysis was performed to determine expected antenna temperatures. The most optimistic (coolest) temperatures were determined by removing the Sun-pointed environmental heating. On the other hand, the hottest temperatures were computed by setting, the bus shade as a boundary temperature. The system-level STV test was conducted in the Sun-pointed condition at 1.0 AU where the bus shade is illuminated on the antenna side. Temperatures of the non-illuminated side were used as the boundary temperature. Pre-maneuver tower spatial temperature predictions arc shown in Fig. 7 (predictions will be considered as direct results from the model whereas estimates refer to calculations resulting from applying any judgement to predictions).

A simple. one-dimensional thermal contraction model was developed. The total tower contraction was determined as

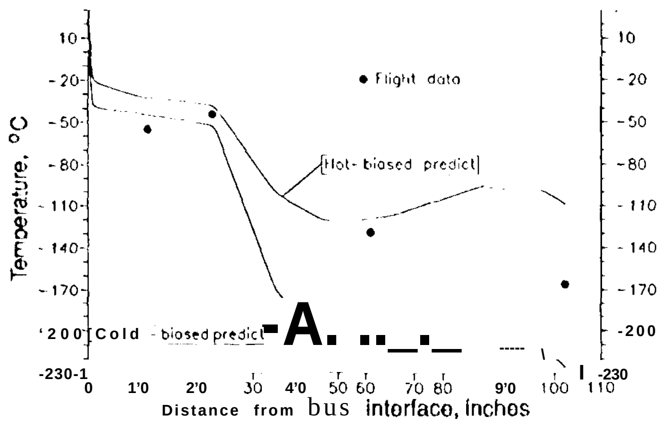

Figure 7- Cooling turn #1 tower temperature predictions

the sum of thermal displacements of each tower element from the antenna huh to the CRM. Since the thermal math model did not represent all the elements in the contraction model, certain interpolations of the temperature predictions were required. Systctn-level STV test data was used either to verify or assist in the formulation of interpolation expressions. Using the thermal math model temperatures, tower cent ract ion bet ween 59 and 92 roils was predicted, and rib rc.lease appeared possible.

On July 10, 1991, the S/C was pointed 165° off-Sun. The total duration at attitude, 32 hours was constrained by the illumination of S/C components such as the Probe that were never intended to be sunlit. However, flight data indicated that steady-state was nearly achieved although none of the stuck ribs released. In addition, flight data indicated that the antenna tower temperature was much more biased towar d the hot predicted temperat urc levels (see Fig. 7). Following the first cooling turn, the flight tower temperature profile was approximated by varying the bus shade boundary temperature of the analytical model until better agreement with flight data was obtained (see Fig. 7). These temper at urc est imates were inserted into the tower contraction model and calculations suggest that 68 roils of contraction was actually attained.

During the first turn, a three watt thermostatically controlled heater was active on the PWS SCP in order to maintain acceptable temperatures. Further analytical work indicated that this heater power dissipation could be responsible for the warmer than expected mid-tower temperat ures. The analysis suggested that an additional eleven roils of contraction could be obtained if the PWS SCP heater were completely turned off. However, a peer review board remained skeptical that such a large benefit would be real ized. A second cooling turn was performed on August 12, 1991 at a heliocentric distance of 1.98 AU, since the prior actual tower contraction appeared to be close to what might cause rib release. The experience gained from the first turn such as bus shade temperature and PWS heater state was used to determine more accurate antenna temperature estimates for the second cooling turn which arc given in Fig. 8.

When the second cooling turn was performed the PWS SCP heater was turned off and the dwell time was increased to 50 hours after a waiver to permit a higher Probe temperature was granted. Unfortunately, there was no indication of rib release, (comparison between predictions and flight telemetry showed better correlation, however, the mirt-tower temperatures still showed the greatest disparity (see Fig. 8). Processing the flight data in a similar manner to the first turn, an additional 2 roils of contraction over the first cooling turn was actually achieved. Another cooling turn was planned, but it was decided to schedule the turn where the cooling effect would be most effective. Due to the nature of the. trajectory, the S/C would reach aphelion (2.27 AU) on December 13, 1991 as shown in Fig. 3. Hence the turn was scheduled for this time.

The analytical model was not satisfactorily predicting mid-tower temperatures, which was causing larger-than-actual tower contraction estimates, Prior to the third cooling turn, an modest effort was undertaken to improve Inid-tower predictions. The bus shade was changed from a boundary node to a diffusion node, but when an empirical effective emittance was sized to produce mid-tower temperatures that agree with flight data, a non-credible value resulted. Use of typical blanket effective emittances resulted in temperatures similar to those calculated with the bus shade as a boundary node. Cabling and wave guide conductances were imported from the detailed Harris Corporation thermal model, but only incremental benefits were real ized. A decision was made to forego the bus shade and cabling/wave guide conductance improvements since they were not significantly improving tower temperat urc predict ions. Furthermore, investigating the effect which is causing the mid-tower temperature discrepancy would be difficult and time-consuming since the

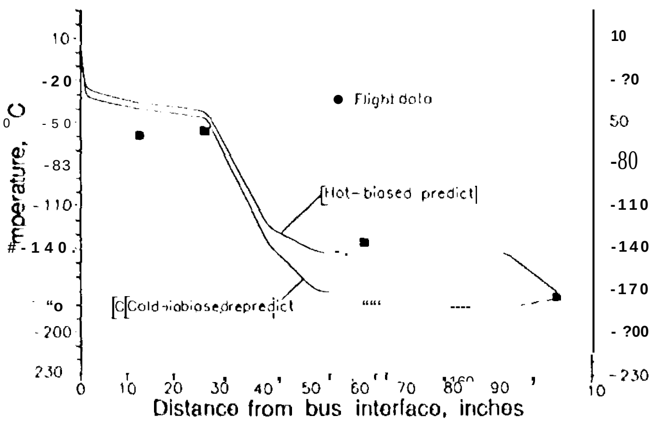

Figure 8- Cooling turn #2 tower temperature predictions

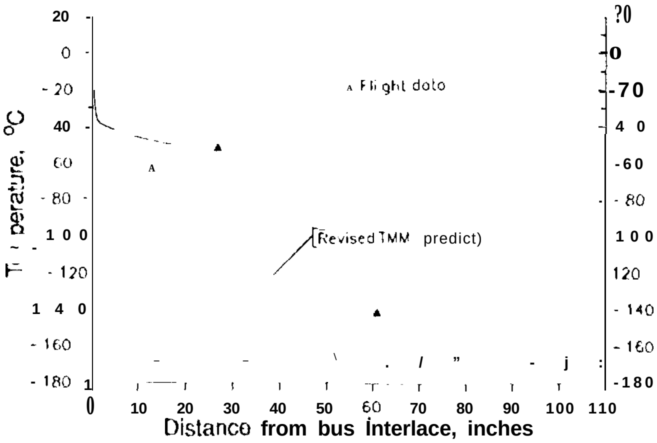

Figure 9- Cooling turn #3 tower temperature predictions

heat flow is small in the cooling turn environment. Many heat paths which have been neglected in the "hotter" Sun-pointed orientation, which was the initial design environment, may no longer be ignored for the cooling, turn attitude,

PI c-cooling t urn #3 antenna tower predictions wei e performed d, but the temperat ures were modified based on the prior two cooling turn flight data (scc Fig. 9). Est imates of tower cent ract ion indicated that 72 mils would be obtained. When the third cooling turn performed, none of ribs were freed, and flight data suggested that indeed 72 mils of contraction was achieved. The two previous cooling turn flight data enabled the team to estimate a more realistic tower contraction without an exhaustive effort to improve the analyt ical model.

Pin Walk-out Hypothesis

While the cold soaks of the antenna were performed, the investigation team began to formulate another strategy for freeing the stuck ribs. l'here was a possibility that the pins may be misaligned with their receptacles by 10 to 15 roils. One pin may be pushing up on its receptacle while the other one is pushing down on its receptacle. When the retaining rib spoke was tensioned prior to launch, a locking taper could have been created. The strength of the lock depends on the misalignment and coefficient of friction at the pin/receptacle contact locations. Analysis indicated that the pins might be "walked" out of the taper lock by alternately expanding and contracting the antenna tower by thermal cycling. The warming and cooling of the antenna tower could significantly displace the tower with respect to the ribs, thus shifting the load between the pins. When the tower is warmed, it expands, thereby creat ing an "upstroke," and similarly a "downstroke" is created by tower cooling. On tbc upstroke, the load increases on the "lower" pin and it becomes a fulcrum around which the pin pair rotates. When the load on the "upper" pin decreases sufficiently, it slips outward on the receptacle surface until a new load equilibrium point is reached. On the following downstroke, the pin pair reverses roles, and the "lower" pin slips. Incrementally, the pins reach the point where the lock has been relieved so that the deployment stt ain energy in the rib overpowers the friction force which restrains it. The hypothesis is based on the pin misalignment and coefficient of friction which are not precisely known.

For the cooling portion of a thermal cycle, the previous 165° off-Sun attitude was retained, but an optimal warming attitude. would have to be determined. Thermal model improvement was necessary since the simplified analytical model could not accurately determine off-Sun heat loads. Originally, the rib geometry was developed by constructing three adjacent ribs and then scaling the results to represent all eighteen ribs. The S/C is spin-stabilized, and the model was originally utilized for Sun-pointed orientations. Such an approximation seemed valid. However, modeling all ribs would be necessary to determine more accurate off-Sun heat ing. Absorbed antenna heating rates for 0" to 90° off-Sun pointing were computed with the improved model. However, the molybdenum mesh was neglected as previously assumed. A parametric analysis was performed

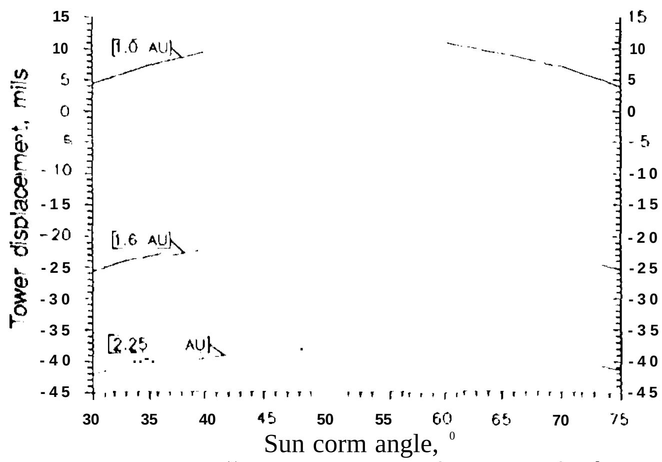

Figure 10 - Tower displacement as a function Of off-Sun angle

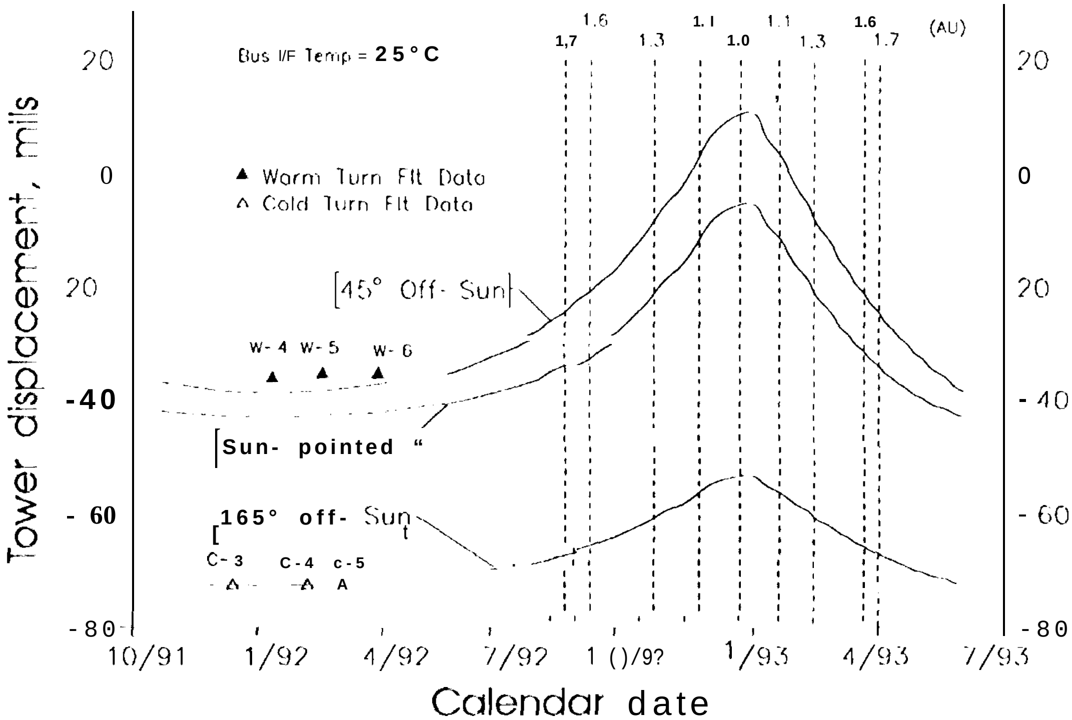

Figure 11 - Tower displacement as a function of calendar date

to determine the tower displacement as a function of off-Sun angle for solar distances of 1.0, 1.6 and 2.25 AU (see Fig. 10). An off-Sun angle of 50° produces maximum tower expansion, however, this angle was not selected for the warming attitude. Shortly after the initial deployment attempt, the S/C was turned 45° off-Sun for 24 hours in hope of warming the antenna near room temperature to relieve pin pre-load. Since the command sequence for turning the S/C 45° off-Sun had been already developed and the tower expansion difference between off-Sun angles of 45° and 50° was incremental, 45° was selected for the warming turn off-Sun angle.

Since the pin walking theory is based on the cumulative effect of cycling the antenna, the tower displacements for all previous turns included the return of the antenna to the nominal Sun-pointed orientation. Using these displacements and reasonably expected values for pin misalignment and coefficient of friction, computer simulat ions of pin walking suggested that the ribs might be freed with six to twelve thermal cycles. A thermal cycling regimen was established and antenna tower displacements for the campaign were estimated as functions of calendar year. Cooling, turn results had factored in the previous experiences, however, no such an experience base for warming turns had been credibly established. Therefore, warming turn predictions were directly reported. Fig. 11 depicts the tower displacement for the proposed thermal cycling strategy.

The off-Sun angles used for thermal cycling were not originally permitted at these solar distances. A great deal of effort was expended to ensure the health and safety of the S/C. The 16S0 maneuvering of the S/C consumed -5 kg of propellant, a precious resource.

The three previous cooling turns constituted the first phase of thermal cycling, From January through July of 1992, four additional thermal cycles were performed. "The tower displacements suggested by flight data for these cycles are plotted in Fig. 11. There was an excellent agreement between the predicted and flight tower temperatures for the warming portion of the cycle. The previous cold soaking experience had led to better predictions for the cold portion of the cycle. After the seventh thermal cycle did not result in rib release, the prospect for freeing any ribs with additional cycling seemed wry remote, Either the values

Table 2 - Summary of Near Earth-2 Flyby Tower Displacement Estimates

Solar Distance (AU)	Sun-pointed Tower Al (mils)	45" Off-Sun Tower Al (mils)
0.986	**-4.4**	**11.5**
1.03	-7.3	8.1
1.0-/	**-9.8**	5.3
1.10	-11.5	3.2

Note: Al > 0 indicates tower expansion and Al < 0 indicates tower contraction

for the dominant parameters were too extreme or the mechanism responsible for rib restraint was not well characterized.

Deployment Motor Hammering

The most aggressive action entailed pulsing the deployment motors many times to "hammer" the ballscrew. The "hammering" is achieved by cycling power on and off to the deployment motors. Motor pulsing tests conducted with the spare flight HGA at JPL demonstrated that the ballscrew rotated beyond the stall point for the motors operating continuously (provided that the motors and gearbox temperatures arc greater than approximately 0°C). Estimates indicated that hammering the ballscrew would rotate it sufficiently to double the deployment force in one of the ribs. As each rib releases, the deploy ment forces arc concentrated in the remaining stuck ribs. Subsequent hammering could produce larger forces as the number of stuck ribs diminishes.

In preparation for the hammering exercises at 1.0 AU, special activities were performed in July, September, and October of 1992 to characterize the S/C thermal response at a 4S off-Sun angle, as well as to calibrate. and characterize the deployment system. Analysis performed in July 1992 estimated the motor temperature as a function of solar distance for a 45° off-Sun attitude (see Fig. 12). At that time, three of the four- warming turns had been conducted at essentially the same solar distance., hence the warming turn flight data base for the motor consisted of just two cases (1 .58 AU and -2.20 A{ J). Extrapolation of this data was accomplished by curve fitting motor temperatures for the Sun-pointed contrition and off-setting the Sun-pointed temperatures by analytically predicted temperature differences predicted bet wcen Sun- point and 45° off-Sun.4

The S/C had not been pointed 45° off-Sun for lengthy durations inside of 1.58 AU. Concerns were expressed that certain S/C elements may overheat. A thermal character ization effort was per formed to ensure the thermal health of the S/C during the 45" off-Sub turn at 1.0 AU. In concert with the overall e ffort, a contingency analysis was undertaken to determine if more benign off-Sun angles could be considered with minor impact to hammer effectiveness. The 45° off-Sun estimates showed that the deployment motors would attain 5 1°C at 1.0 AU. Results of this study demonstrated that the motors would achieve 44°C and 49°C for off-Sun angles of 20° and 30", respectively at 1.0 AU. These angles would be acceptable alternatives for warming the motors above room temperature.

In October 1992 and at a solar distance of 1.30 AU, the S/C was t urned 45" off-Sun for about 48 hours and the deployment motors were pulsed on and off a fcw times. Flight data was in excellent agreement with the motor temperature estimates (see Fig. 12, DDA3). In addition, there were no adverse thtmnally-induced S/C problems, therefore, the off-Sun warming angle of 45° was used.

The motor hammering provided a means to increase rib

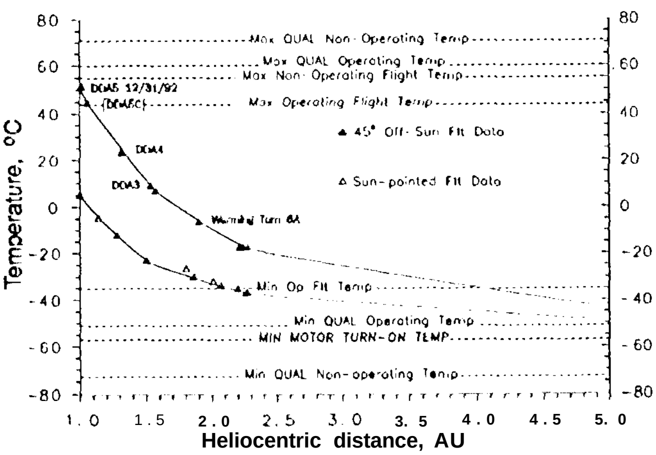

Figure 12- Deployment motor temperature as a function of solar distance deployment forces. Since the motor hammering activities were scheduled for Galileo's final Earth flyby, tower expansion would be significant, There was a possibility that the rib -binding mechanism may abate with increasing tower expansion and free the ribs as the S/C approached 1.() AU. Additionally tower displacement analyses were performed to assist the Earth flyby planning, The flyby solar distance was 0.986 AU and hammering activities were performed at 1.03, 1,07, and 1.10 AU. The thermal model predictions which produced Fig. 11 were changed slightly using flight data extrapolations from the first warming turn at 1.58 AU. The tower displacements for Sun-pointed and 45° off-Sun arc summarized in Table 2. Tower displacements at 1.10 AU were determined to be 7 and 8 roils less than 0.986 AU for Sun-pointed and 45° off-Sun, respectively.

From late-December 1992 to mid-January 1993, the deployment motors were pulsed over 13,000 times while the S/C was 45° off-Sun. Again, flight data of motor temperature was in excellent agreement with pre-hammering estimates (see Fig. 12, DDA5 and DDA5C). Although flight telemetry indicated that the antenna rib configuration had changed, the stuck ribs had not been freed. By the end of February 1993, the investigative team was dissolved, and tbc Project proceeded with the implementation of ncw capabilities to perform the mission with the LGA in accordance with plans established in April 1992. At least 70% of the mission objectives will bc achievable using the LGA.

Epilogue

An intensive effort was performed to thermally characterize the antenna and tbc S/C. Initially, correlation for the cooling, turns was lacking. However, with additional flight experience, the predictive capability improved substantially. The analytical model, itself, has evolved over the course of time, where it has demonstrated good agreement with flight data especially for warming turns and Sun-pointed attitudes,

Acknowledgements

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