MSFC'S ROLE IN THE SKYLAB REACTIVATION MISSION

INTRODUCTION

Slide 1

On July 11, 1979, Skylab impacted the Earth surface. The debris dispersion area stretched from the South Eastern Indian Ocean across a sparsely populated section of Western Australia. This presentation discusses in some detail the events leading to the reentry of Skylab and the role the Marshall Space Flight Center played in these events.

BACKGROUND

On February 9, 1974, Skylab systems were configured for a final power down and Skylab was deactivated. Prediction of solar cycle 20 activity, the solar cycle predicted to begin in 1977, indicated that the final attitude in which Skylab was left, the gravity gradient attitude, would result in a potential storage period of 8 to 10 years. However, in the fall of 1977 it was determined that Skylab had left the gravity gradient attitude and was experiencing an increased orbital decay rate. This was a result of greater than predicted solar activity at the beginning of solar cycle 21. This increased activity increased the drag forces on the vehicle. Skylab was not predicted to reenter the Earth's atmosphere in late 1978 or early 1979 unless something was done to reduce the drag forces acting upon it. It was necessary to make a decision to either accept an early uncontrolled reentry of Skylab or to attempt to actively control Skylab in a lower drag attitude thereby extending its orbital lifetime until a Shuttle mission could effect a boost or deorbit maneuver with Skylab.

Slide 1A (leave up)

In order to verify what options could be accomplished with the onboard Skylab systems, a small team of NASA engineers went to the Bermuda Ground Station to establish communications and interrogate Skylab systems. On March 6, 1978, the Airlock Module (AM) command and telemetry (TM) systems were commanded on from the Bermuda Ground Station. The reception of the AM TM carrier at Bermuda was proof that the onboard AM system had responded to the commands. For the next several days, the AM electrical power system was properly configured and the AM batteries charged whenever the simultaneous conditions of ground station coverage at Bermuda and solar energy availability permitted. Subsequently AM power was transferred to the Apollo Telescope Mount (ATM) systems and the operational status of the ATM systems was determined. On March 11, 1978, power was applied to the ATM Attitude and Pointing Control System (APCS) bus which in turn supplied power to the primary Apollo Telescope Mount Digital Computer (ATMDC)/Workshop Computer Interface Unit (WCIU). Power was maintained on the APCS bus for approximately 5 minutes and the receipt of ATMDC telemetry data at Bermuda was confirmed. The receipt of this data indicated that the primary ATMDC/WCIU hardware and attendant software were operational and cycling. On March 13, 1978, engineers concluded the interrogation test on Skylab. The resulting data indicated no discernible degradation of the Skylab systems during its 4 years of orbital storage. Aided with this data, and the knowledge that Skylab was in an unstable tumble prompted investigation into schemes which might extend the orbital lifetime of Skylab.

Scheme Development and Operational Modes March 1978 to July 1979

The first scheme investigated was to use the onboard Thruster Attitude Control System (TACS) to maintain a quasi-stable tumble of Skylab. However, it was soon determined that this option would not extend Skylab lifetime sufficiently to correspond to the operational readiness of the Space Shuttle for a possible reboost or deorbit mission. The only alternative left was to reactivate and continuously control the Skylab in a minimum drag attitude. In order to accomplish this the End On Velocity Vector

Slide 2 (EOVV) minimum drag attitude control scheme was developed by MSFC engineers, and used after the initial Skylab reactivation on June 11, 1978.

The EOVV mode was a minimum drag attitude with the relatively small surface areas of the front or back ends of Skylab being pointed approximately along the velocity vector. This mode was a modification of the Z Local Vertical (ZLV) mode (vehicle "Z" axis along the local vertical) that was used during the original Skylab Mission. In the EOVV mode, the vehicle coordinate axes were offset slightly from the ZLV axes to align the vehicle principle axes with the ZLV axes. The vehicle was then rolled such that its solar arrays pointed toward the sun near orbital noon for maximum power collection and attitude reference updating. Desaturation of CMG momentum was done with gravity gradient torques and was continuously active around the orbit.

There were two subsets of the EOVV mode, EOVV A and EOVV B. The EOVV B mode can be thought of as a backward EOVV A mode. The EOVV A mode had the Skylab Command Module docking port pointed along the velocity vector while the EOVV B mode had the aft end of the workshop pointed along the velocity vector. The EOVV B mode was developed to prolong the life of CMG #2 by allowing maximum solar impingement on CMG #2 spin bearings for negative sun angles. For the same reason, EOVV A was utilized when the vehicle experienced positive solar angles.

The EOVV mode was used in the first part of the Skylab Reactivation Mission to reduce as much as possible the Skylab descent rate. It was hoped that the orbital life of Skylab could be extended until a reboost/deorbit mission by the Space Shuttle could be launched. The effect of the EOVV mode on the descent rate is shown in the next view graph (Slide 3) There was a noticeable slowing down of the Skylab fall when EOVV was entered June 11, 1978. It was estimated that if Skylab had remained in EOVV that reentry could have been delayed until at lease April of 1980.

Slide 3

~~Referring to slide 1A, the transition from a no control to a controlled mode (solar inertial) occurred June 9. This was followed two days later when the transition to the EOVV A attitude occurred.~~ It should be noted that transitions from the old Skylab operational modes (SI, ZLV, etc.) to these new operational modes first attempted June 9th and 11th (Slide 1A) required many hours of equation and scheme development, software implementation and verification, the generation of computer

Slide 1A

uplink loads and their verification, and finally close surveillance of vehicle operation once the operational mode was activated to insure that the vehicle responded as the theory predicted it would. Numerous meetings were held within MSFC and JSC and at NASA Headquarters to ensure all levels of NASA Management approved and agreed with proposed Skylab operations. For example, between January 1978 and the initial Skylab SI acquisition on June 9, 1978, four Skylab presentations were made to Mr. Yardley, one to Dr. Frosch, and two to other headquarters personnel.

Unfortunately all did not go well and ~~Referring to Slide 1A~~, a transition from EOVV A to SI occurred on June 28. This was necessary because of abnormal momentum states which could lead to CMG gimbal stop problems. The problem was eventually traced to the inability of the strapdown updating scheme to compensate for the movement of the inertial reference, particularly at high sun angles. When this was understood, a strapdown update bias term was successfully used to compensate for the observed Z axis drift due to orbit plane and sun motion. On July 6 the vehicle was again returned to the EOVV-A attitude.

On July 9 total vehicle control was lost including attitude reference. The cause of this loss of attitude was due to a power failure. The vehicle had been placed in a power configuration with the AM batteries not on the line due to two unexplained battery charger failures in that system. The ATM power system and the AM solar arrays were not sufficient to carry the load in the EOVV mode causing the ATM batteries to automatically trip off the line. As was done previously, it was decided to go from the uncontrolled attitude to SI (July 19) and then to the EOVV-A attitude (July 25).

EOVV-A to EOVV-B Transition

On November 4, 1978, Skylab was maneuvered 180 degrees from its normal EOVV orientation with the MDA pointing toward the positive velocity vector (EOVV-A) to a new EOVV orientation with the MDA pointing toward the negative velocity vector (EOVV-B). The purpose of this maneuver was to increase the probability for extended Skylab lifetime by providing the most favorable thermal conditions, in EOVV operation, to reduce the stress on CMG 2.

Analysis of Skylab data at MSFC obtained during EOVV operation up to this time showed a relationship between the occurrence of CMG 2 anomalies, the sun angle, and the operating temperature of CMG
lide 4 2 (Slide 4). This data indicated that the stress conditions on CMG 2 could be avoided or reduced by providing a higher operating temperature environment for CMG 2. The EOVV-A orientation provided more solar exposure for CMG 2 at positive sun angles while an EOVV-B orientation would provide more solar exposure
lide 2 at negative sun angles as shown in Slide 2.

The 180° transition maneuver was scheduled for early November 1978 to coincide with the upcoming positive-to-negative change in sun angle (i.e., sun angle movement from North to South of the orbit plane). A modification to the flight software had to be developed (SWCR-S4016, buffer 15) and was implemented to account for computational differences associated with the EOVV-A and

EOVV-B orientations and to automate maneuver sequencing to support the transition maneuvers.

Slide 5

The transition maneuver sequence was developed and simulated, based on available station coverage (Slide 5) to minimize TACS utilization and to provide favorable conditions for initiation of EOVV-B operations.

Normal and contingency procedures to support the transition maneuver were developed and executed from 11/2/78 through 11/4/78 with the transition maneuver taking place on 11/4/78 as the sun angle passed through zero. It should be noted that the design and simulation effort enabled the maneuver plan to be executed for no TACS usage, saving this limited resource for future operations.

Skylab remained in the EOVV-B attitude from November 4, 1978 until January 25, 1979. During this time, all Skylab systems functioned satisfactorily.

After Skylab was brought under active control, in a low-drag attitude to minimize its rate of decay, it was decided in mid-1978 to accelerate the development of an orbital retrieval system that might be accommodated on an early flight of the Space Shuttle, this increasing chances of rendezvousing with Skylab. A proposed mission sequence with the Skylab boost/deboost

Slide 6

options is shown in Slide 6.

The rate of orbital decay, however, continued to increase due to increased solar activity. Skylab's onboard systems also showed signs of deterioration and there were increasing concerns over the Space Shuttle's schedule. For these reasons, the concept of Skylab recovery was terminated in December 1978. At that time, it was decided to reorient and control the vehicle in a solar inertial attitude which was the normal vehicle orientation for original Skylab mission operations. This was accomplished January 25, 1979. The vehicle remained in SI control until June 20 when TEA control was activated.

TEA Control

As Skylab's altitude decreased, the magnitude of the aerodynamic torques on the vehicle increased. Studies at MSFC indicated that vehicle control in the solar inertial orientation would no longer be possible below about 140 n.m. due to these increased aerodynamic torques and the limited control authority available from the Vehicle Control Moment Gyros (CMG's). Aerodynamicists and control engineers at the Marshall Space Flight Center (MSFC), while investigating vehicle orientations which produced minimal disturbance torques on the vehicle, found certain orientations where the summation of these disturbance torques was zero. These attitudes were called Torque Equilibrium Attitudes (TEA's). A TEA attitude control law was developed to utilize these zero torque points. This control law was unique because it was the first spacecraft control scheme which used upper atmospheric aerodynamic torques to desaturate CMG momentum. In the normal SI Skylab mode, CMG momentum was managed by dumping excess momentum using gravity gradient torques. In a TEA attitude, the aerodynamic torques and gravity gradient torques are equal and opposite. By offsetting the vehicle slightly from this attitude, the relative magnitudes of the gravity gradient and aerodynamic torques can be increased or decreased as desired to maintain the CMG momentum at the desired state. Through a concentrated effort at MSFC, the TEA control law was developed, programmed and verified between January and May 1979.

There were several TEA attitudes and each resulted in different atmospheric drag on the vehicle. The limiting factors in maintaining control were meeting the electric power requirements and being in a dense enough atmosphere to generate the desired aerodynamic torques. Most of the TEA attitudes were unuseable because the Skylab solar arrays could not collect sufficient solar energy to run the various Skylab systems in the specified attitude. Other attitudes could be used only during a range of certain sun angles and below certain altitudes. Two of the useable attitudes, the T275 and T121G are shown in Slide 7. The T275 attitude has a smaller projection of surface area into the direction of flight and a corresponding lower atmospheric drag than the T121G attitude. By maneuvering between TEA attitudes the drag on the vehicle could be modulated to slow or speed the desired descent rate of Skylab. This provided the capability to shift the reentry time several orbits if necessary.

Slide 7

Based on early reentry predictions of mid-June 1979, initial procedures were developed to begin TEA operations in the T121G attitude on May 26, 1979. At this time the vehicle altitude was predicted to be approximately 150 n.m. and the sun angle profile such that the T121G attitude would supply sufficient solar power from this point to the predicted reentry. However, as the time approached, it became apparent that Skylab was not reentering as fast as predicted and reentry slipped to early July 1979. As a result of this delay in reentry, a maneuver from T121G to T121P or T275 would be required to provide sufficient power over the sun angle range from 20 of May to reentry. Because of this, and the fact that Skylab would be around 157 n.m. on May 26, it was decided to delay TEA operations and stay in SI control until late June 1979. In the June 18-20 time frame, Skylab altitude would be approaching its lower limit for SI

Slide 8 control (140 n.m.) and the sun angle would be such that the T121P (Slide 8) attitude would provide sufficient power all the way to reentry.

In addition to requiring only one TEA orientation for solar power, this delay provided additional benefits. More time was available for TEA control analysis; development of procedures for power management, rate gyro bias compensation, TEA parameter updating, and contingencies; and ground controller training.

On May 20, the altitude of the vehicle was approximately 160 n.m. Skylab could be controlled in the SI mode only until

~~approximately 140 n.m. The Skylab descent rate and expected solar activity indicated that this altitude would be reached near June 18-20. Because of the sun angle at this time, the T121P attitude was the most favorable of the TEA attitudes that were available.~~ ~~This~~ The TEA 121P attitude, ~~shown in figure 2-18,~~ was near perpendicular to the orbital plane and the velocity vector and provide a high atmospheric drag on the vehicle.

~~The sun angle would allow sufficient power for the T121P attitude through the end of July, which was well past the predicted reentry time.~~ Also, as reentry neared greater atmospheric density would allow the T275 attitude to be useable. It was planned to use the T121P and T275 attitudes for drag modulation during the fnal 36 hours prior to reentry if the predicted reentry occurred during a highly populated orbit.

At 3:24 GMT, June 20, the delayed ZLV commands containing the time to start TEA acquisition and the ZLV offsets were uplinked. At 4:50 GMT, TACS control was reenabled. At 8:17 GMT, the CMG gimbal rate limit was increased to 2 degrees/second to allow for more control authority during acquisition and initial phases of TEA control. The maneuver sequence for going from solar inertial to T121P is shown in Slide 9. The delay ZLV maneuver was initiated at 12:53 GMT while the vehicle was outside of site coverage. At 13:01 GMT, shortly after the Santiago station was acquired, the CMG's were caged to the momentum desired for the new TEA attitude. At 13:13 GMT, the maneuver to the TEA attitude was complete.

Slide 9

TEA Control Reacquisition

To support the normal maintenance of TEA control, ~~the~~ a slope matrix was programmed to receive updates by ground uplink. This was a 3 by 3 matrix relating the momentum errors to attitude errors about the torque equilibrium attitude. This slope matrix was a function of atmospheric density and the TEA attitude. Since atmospheric density was increasing with the vehicle descent, the slope matrix required periodic adjustment.

At 16:13 GMT on June 24, the first slope matrix update since TEA acquisition was uplinked. However, the flight program required that the slope matrix elements be commanded in row order, but it was uplinked from the ground in column order. This meant that the elements in the slope matrix were reversed and the flight program had actually received the transpose of the desired matrix. With an incorrect slope matrix, the vehicle ~~cannot~~ could not properly manage the CMG momentum and ~~will~~ would slowly lose attitude control.

The first pass through the TEA control calculations with the transposed slope matrix occurred after the telemetry station was lost. There was no indication of a problem until the next station acquisition occurred at 17:44 GMT. The telemetry data from this station showed that the CMG momentum was becoming saturated, TEA control parameters were off-nominal, TACS had been used and that, in general, TEA control authority was being lost. An analysis of the DCS commands issued during the previous pass was made and it was discovered that the transpose of the slope matrix had been transmitted.

A contingency TEA control reacquisition procedure had been previously developed for use during the initial TEA control acquisition. Although this contingency procedure was developed assuming that TEA control might be lost due to an offset in the assumed X axis center of pressure, it also applied to the current situation. The commands necessary for the procedure were already resident at the ground stations and were readily available. The reacquisition procedure was executed when the next station coverage occurred over Madrid.

The entire process of losing TEA control and reacquiring TEA control used approximately 1100 lb f-sec of TACS fuel. Although this fuel usage had been unplanned, there was still sufficient fuel remaining for any required maneuvers prior to reentry.

Skylab Reentry

Following acquisition of TEA control, detailed procedures were developed which would provide flight controllers with a limited amount of reentry control capability. Procedures to maneuver Skylab from the high-drag T121P attitude to a low-drag TEA (T275) or ZLV attitude were developed to provide a means of shifting the reentry prediction. By maintaining a low-drag attitude, the orbit lifetime could be extended over that in the T121P attitude. This would make it possible to shift the predicted reentry from an orbit of high population density to one with a lower population density.

Since several factors indicated that TEA control (T121P) or T275 and TACS only control could not be reliably maintained below 80 n.m., procedures were also developed to initiate a random vehicle tumble. A random tumble results in a predictable average drag which can be used in reentry predictions. By controlling the time at which the vehicle drag changed due to a tumble, the impact prediction accuracy could be maintained. However, if the tumble occurred at some unknown time due to a loss of TEA or TACS only control, the impact prediction would be degraded.

Beginning on July 9 at 48 hours prior to predicted reentry and each six hours thereafter, NORAD supplied NASA Headquarters, MSFC and JSC with Skylab tracking data and reentry predictions. Communications between these centers was constantly maintained over a telecommunications network loop. Decisions pertaining to executing procedures for shifting Skylab reentry were made by NASA Headquarters under a set of previously defined ground rules.

As it turned out, only T121P control was required. NORAD data received between the 48 and 18-hour-to-go time points indicated that Skylab would reenter during the minimum population density orbit, but the predicted impact point was in the highest population density area of the orbit.

This was reconfirmed at the 12-hour time-to-go point. The decision was therefore to continue the T121P attitude until altitude of approximately 80 n.m., at which point the vehicle control was finally terminated when Skylab was commanded to tumble approximately 9 hours before reentry. (Reentry took place on July 11, 1979, at 16:37 - 28 GMT.) The vehicle tumble

Slide *10*

decreased the vehicle drag and by selection of the time before entry to initiate the tumble, an extension of the footpring by approximately one quarter of a revolution was realized.

FINAL COMMENTS

During both the primary and reactivation missions, many Skylab systems were required to operate in modes never intended by its designers and to accomplish tasks dictated by unforseen events. The Skylab reactivation mission offered NASA a unique opportunity to evaluate complex power generation, mechanical, computer and environmental control systems after having been in a space environment for over six years. Further, these systems were in orbital storage for over four of the six years in an uncontrolled space environment before being reactivated in March 1978. System degradation was found to be minimal.

Unique control schemes were developed (EOVV and TEA) which enabled Skylab to fly through the gravity gradient/aerodynamic torque transition region. Torque equilibrium points were discovered where gravity gradient and aerodynamic torques balanced. At these points very little vehicle control authority was required to maintain control. Moreover, vehicle orientations at these points were such that one could choose attitudes exhibiting high or low vehicle-drag characteristics. By modulating between these orientations, the rate of vehicle descent could be increased or decreased. forcing it into an impact orbit characterized by a low population density. After control of Skylab was regained in June 1978, at an altitude of 218 nautical miles, the vehicle was essentially under control down to approximately 80 nautical miles before it was commanded to reentry. (Reentry took place on June 11, 1979, at 16:37 - 28 GMT.) The vehicle tumble decreased the vehicle drag and by selection of the time before entry to initiate the tumble, an extension of the footpring by approximately one quarter of a revolution was realized.

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~~During both the primary [illegible]~~
~~[illegible]~~