rate used, which is only one tenth of the full scale capability of this instrument.

To test the system over its full dynamic range another series of steady-state tests was run using a precision current source (North Hills) applied to a second torquer which happens to exist on the output axis of the gyro. Current corresponding to vehicle rates up to 8 deg/sec was applied and the same averaging techniques described above were used to eliminate the influence of current noise. Again, the linearity proved to be 0.01% of the maximum rate.

Transient response tests were run on this system to assess the control loop stability.

These tests confirmed that the linear analysis was useful in determining large-signal stability. It was also shown that a limit cycle oscillation of approximately 100 Hz will exist if the 6.4 KHz ripple present in $V(t)$ is too large. The amplitude of this oscillation increases as the ripple amplitude increases and it can be observed as a fluttering of the edge of the pulse train at the output of the synchronizer. The filter and compensator described above eliminated this limit cycle oscillation. However, a slight flutter, one clock pulse width in magnitude, exists even when $V(t)$ is reduced to zero. This appears to be inherent in the binary switch and not dependent on the other parameters in the system.

References

[1] Scoville, A. E. and Yamron, J., "The Mechanization of a Strapdown Inertial System Based on Time-Modulated Torquing," AIAA/JACC Guidance and Control Conf., Seattle, Wash., Aug. 1966, pp. 136–148.

[2] Roantree, J. P. and Kormanik, N. J., "A Generalized Design Criterion for Strapped-Down Inertial Sensor Loops," AIAA/JACC Guidance and Control Conf., Seattle, Wash., Aug. 1966, pp. 149–162.

[3] Fehr, T. D., Fosth, D. C., and McDonald, R. K., "High Accuracy Approach Guidance System for Grand Tour," AIAA Paper 72-867, Stanford, Calif., 1972.

[4] Otten, D. D., "A Look into Strapdown Guidance—I," *Control Engineering*, Oct. 1966, pp. 61–67.

[5] Lory, C. B., "Compensation of Pulse-Rebalanced Inertial Instruments," Rept. T-495, Jan. 1968, MIT/IL, Cambridge, Mass.

[6] Gilmore, J. P. and Feldman, J., "Gyroscope in Torque-to-Balance Strapdown Application," *Journal of Spacecraft and Rockets*, Vol. 7, No. 9, Sept. 1970, pp. 1075–1082.

[7] Gilmore, J. P. and McKern, R. A., "Strapdown Inertial Attitude-Indication Evaluations," *Journal of Spacecraft and Rockets*, Vol. 7, No. 7, July 1970, pp. 825–831.

Mission Planning Aspects of Skylab Earth Resources Experiments

David D. DeAtkine*
NASA Johnson Space Center, Houston, Texas

Introduction

ONE of the major objectives of the Skylab program is the return and processing of Earth resources data taken with a set of multispectral remote sensors, referred to collectively as the Earth Resources Experiments Package (EREP). The Skylab orbital workshop (OWS) was launched in late spring of 1973 to circle the Earth in a controlled 234-naut mile altitude circular orbit. The workshop was visited by a crew of three, aboard an Apollo command and service module (CSM), on three occasions during the 8-month lifetime of the orbiting laboratory. This schedule allowed observation of the Earth under a variety of seasonal conditions.

Presented as Paper 73-619 at the AIAA/ASME/SAE Joint Space Mission Planning and Execution Meeting, Denver, Colo., July 10–12, 1973; submitted August 27, 1973; revision received December 10, 1973.

Index categories: Earth-Orbital Trajectories; Space Station Systems, Manned.

* Aerospace Engineer, Orbital Design Section, Mission Integration Branch, Mission Planning and Analysis Division.

Mission Requirements

The EREP mission requirements consist of a comprehensive set of objectives aimed at obtaining data for both sensor performance evaluation and Earth resources applications. The predetermined, calibrated sites, nearly 700 in number, are distributed world-wide, but are concentrated mostly in the U.S. and surrounding coastal areas. Other targets, such as hurricanes and active volcanoes, are to be determined in real-time. Earth resources experiments were submitted by more than 130 American and foreign principal investigators and range from regional planning and agriculture to oceanography and weather observation. Each experiment specifies for its associated sites a detailed set of required conditions for data taking. These conditions include such parameters as sun angle, season, number of data takes, acceptable cloud cover, and instrument requirements. The task of completing a maximum number of these proposals through mission planning is complicated by the wide variety of required site conditions encountered on any given EREP pass.

EREP Pass Planning Considerations and Methods

The EREP data passes are performed in a local-vertical (Z-LV) attitude hold.† Because this attitude is a deviation from the normal solar inertial (SI)‡ mode for thermal and power design reasons, these Z-LV holds must be constrained in duration, number, and solar angular relationship. The Z-LV constraints are briefly as follows: a) the angle between the sun-Earth line and the orbit plane (known as the beta angle) must be within $\pm 65°$; b) the Z-LV pass length should be less than 160° orbital angle; and c) there should be no more than three Z-LV passes per day.

The total number of Z-LV EREP passes originally available for all three Skylab missions was 60; however, this constraint was removed, and for the later two missions the number is dependent on available consumables. Other constraints which significantly affect EREP operations are terrain lighting conditions and weather (cloud cover); weather conditions over EREP sites greatly affect data takes and are discussed later with the real-time operations. In the premission planning, clear weather is assumed.

Lighting Effects of Launch Time and Season

Almost all of the Earth resources proposals specify desired sun lighting conditions; most of these are daylight conditions with sun angles (measured with respect to the local horizontal) above 20°–30°. It is desirable, therefore, to design the launch time and date, if possible, to allow for maximum sun elevation angles in the northern hemisphere; the lighting is to be maximized in the U.S., where almost 80% of the EREP sites are defined. However, other mission factors are affected by launch time and date as well, some more constraining and considered more important than the EREP requirements. Shown in Fig. 1 is the effect of SL-1 (the OWS) launch data on subsequent adequately-lighted U.S. pass opportunities. A three-mission maximum

† Some EREP data takes are planned while the orbital assembly (OA) is in the solar inertial mode (approximately five passes) under specific conditions; however, the discussion herein is restricted to the normal Z-LV attitude cases.

‡ The solar inertial mode is an inertial attitude hold which points the OWS + Z axis at the sun.

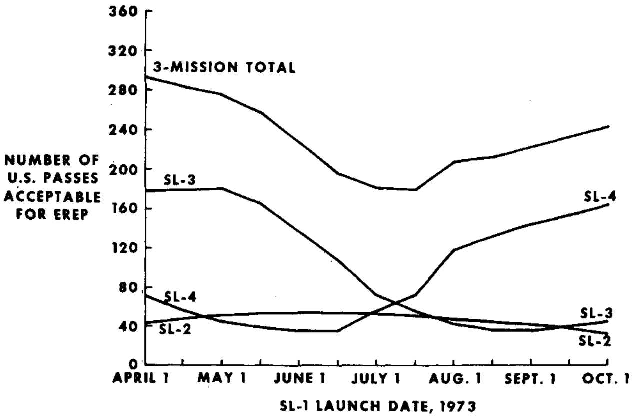

Fig. 1 Number of U.S. passes acceptable for EREP as a function of SL-1 lift-off date and time.

occurs for a March SL-1 launch, because all three missions are spaced across the spring, summer, and fall months (the time between missions is assumed fixed). A three-mission minimum is the result of a mid-July launch, because the two longer-duration missions, SL-3 and -4, occur during winter months. Because of other considerations, the planned launch date of the workshop is mid-May, which, in relative terms, is very good for EREP three-mission total lighting.

The effect of launch time of day on the first manned mission, SL-2, for mid-May launch of SL-1 is shown in Fig. 2. As can be seen, ascending (in latitude) and descending passes have favorable lighting at different portions of the SL-2 mission as a function of the time of day of SL-1 launch, with a 2-day period during which both types of passes are acceptable. For SL-1 launch times of 1130 est to 1530 est, acceptably lighted passes are available every day of the mission; however, because of other, more constraining factors, the launch window for SL-1 extends from 1230 to 1400 est.

Controlled Repeating Groundtrack Technique

The Skylab OWS orbit is planned such that the groundtrack will repeat itself every 71 Earth-fixed revolutions, or approximately every five days. The orbital period (93.237 min) is to be maintained through the use of small adjustments with the CSM reaction control rockets (the CSM is docked with the OWS) to keep the groundtrack within ± 3 naut miles of the planned track. The adjustment maneuvers are performed while the OA is in the solar inertial attitude, either at orbital midnight or noon, depending upon whether a plus or minus change in velocity (ΔV), respectively, is required. This controlled repeating groundtrack is implemented primarily to aid EREP operations. Advantages of this condition include multiple identical pass opportunities for cloud cover considerations and for multiple pass data requirements; the repeating orbit also allows simplifying and systematizing the EREP pass planning procedures, based on 5-day 71 revolution cycles. Many EREP sites were relocated or adjusted according to this pattern to afford better and more frequent data acquisition opportunities. Control of the orbit also permits changes in the orbit period so that the ground-track pattern can be repositioned. This procedure could permit sensor acquisition of EREP sites which would be missed if a single pattern were maintained.

To simplify mission planning procedures for this repeating orbit, the concept of track identification was introduced. The first 71 Earth-fixed revolutions of the SL-1 OWS are referred to as tracks; all revolutions thereafter are simply repeats of this set, and are referred to by their appropriate track number. For example, SL-1 revolutions 1, 72, 143, and 214 are all recognized as track one. The only difference between these revolutions is the 2-hr local time difference at any point on the ground-track for each succeeding 71-revolution increment. The track reference longitude is 25°W, rather than the Kennedy Space Center (KSC) longitude commonly used for revolution count, in order to avoid the problem of track number change during a U.S. EREP pass over the east coast. Unfortunately, the separation of the chosen pattern is too wide to allow complete coverage of the Earth between 50° latitude by the EREP instruments with smaller fields of view. The pattern which would do so requires an orbital altitude outside Skylab vehicle performance capabilities.

Skylab-2 EREP Pass Selection

The premission Earth resources pass planning on Skylab, then, consists basically of three planning steps: a) analysis and selection of a repeating groundtrack pattern, which is optimized in coverage of EREP sites (this pattern may be changed for each mission, if necessary); b) analysis and selection of a number (14 for SL-2) of tracks which are optimum in numbers of sites covered (and investigations satisfied); and c) selection of properly-lighted revolutions within Z-LV limits for these tracks, and integration of these time blocks into the flight plan as EREP passes. Clear weather is assumed. The highly significant impact of weather on EREP pass planning is discussed in the next section.

Briefly, the procedure followed to select the EREP passes planned for SL-2 was as follows. The selection of the ground-track pattern for SL-2 followed an analysis of a basic, 40.9° launch azimuth insertion orbit of SL-1, and a small number of patterns displaced from this basic pattern. The basic pattern was nearly optimum in site coverage, and had the additional advantage of requiring no initial "drifting" orbit period, or additional adjustment maneuvers. Thus, the basic insertion orbit pattern was selected for SL-2. The orbit control procedure for SL-2 is pictured in Fig. 3. As can be seen, the OWS is nominally inserted slightly high in period so that the process of orbit decay will keep the groundtrack ascending node close (within ± 3 naut miles) to the reference until the first required adjustment nine days into the mission. In the event of a non-nominal insertion, an adjustment maneuver (nominally zero) is scheduled for the first day after docking. A boost maneuver is performed at nine days to maintain the track within ± 3 naut miles of the reference. A final maneuver is scheduled for day 25 to boost the orbit up so that drag decays it to a near repeating altitude for SL-3, which begins approximately two months later. Other adjustment maneuvers can be inserted into the flight plan if orbit drag or other orbit changing parameters are outside expected limits. The pattern selected for SL-2 will not necessarily be carried through the later missions. As mentioned previously, the capability exists to shift the pattern if between-mission data analysis or other conditions should indicate that such a shift would be desirable.

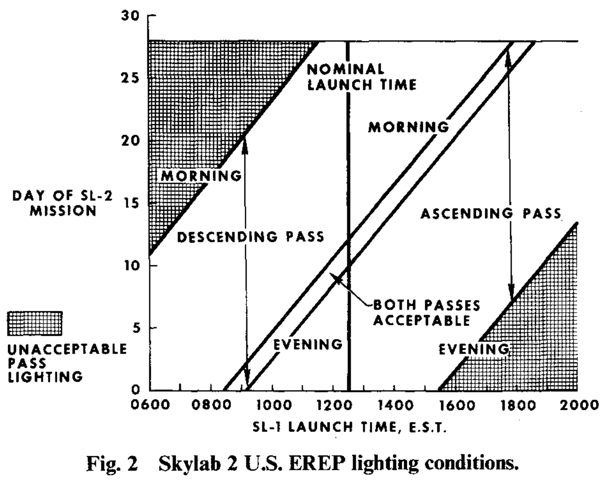

Fig. 2 Skylab 2 U.S. EREP lighting conditions.

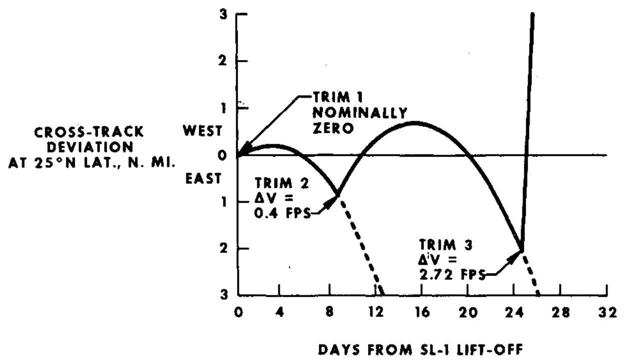

Fig. 3 SL-2 docked trim sequence for groundtrack control.

Once the groundtrack pattern was chosen, the selection of a set of 14 prime tracks from among the available tracks was undertaken. Since SL-2 preflight planning guidelines called for all U.S. passes (with some extensions into foreign areas), the analysis considered only the 32 tracks which included a portion of the U.S. A computerized scoring process was carried out. The tracks were ranked according to the number of sites within the U.S. and surrounding coastal areas which had the required sensor coverage. Seasonal conditions for these sites were also considered. Other details, such as instrument modes and sensor configuration conflicts, were not considered. The top-ranking 14 tracks and several alternates (ranking 15th through 19th) were selected as candidates for EREP passes on the SL-2 mission. The higher-ranking tracks passed over high site-density areas such as the Houston Area Test Site, the Atlantic Seaboard, and the Southern California-Phoenix area.

The final step consisted of fitting these tracks into the total Skylab-2 flight plan. First, the revolutions associated with each track which have proper sun angles for the U.S. portion were found. From Fig. 2, the ascending passes must occur in the first half of the mission, the descending passes in the second half. Because of flight plan conflicts (Earth resources is ranked behind other major experiment disciplines in priority on SL-2), not all of the 14 prime tracks were scheduled; two lower-ranking alternate tracks were inserted in the place of two prime tracks which interfered with other flight activities. The U.S. passes were extended into foreign areas whenever foreign sites in sufficient number were available within lighting and Z-LV constraints.

The EREP pass planning process for the later missions, SL-3 and SL-4, is similar, but these missions include some foreign passes, and SL-4 EREP passes are slanted somewhat toward completion of investigations which have unfinished tasks; this results in short "piece-meal" passes.

Real-Time Pass Planning

EREP pass planning is heavily affected by actual weather conditions; cloud cover adversely affects data acquired by the visible to IR range sensors, while the microwave instruments are not as sensitive to these conditions. The real-time pass planning procedure is essentially that discussed previously, except that cloud cover is considered, and instrument modes and configuration conflicts are considered in great detail.

Several days prior to any given mission day, the possible passes for that day are evaluated (based on the predicted cloud coverage) by using the interactive computer programs which were applied in the preflight planning; candidates are selected based on the task/site completion criteria as applied for the premission planning. Approximately 24 hr prior to the mission day, a prime pass or passes (not more than three) are selected and fitted into the flight plan for execution. If it were not for cloud cover, the pass would correspond to the one in the premission flight plan. However, based on simulation experience, actual cloud coverage results in changed EREP passes approximately 50% of the time, as well as reducing the number of sites acquired by approximately the same percentage. The EREP instrument on/off times are telemetered up to the OA at approximately pass time minus 12 hr and are based on later weather forecasts. At pass time minus 3 hr—too close to the pass to update the EREP time line—a GO/NO-GO decision is given based on latest weather.

Preliminary SL-2 EREP Results

Despite the systems problems encountered on the first manned Skylab mission, significant EREP data were taken. Because of the power, attitude maneuvering, and crew time limitations, the number of Z-LV passes accomplished was 11, rather than the planned 14. These passes consisted of data takes, averaging 13 min each, over most of the continental U.S., plus some coverage of the Pacific and Atlantic Oceans, the Gulf of Mexico, Mexico, and Central and South America. In addition, S193 (radiometer/scatterometer) and photographic data were acquired of a hurricane in the Pacific off the coast of Mexico. All six instruments and their related systems apparently functioned normally, and data for all disciplines, both applications and sensor development, were obtained.

Conclusions

Mission planning techniques have been developed to optimize the data return from the Earth Resources Experiments Package on Skylab. The techniques are designed to cope with a variety of missions, systems and weather constraints, and sensor development and science applications data requirements. The procedures have been computerized in an interactive real-time system for simulation and actual mission use. The planning techniques developed for Skylab are applicable to later generation orbital programs, both manned and unmanned, which involve the use of remote-sensing instrumentation for Earth resources.

Spaceborne Very-Long-Baseline Radio Astronomy Interferometry

T. A. Heppenheimer*
Rockwell International Corporation, Downey, Calif.

Introduction

In recent years, the techniques of very-long-baseline interferometry (VLBI) have made possible the observation of celestial objects at resolutions of 10^{-3} to 10^{-4} arcsec, or 3 to 4 orders of magnitude better than optical telescopes achieve. However, VLBI experiments have been performed on an ad hoc basis, there being no dedicated VLBI observatory.

VLBI methods may permit mapping of the Milky Way's small, active core on a scale of 1 a.u.; other galaxies could be mapped at a scale comparable to the Solar System. VLBI also offers such applications as: determining sky positions to 10^{-3} arcsec; measuring the length of the day to 10^{-4} sec; measuring global

Received November 2, 1973; revision received December 10, 1973. This work was performed as a National Science Foundation Graduate Fellow, Department of Aerospace Engineering, University of Michigan, Ann Arbor, Mich.

Index category: Earth Satellite Systems, Unmanned.

* Member of the Technical Staff, Space Division. Member AIAA.