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PROPOSED GRAVITY-GRADIENT DYNAMICS EXPERIMENTS USING THE RAE-I SPACECRAFT

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JULY 1970



GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

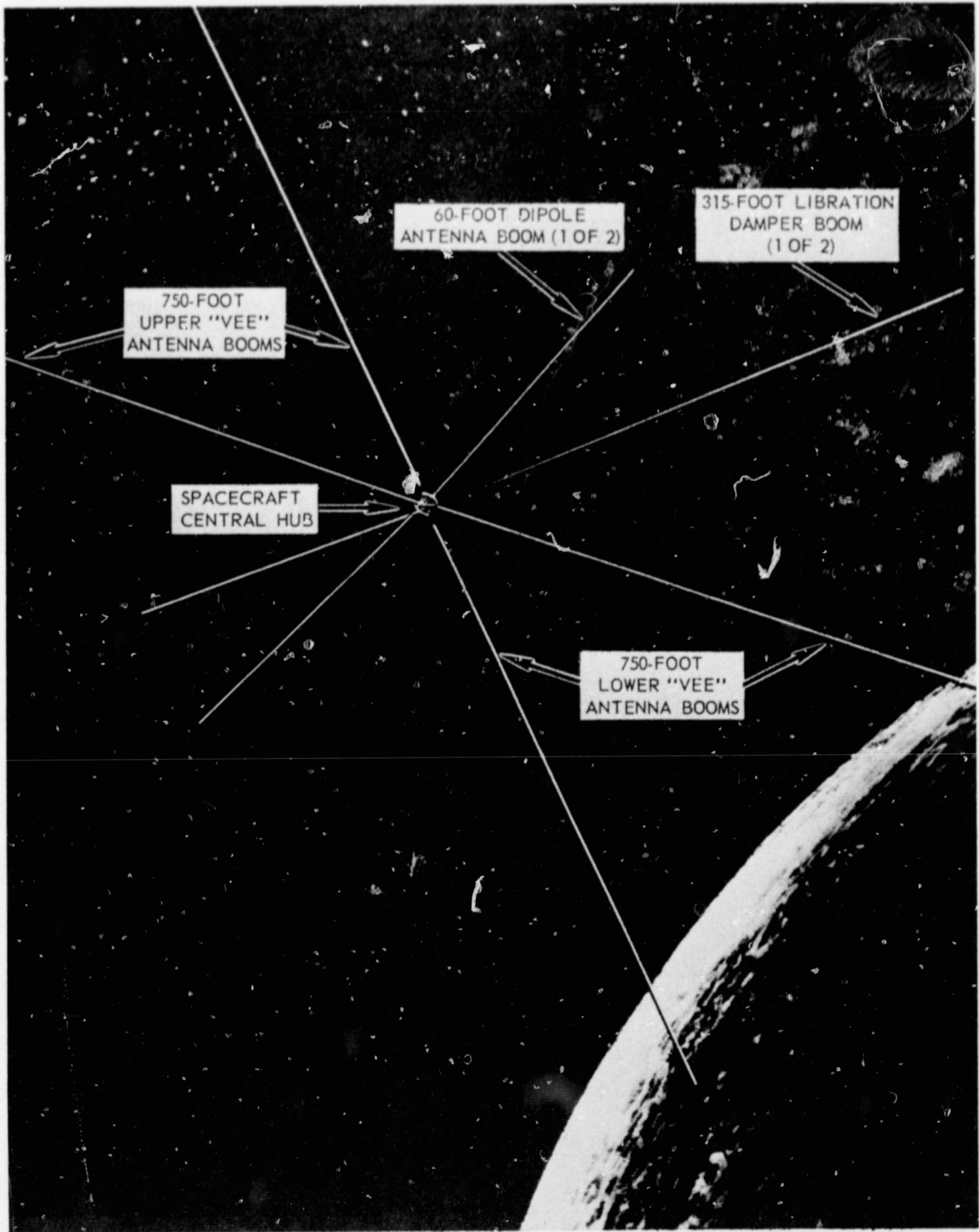
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland



Frontispiece. Artist's Concept of the RAE-I Spacecraft In Earth Orbit

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ABSTRACT

A series of six gravity-gradient dynamics experiments is proposed using the Radio Astronomy Explorer (RAE-I) satellite currently in Earth orbit. It is believed that none of the experiments will impair the spacecraft structure or adversely affect the continuance of the scientific mission of the satellite following completion of the proposed experiments. Two experiments involve clamping the libration damper mechanism, once when the orbits are in full sunlight and once when each orbit is partially occulted. Observations will then record any librational disturbances to the steady-state condition. The other four experiments involve retracting or extending one boom or a pair of booms from the lower "Vee" antenna, both with the damper clamped and unclamped. By the law of conservation of angular momentum, changes in the lengths of the primary booms (which are currently fully deployed at 750-foot lengths) will induce angular librations of the spacecraft. Data from these experiments will provide information relating to damper effectiveness (especially at large amplitude attitude motions), the dynamics of particular asymmetrical spacecraft configurations, the boom structural damping, the spacecraft dynamics in the absence of a damper, and the effects of partial solar occultation with the damper clamped. As a result of the performance of these experiments and a thorough analysis of the observational data, the probability of success for the proposed RAE-B lunar mission will be significantly enhanced, particularly for certain possible failure modes. In addition, information gained from an analysis of the experimental results will be generally applicable to advancing current understanding of all passive three-axis gravity-gradient-stabilized spacecraft control systems.

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PROPOSED GRAVITY-GRADIENT DYNAMICS EXPERIMENTS USING THE RAE-I SPACECRAFT

SECTION I

INTRODUCTION

It is the purpose of this document to propose a series of gravity-gradient dynamics experiments using the Radio Astronomy Explorer (RAE-I; Explorer 38) spacecraft which is currently in Earth orbit.

The general objectives of this series of experiments are to ascertain definitively the in-orbit motions and to understand more fully the gravity-gradient dynamical behavior of the RAE-I spacecraft under adverse conditions such as large amplitude attitude librations, mismatched boom lengths, and an inactive damper system. Such an understanding will, in particular, enhance the probability of success for the proposed RAE-B lunar mission (Reference 1), and will, in general, advance current understanding of passive three-axis gravity-gradient stabilization systems.

Because of the small orbital eccentricity (approximately 0.0015) and the completely nominal deployment of the main "Vee" antenna booms to full 750-foot lengths, the RAE-I spacecraft has been more dynamically stable than even optimistic pre-launch predictions (Reference 2). In fact, the librational motions of the central hub have remained less than ± 4 degrees about all axes since attaining steady-state conditions following final deployment of the main booms on October 8, 1968 (References 3 and 4). Consequently, no pertinent information has been obtained on spacecraft behavior under adverse conditions, and it is difficult to improve the ground-based estimates of various spacecraft mechanical parameters. As a result of this lack of dynamical information, a series of experiments is herein proposed to perturb the spacecraft librational motions. The series of experiments with associated anticipated results is summarized in Table 1 generally in the order of increasing risk to the spacecraft. The preliminary and the final experiments will be merely a clamping of the damper mechanism for several orbits. The general intent of the remaining experiments will be to cause an asymmetric spacecraft configuration by retracting a boom or a pair of booms and, through the law of the conservation of angular momentum, to induce thereby a perturbation in the pitch angular motions of the spacecraft.

The information to be gained from this study of the spacecraft dynamics under adverse conditions will enhance the probability of a successful RAE-B lunar mission (currently proposed for a late 1972 launch) if: (1) a failure were to occur

in a primary boom or in the damper boom deployment mechanisms, or (2) the final lunar orbit were not as circular as the Earth orbit achieved for the RAE-I. It is also anticipated that the experience gained in determining definitive attitude information during these dynamics experiments will result in a more refined attitude processing operation during the RAE-B lunar mission. Finally, since the RAE-I satellite is the lone success of approximately a dozen attempts at passive three-axis gravity-gradient stabilization, the information to be obtained from these experiments will aid in understanding in greater detail the reasons for its unique dynamical stability.

Table 1

Proposed Gravity-Gradient Dynamics Experiments

Experiment 1: Damper clamped during full sunlight orbits

Date	As soon as possible following onset of full sunlight phase
Objectives	Study effects of forcing functions from steady-state conditions in the absence of an active damper
Anticipated dynamical behavior	Increase of one to three degrees amplitude in the present attitude motions about equilibrium of 3 to 5 degrees in amplitude
Information to be gained	Boom structural damping, effectiveness of damper mechanism, effects of forcing functions from steady-state conditions, and length of time the system might be stable in the absence of a damper
*Risk level	Very low

Experiment 2: Single boom retraction with damper active

Date	Three weeks following Experiment 1
Objectives	Study dynamics of this particular asymmetrical spacecraft configuration
Anticipated dynamical behavior	Moderate amplitude attitude motions (10 to 20 degrees) coupling into large boom flexures, with the motions damping to steady-state conditions in several days
Information to be gained	Solar pressure effects, damper effectiveness at moderate angular librations (induced, for example, by excessive orbital eccentricity), and effects of configuration asymmetry on the dynamics, such as might be encountered by a boom deployment mechanism failure
*Risk level	Low

Table 1 (Continued)

Experiment 3: Single boom extension with damper clamped

Date	One month following Experiment 2
Objectives	Study dynamics of symmetrical spacecraft configuration in the absence of an active damper
Anticipated dynamical behavior	Moderate amplitude attitude motions (10 to 20 degrees) coupling into large boom flexures, with little damping
Information to be gained	Effects of a damper failure with a symmetrical configuration during moderate angular librations, likelihood of attaining steady-state conditions, and improvement in the estimation of spacecraft engineering parameters
*Risk level	Low

Experiment 4: Double boom retraction with damper clamped

Date	One month following Experiment 3
Objectives	Study dynamics of a different asymmetrical spacecraft configuration in the absence of an active damper
Anticipated dynamical behavior	Large amplitude attitude motions (30 to 45 degrees) with little or no damping, possibly coupling into a yaw flip
Information to be gained	Effects of a damper failure with this particular asymmetrical configuration and likelihood of attaining steady-state conditions from such large angular librations
*Risk level	Somewhat higher

Table 1 (Concluded)

Experiment 5: Double boom extension with damper active

Date	One month following Experiment 4
Objectives	Study dynamics of large amplitude attitude motions with a symmetrical spacecraft configuration
Anticipated dynamical behavior	Large amplitude attitude motions (30 to 45 degrees) with the motions damping to steady-state conditions in several days
Information to be gained	Damper effectiveness at large angular librations (induced, for example, by improper conditions at initial deployment with other systems nominal) and improvement in the estimation of spacecraft engineering parameters
*Risk level	Somewhat higher

Experiment 6: Damper clamped during partial solar occultation

Date	Shortly following onset of partial solar shadowing phase
Objectives	Study effects of thermal forcing functions caused by partial solar occultation from steady-state conditions in the absence of an active damper
Anticipated dynamical behavior	Increase of one to three degrees amplitude in the steady-state attitude motions about equilibrium
Information to be gained	Thermal gradient across booms, boom structural damping, solar pressure effects, and effects of thermal forcing functions from steady-state conditions
*Risk level	Low

*It is not possible to associate numerical values with the admittedly vague relative terms "very low", "low", and "somewhat higher". However, it is believed that none of the six experiments above is potentially destructive in nature to the RAE-I spacecraft.

SECTION II

EXPERIMENT OBJECTIVES

The specific objectives of these experiments will be to:

- a. observe the spacecraft dynamical stability and system damping at large amplitude attitude librations with both matched and mismatched boom lengths, and with both a clamped damper and an active damper system,
- b. attempt to fit the spacecraft librational motions using mathematical models and computer simulations previously developed,
- c. establish limits of main antenna boom tip excursions, based on observations and computer simulations, at these large amplitude librations, and
- d. establish a definitive spacecraft central hub attitude determination system by the use of a dynamics model in conjunction with spacecraft central hub attitude data.

The four parameters which significantly affect the dynamical stability of a large flexible gravity-gradient-controlled spacecraft such as the RAE-I are the following: the spacecraft configuration (as measured by the inertia ratios), the orbital eccentricity, the boom bending stiffness, and the thermal gradient across the booms. The last two parameters are fixed at the time of launch and should be fairly well known from ground measurement studies; the first two parameters are indeterminable until the final orbit is achieved and the spacecraft is fully deployed and, in fact, may change subsequent to this.

No problems with spacecraft configuration developed during the RAE-I mission, since all primary and damper booms deployed fully and any boom warpage that occurred was fairly minimal. However, either a mechanism failure or a lack of sufficient boom straightness would have significantly affected the spacecraft configuration and, consequently, the dynamical behavior. The first objective of these experiments is to mismatch deliberately the boom lengths and observe the resulting librational motions in order to gain a general understanding of the spacecraft dynamics under these adverse conditions. The second objective is to compare these motions to predictions of computer simulations and attempt by a parameter variation to obtain a best fit to the observational data. This will lead to greater preparedness for any such failure mode that might be experienced during the RAE-B mission.

The orbital eccentricity attained for the RAE-I spacecraft is nominal, i.e., approximately 0.0015 or less. Recent studies (Reference 5) indicate that it is highly probable that the orbital eccentricity for the RAE-B will vary markedly with time (due to lunar gravitational perturbations) and may significantly exceed the very low value achieved for the RAE-I. Figure 1 represents the results of a numerical integration of the nominal orbit for the proposed RAE-B lunar mission using a lunar potential model with third-body perturbations of the Earth added. Eccentricity causes a direct perturbation in the spacecraft pitch libration and couples indirectly to roll and yaw angular motions. The orbital eccentricity for the RAE-I cannot be changed since no on-board thrusting system is available. However, large librations can be induced by boom retractions and deployments in order to study the effectiveness of the damper. The "deadbeat" and "double deadbeat" deployment techniques were so effective during the RAE-I mission that large oscillations were never experienced. Thus, the damper system has never been fully utilized. However, these disturbances with the resulting damper action will aid in estimating spacecraft performance in a more highly eccentric orbit.

The thermal gradient across the booms and the bending stiffness of the booms are parameters difficult to assess from available data since, as a result of the deployment process and the damper action, the librations have remained less than ± 4 degrees about all three axes since attaining steady-state conditions following final deployment to 750-foot boom lengths. The amplitudes of these motions are about equal to the limit of precision which was initially stated for the attitude determination system. Because of these well-behaved motions and the limit of precision of the attitude determination system, it has been very difficult to perform any meaningful spacecraft parameter study. This is so despite the fact that there is considerable evidence that there may exist substantial discrepancies between some of the parameters as measured in ground studies before launch and as determined by those values which give the best fit in computer simulations. Inducing larger librations will make it possible to evaluate the parameters more accurately and, finally, to assess limits on the excursions of the main boom tips.

A final objective of these experiments is to provide definitive attitude information relative to the spacecraft central hub for large angular librations using the observational data in conjunction with a mathematical model of the dynamics. Deterministic methods have been sufficient to date because of the small oscillations about equilibrium values in three-axis motions. These require smoothing techniques in order to obtain a continuous time history of central hub librational motions over moderate time intervals. Thus, a further objective of these dynamics experiments is the improvement in attitude determination accuracies over relatively long time intervals as well as the establishment of an operational

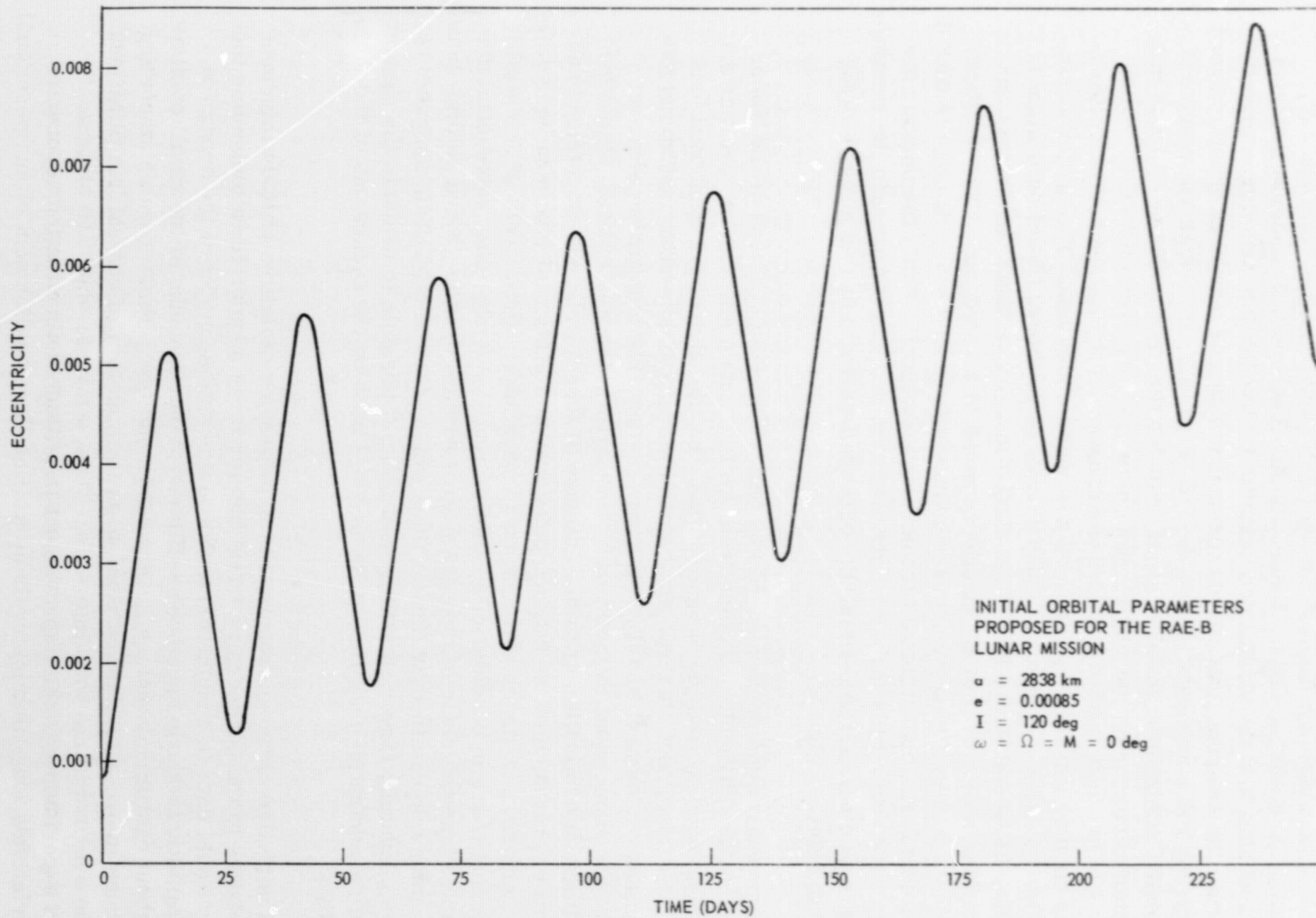


Figure 1. Evolution of Orbital Eccentricity for a Lunar Satellite

procedure for providing definitive attitude librational angles on a routine basis. Such an operational procedure, which was never required for RAE-I mission support because of well-behaved dynamical motions, may be required for the RAE-B lunar mission, particularly during the initial phases following full deployment of the booms in lunar orbit.

In addition to the prime objectives, information will be obtained relative to motor lifetime, solenoid lifetime, and electrical and mechanical component lifetimes by the experiments proposed herein.

The dynamics experiments will be considered successful if only one of the two lower primary booms will retract, enabling performance of four experiments. It is anticipated that if all the objectives of the experiments are met, understanding of the spacecraft dynamical performance under adverse conditions will be substantially increased. Also, a better estimation of certain spacecraft parameters such as boom bending stiffness, thermal gradient across the booms, antenna deployment root angles, and boom straightness of the lower antenna will be obtained. Finally, information on component lifetimes will be gained. All of this information will be a significant contribution toward a successful future RAE-B mission.

SECTION III

EXPERIMENT PROCEDURE

The experiments are arranged approximately in order of increasing risk to the spacecraft and with due consideration for continuing the scientific mission of the spacecraft. Because of power requirements and possible perturbations to the spacecraft during partially solar eclipsed orbits, it seems highly desirable to perform the complete series of experiments while the orbits are in full sunlight. Figure 2 shows that this period extends from August 8, 1970 through February 25, 1971. This allows more than six months for the performance of the experiments.

The experiments should be spaced at intervals of at least one month so as to allow time for the librations to reduce to near equilibrium conditions and also to allow sufficient time for a thorough understanding of the dynamical behavior resulting from one experiment before proceeding to the next. Figure 2 also shows an approximate schedule for these experiments which allows some possible slippage in the scheduling of the first five experiments. It is intended that a report of the observations and interpretations will be compiled following the performance of each dynamics experiment. Table 1 gives a synopsis of these experiments which are discussed below in greater detail.

Experiment 1

In order to study the effects of the steady-state forcing functions of the spacecraft dynamics with no damper action, the first experiment will be to cage the damper mechanism for about two days and observe the resulting spacecraft motions. This is a near-zero risk experiment and will furnish information on antenna boom structural damping; the forcing effects of orbital eccentricity, thermal bending, and solar pressure; and the need for a damper during steady-state conditions. It is anticipated that the librational motions will remain near their present low levels of ± 4 degrees about equilibrium values.

Experiment 2

One of the lower booms will be retracted to a length so as to induce 10- to 20-degree librational disturbances. The damper will be left uncaged throughout and the resulting dynamical behavior observed. This will provide dynamical information at motions of moderate amplitudes and with an asymmetrical spacecraft configuration. Most of the librational motion should damp out within a week, so that the steady-state condition will be achieved before the next experiment is initiated. An estimate of the anticipated behavior may be obtained from

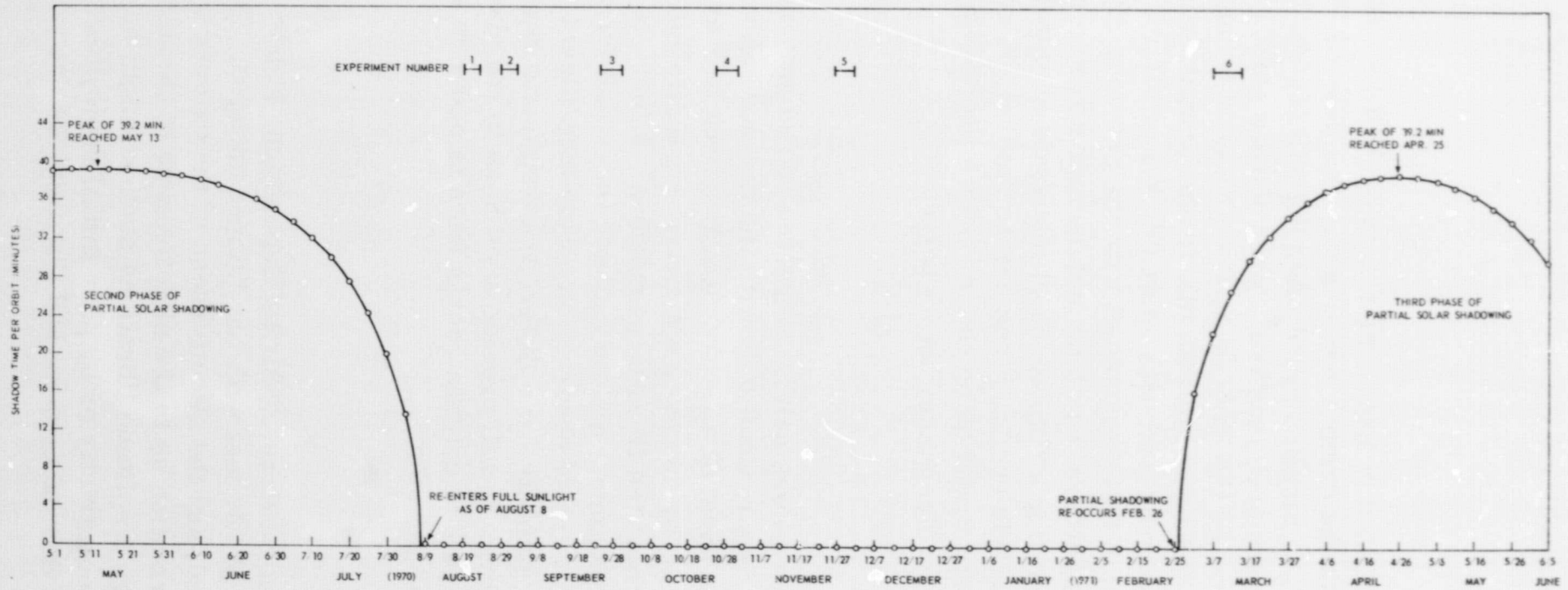


Figure 2. Shadow Time Predictions for the RAE-I Satellite (May 1, 1970 to June 5, 1971) and Possible Experiment Schedule

a study of computer simulations showing the roll, pitch, and yaw motions for somewhat similar initial conditions (Reference 2; run presented in Figures 3, 4, and 5.

Experiment 3

The boom which was retracted in Experiment 2 above will be redeployed to its full length of 750 feet with the damper now caged. The induced librations will again be 10 to 20 degrees in amplitude, but damping will tend to be protracted with the damper system rendered inactive. After about a week of observation, it will be necessary to uncage the damper so that the system can damp to a steady-state condition. The behavior with the damper caged will indicate the problems that might be encountered with a damper system failure on future missions. A comparison of this experiment with the previous experiment will provide information on structural damping and damper effectiveness. Also, the spacecraft dynamical behavior at librations of moderate amplitude with a symmetric versus an asymmetric configuration can be studied. A rather thorough study of Experiments 2 and 3 will be conducted before proceeding to the next two experiments, which involve somewhat higher risks.

Experiment 4

The lower pair of antenna booms will be retracted sufficiently to induce a pitch libration of 30 to 45 degrees in amplitude with the damper caged. It will be necessary to monitor the dynamics rather closely during this experiment, since very little damping will occur and the asymmetric configuration may allow the external torques to increase the librational motions. If there is any indication of divergent motions, the damper will be uncaged immediately; otherwise, it will be uncaged after about a week of observation. This experiment will provide information on dynamical stability for a different asymmetric configuration than that of Experiment 2 above. It will provide a guide as to the choices to be made if an actual failure of a pair of antenna booms were to occur in a future flight such as the RAE-B lunar mission.

Experiment 5

The pair of antenna booms retracted during Experiment 4 above will now be redeployed to full lengths of 750 feet with the damper uncaged. The dynamical motions will be observed, and the effectiveness of the damper system evaluated. This shall provide information as to the effectiveness of the damper mechanism under conditions of large amplitude librations such as might be induced by a large value of orbital eccentricity or by poor initial deployment conditions. Again, a comparison of this experiment and the previous one will provide

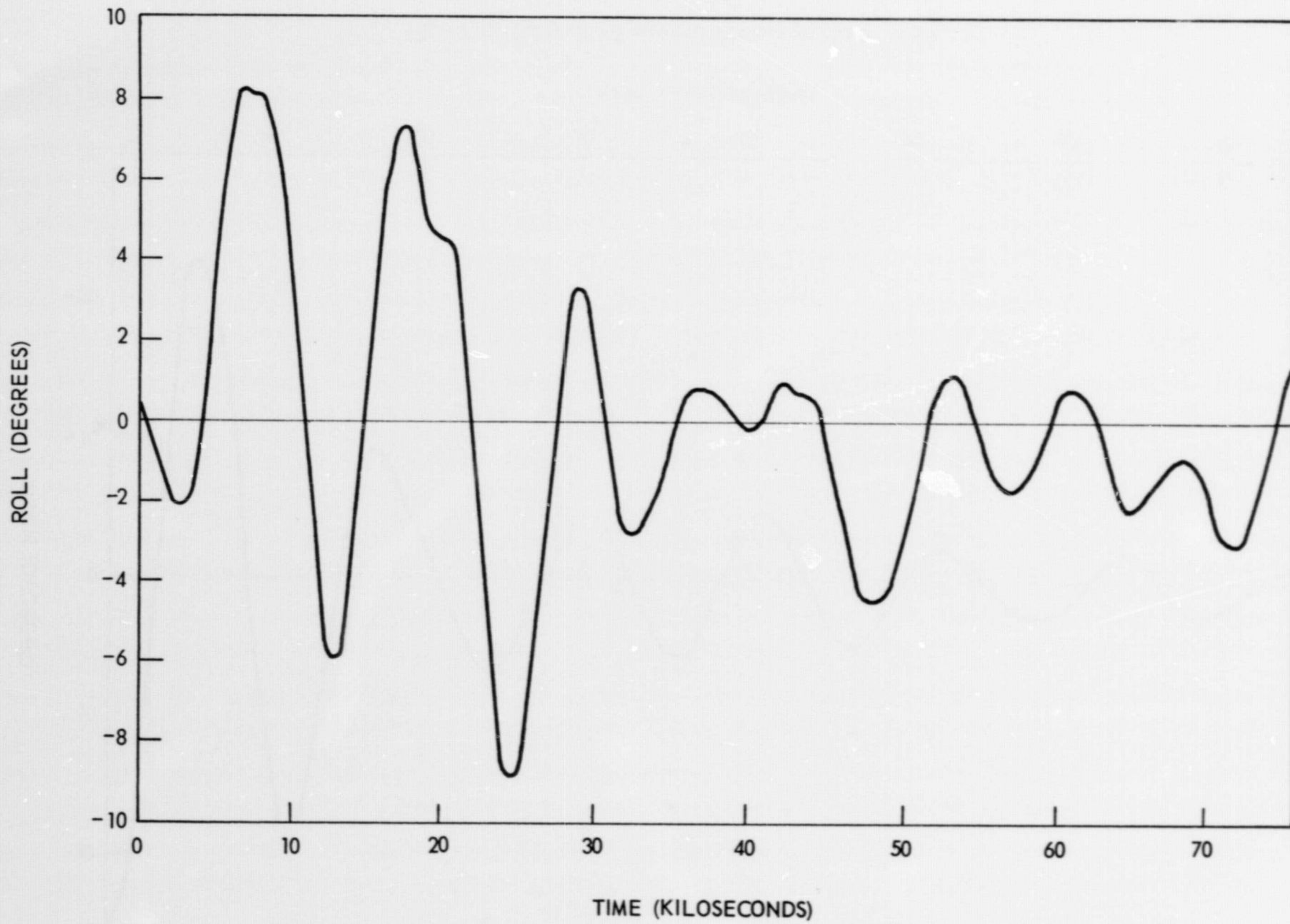


Figure 3. Computer-Simulated Motions in Roll Angle

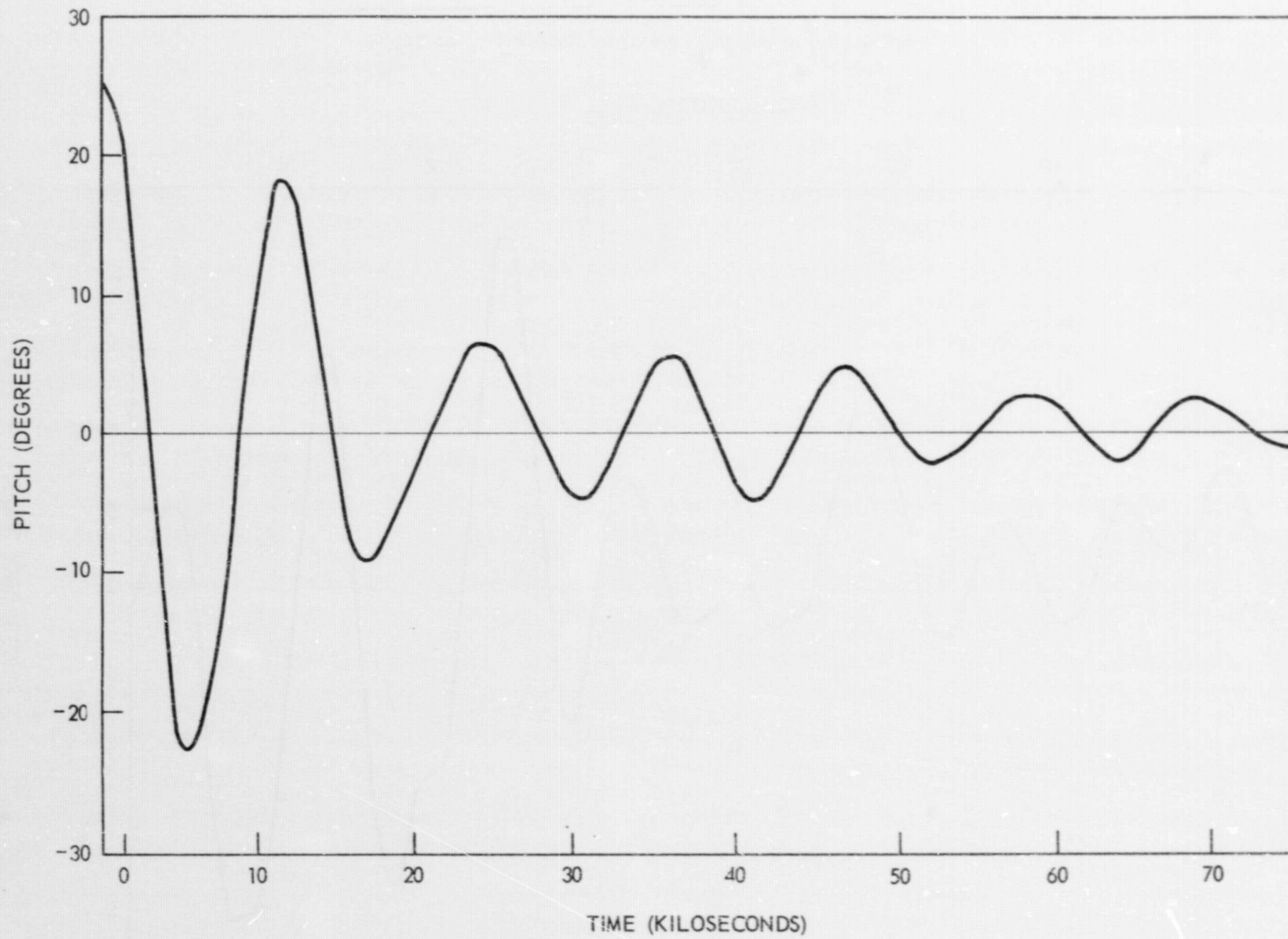


Figure 4. Computer-Simulated Motions in Pitch Angle

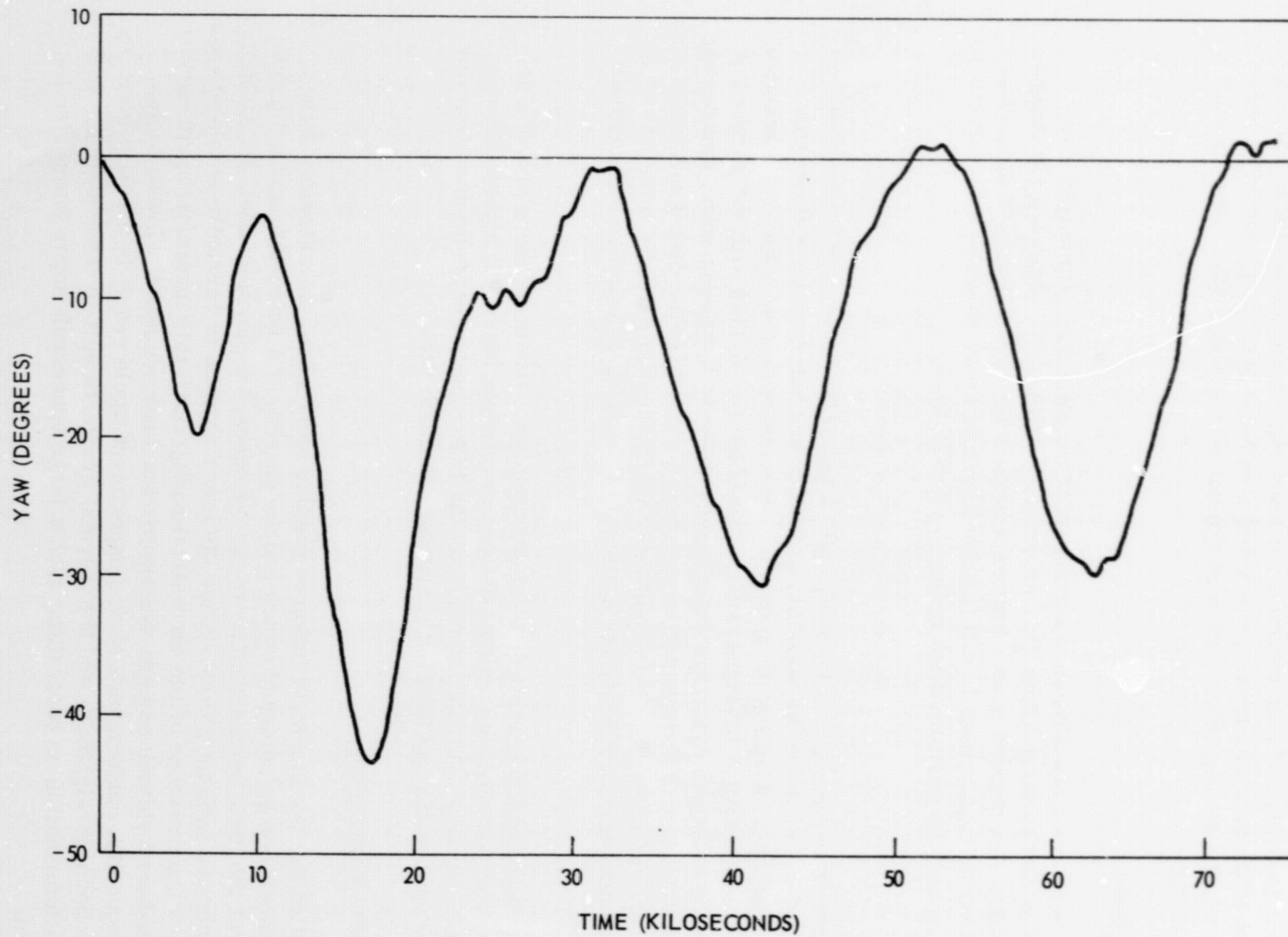


Figure 5. Computer-Simulated Motions in Yaw Angle

information on structural damping, damper effectiveness at large librations, and spacecraft dynamics with a symmetric versus an asymmetric configuration different from that of Experiment 2. A most significant study will be the comparison of the pair of Experiments 4 and 5 with the preceding pair of Experiments 2 and 3 and the examination of dynamical stability under two different asymmetries.

Experiment 6

In order to study the effects of partial solar occultation on the spacecraft dynamics and boom motions, this experiment will involve clamping the damper mechanism for about a week. This is a near-zero risk experiment and, when compared to Experiment 1, will furnish information on antenna boom structural damping and the perturbations caused by occultation.

* * * * *

This series of six experiments is really a set of three pairs of experiments as indicated in the above discussions, and maximum information will be gained from them by performing the indicated correlation studies. It is recommended that an Ad-Hoc RAE-I Dynamics Committee be established with the purpose of reviewing proposed dynamics experiments prior to implementation, monitoring the performance of the adopted experiments, and reviewing post-experiment data reduction and analysis. This committee would meet at periodic intervals or as deemed necessary following the approval of the RAE-I dynamics experiments concept.

This completes the proposed set of experiments. However, there are at least two further experiments which are very worthwhile but of yet higher risk. It would seem very desirable to perform the following two experiments when the RAE-I spacecraft has fulfilled its useful scientific life.

Spacecraft Inversion

Based on the law of conservation of angular momentum, an inversion of the spacecraft can be achieved by the proper phasing of a retraction and a deployment of the main booms similar to the "deadbeat" deployment used for extending the primary antenna booms. Since the lower antenna is currently obscured from view by the presence of the terrestrial background, this inversion would permit the on-board vidicon camera system to view what are now the lower booms. Consequently, performance of this experiment would result in the first estimates of the boom straightness and the thermal gradients across these booms. Additional information on controlling such a large spacecraft array would also be gained.

Gravity-Gradient Pump

By proper phasing of retractions and extensions of the main booms, it is possible to use the gravity-gradient forces to increase the pitch motions of the spacecraft array until a pitch spin is attained. This procedure is quite analogous to a person "pumping up" a playground swing. If a damper boom were not present to complicate the dynamics, it seems quite feasible that one could use this technique to spin up large arrays using only the energy in the gravitational field and the electrical power required to drive the booms in and out. Most current concepts require the expenditure of control gas for the spin-up of such a large array. It seems that the "G-G pump" technique could be a useful one for future applications to large arrays.

SECTION IV

CONCLUSION

Considerable resources have been expended in the development, fabrication, launching, and tracking of approximately a dozen separate spacecraft projects of the type which are passively stabilized about three axes by gravity-gradient forces in orbit. Some of these spacecraft have been designed with the specific purpose of gaining information about such a gravity-gradient control system. To date, only the RAE-I spacecraft has been completely stable in the dynamical sense. In fact, it has remained more stable than predicted in pre-launch simulations by persisting in librational motions that are bounded within ± 4 degrees in amplitude about three-axis equilibrium values ever since attaining steady-state conditions following final deployments on October 8, 1968. The proposed series of experiments will permit, for the first time, detailed investigation of the RAE-I dynamical in-orbit behavior. In addition, data will be obtained on the spacecraft characteristics of this well-stabilized control system under certain adverse conditions. Such observational data, otherwise unobtainable, will improve the general understanding of such passive three-axis gravity-gradient control systems and, in particular, indicate their ability to stabilize asymmetric spacecraft configurations.

However, because of the fact that the RAE-I satellite has been operating in the hostile environment of space since its launch on July 4, 1968, the possibility of an electrical or mechanical failure in a component cannot be overlooked. Such a failure could conceivably thwart the successful completion of one of the proposed dynamics experiments, and, in so doing, result in a permanent modification to the spacecraft configuration. Nonetheless, the continuance of the scientific mission of the RAE-I satellite would not be jeopardized because the upper "Vee" antenna and the dipole antenna would not be affected during the performance of any of the proposed dynamics experiments. It is the upper "Vee" antenna which is of primary importance to the collection of radio astronomy data from celestial sources, and any modification in the configuration of the lower "Vee" antenna would be of minor consequence. In addition, the dipole antenna would continue to gather radio astronomy data throughout the performance of the dynamics experiments, since the dipole antenna is not adversely affected by even large amplitude attitude librational motions. It should also be noted that the damper mechanism itself is a "fail-safe" device. That is, virtually any conceivable electrical or mechanical failure in the clamping solenoid would return the damper to the active state. One further possibility is that the boom retraction mechanism will not function at all after more than two years in the space environment. This would still permit the performance of two of the proposed dynamics experiments, namely, those that involve clamping the damper mechanism.

In conclusion, it would appear highly desirable and timely to undertake in the near future a series of gravity-gradient-related dynamics experiments such as those proposed herein in light of the following facts: (1) the probability of a successful RAE-B lunar mission in the future will be substantially enhanced by the information resulting from the experiments and the associated studies, (2) the experiments and the post-experiment analyses will advance the general understanding of passive three-axis gravity-gradient stabilization control systems, (3) the performance of such dynamics experiments will involve little or no risk to the continuation of the scientific mission of the RAE-I satellite in the post-experiment time frame, and (4) a delay in the initiation of the series of dynamics experiments might necessitate performance of certain critical experiments in the higher risk partial solar occultation phase or, alternatively, until the following full sunlight phase, at which time the spacecraft systems may be of dubious reliability.

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