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ANALYSIS OF SATELLITE DRAG AND SPIN DECAY DATA

by

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1. Introduction

The work reported was begun as an effort to obtain satellite drag and upper atmospheric wind data from a spinning spherical satellite to be launched from the space shuttle scheduled for the STS-11 flight. The satellite was an inflated sphere having high area-to-mass ratio which would result in measurable orbital decay due to aerodynamic drag forces experienced by the satellite in the earth's upper atmosphere. The satellite would also experience a spin decay due to the aerodynamic torque acting to slow the satellite spinning. The original proposal was to develop data analysis procedures to be employed to extract the desired information.

Work was performed concerning the data analysis procedure prior to the STS-11 launch however the major effort was to begin after the data had been obtained. The work performed is reported in Appendix A. Unfortunately, the launch of the inflatable sphere on STS-11 was a failure in that the sphere did not inflate properly and no data was obtained. The emphasis of the work planned under this effort was then changed to develop a proposal for a series of experiments similar to the one originally planned for STS-11. The proposal developed in this effort is reported here as Appendix B.

The work reported in Appendix B was based on information available at the time. More recent information has been obtained to modify the planned effort. This document then reports on the latest plans based on the most recent information. In particular, recently obtained gas surface interaction data at shuttle altitude has caused us to plan on making use of that and similar data in the development of the proposed experiment. Second, the launch technique proposal in Appendix B is considered to be more elaborate and expensive than required. Third, the data acquisition technique proposed in Appendix B is likely not accurate enough to obtain the information desired. It is proposed that a new data acquisition method be studied for application to this effort. Finally, it is proposed that the capability of the proposal experiment be re-evaluated in view of the increased sensitivity of the experiment. That is, the experiment could potentially obtain drag and lift data, atmospheric wind data, and atmospheric density data of an accuracy and time resolution that has never been achieved. This report then addresses these four proposed efforts in the following four sections.

2. Drag Coefficient Updating

Recent results have been obtained by Dr. P. Peters and Dr. J. Gregory on the interaction of atomic oxygen at shuttle altitude with surfaces. This information is the first such measurements of the reflection of atomic oxygen at orbital velocities. The results have direct application to the determination of drag and lift coefficient on objects at shuttle altitude. The information was obtained by Peters and Gregory using a passive instrument called a reflectometer which was flown on Shuttle Flight STS-8. Figure 1 shows the operating principle of the reflectometer in which incident particles are collimated into a sheet beam which reflects off a surface at a fixed angle with respect to the incident direction. The distributed reflected beam is detected via a silvered surface which reacts with the atomic oxygen. The measured distribution is shown in Figure 2 showing that the distribution is partially accomodated. Figure 3 shows a picture of the flight instrument.

It is proposed here that data such as that obtained by Peters and Gregory be carefully analyzed to determine the effect such information has on the prediction of drag coefficient of objects at shuttle altitude. Since, the data currently available is not sufficient to determine the drag coefficient completely it is also proposed that additional flight experiments be planned in which reflectometers are flown having various surfaces and angles of incidence. In addition, it is expected that ground based facilities will be soon be available at Los Alamos and MSFC in which reflection studies can be performed using atomic oxygen beams. Experimentation in these facilities coupled with the shuttle flight data will help develop a accurate experimental base for the prediction of drag coefficients at shuttle altitude.

3. Study of Satellite Launch Technique from the Shuttle

In order to insure that a number of spheres are launched from the shuttle on a regular basis, a launch technique needs to be developed which makes use of the Gets Away Special (GAS) containers or something similar. The advantage of the GAS containers is that they can be readily integrated into a Shuttle payload at relatively low cost. Thus use of the GAS containers will help insure that numerous flight opportunities exist and that the cost of launching the spheres is as low as possible. It is proposed then that a study be made of making use of the GAS containers or similar containers for launching the spheres required in this program. The work will involve first a review of launch techniques which have been utilized or planned to date to determine if a technique may already exist. Then a design will be developed to fit the requirments of the program.

4. Study of Data Acquisition Techniques

It is proposed that optical methods be studied and developed to provide data of the accuracy required for this program. The optical technology which has been used successfully in LAGEOS program appears to be of the accuracy required in this program. The design of the optical reflector at the satellite has become of special interest to those in the Center of Optics at UAH. This group could provide valuable guidance in the development of the optical requirements of the proposed experiment. The ground or shuttle based observations of the satellite using appropriate laser equipment will provide the needed data on real time acceleration rates of the satellite to an accuracy that has not been achieved before. Past drag studies have utilized time averaged data which masks much of the real time flucuation in the atmosphere. The high resolution data obtained in the proposal experiment will require advancement in the data analysis techniques.

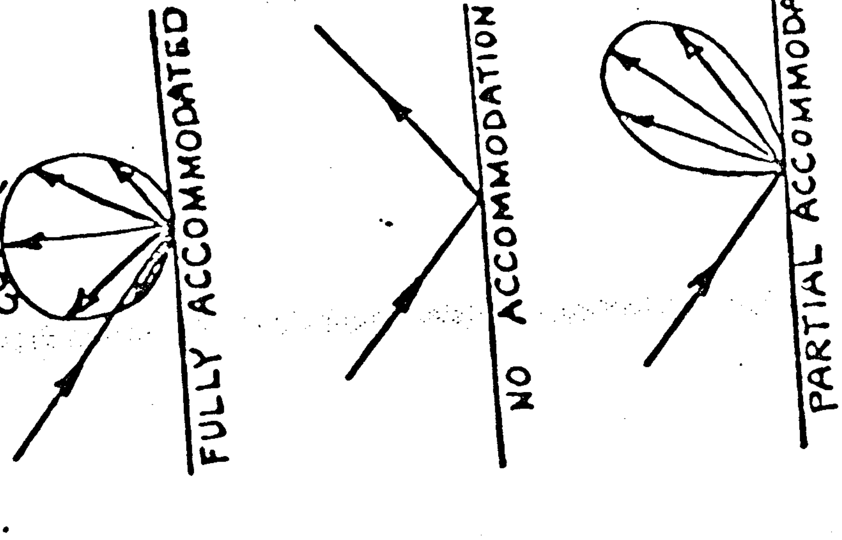
5. Study of Data Analysis Techniques

The data which can potentially be obtained in the proposed experiment will be of an accuracy and time resolution that has never been achieved for satellite drag studies. The data will be rich in information concerning the atmospheric flucuations. High resoultion information should be obtained on wind velocity, wind direction, and density variations. Also, as the satellite enters more dense regions of the atmosphere, the change in aerodynamic characteristics should be detectable. That is, the departure from free molecule flow should be observed as the satellite reaches more dense regions of the atmosphere. Since the free molecule drag coefficient will be well known for these spheres, the data obtained in the near-free molecule region could be of special importance in understanding this aerodynamic region.

6. Summary and Conclusions

In summary, it is proposed that a four point program be initiated to (1) update the current knowledge of drag coefficients at shuttle altitude, (2) develop a design of a cost effective launcher of spheres from the shuttle, (3) develop an optical method of obtaining accelerations from the spheres launched from the shuttle and, (4) develop data analysis techniques to take advantage of the high quality data that can be obtained in the proposed experiments.

It is expected that the UAH support for such an effort would amount to one man year per year for the next four years. This would include the efforts of Dr. G. R. Karr, Dr. J. C. Gregory, and one or two graduate students. Drs. Karr and Gregory will direct the drag coefficient update effort which will include experiments designed for the shuttle and ground based facilities. Later efforts will be directed at the design of the launch system and data acquisition and analysis.



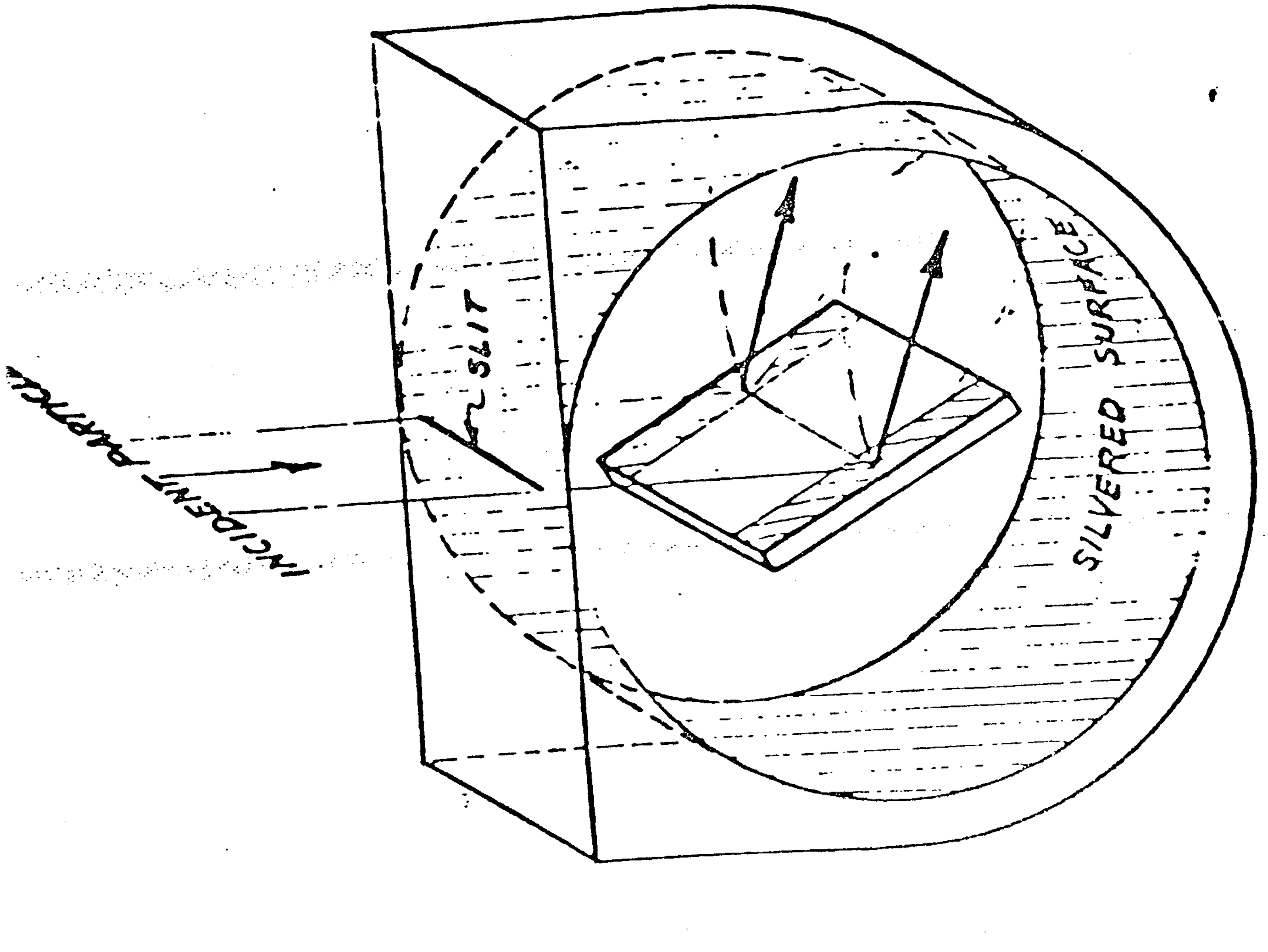


Figure 1 Cutaway View of Reflectometer

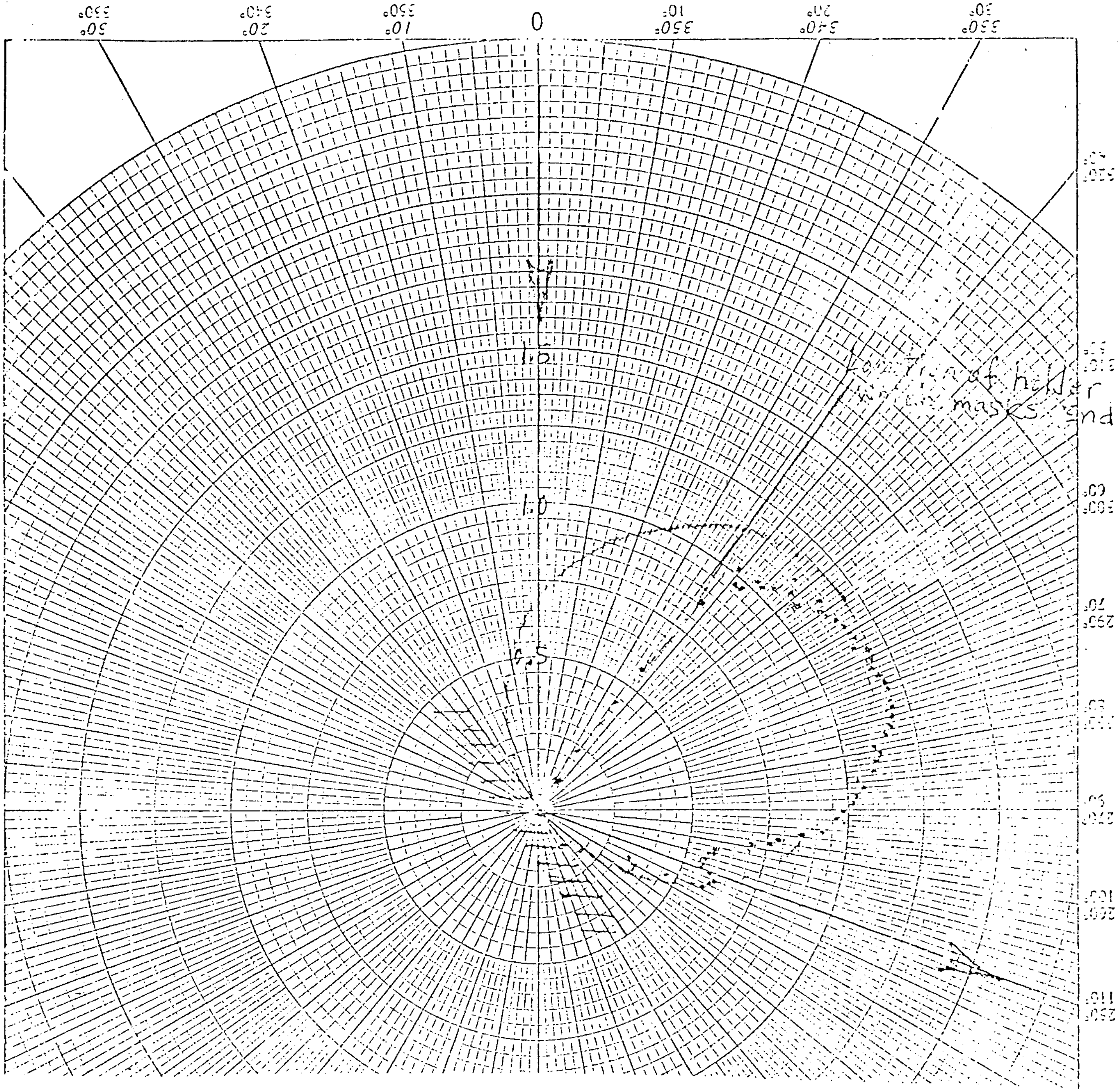


Figure 2. Reflected Distribution of Measured Atomic Oxygen Beam

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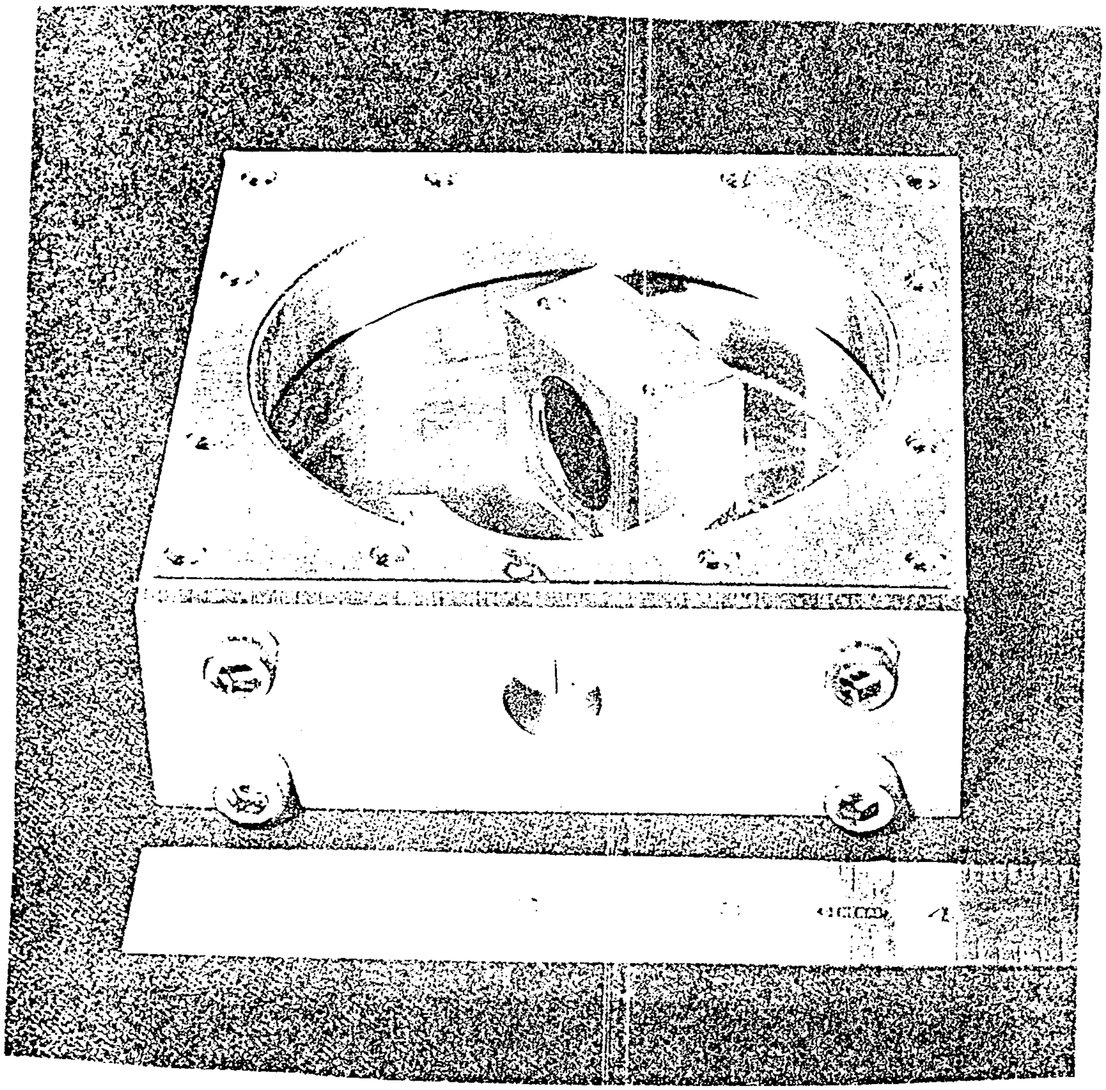

Figure 3. Flight Reflectometer

APPENDIX A

SHORT TERM DENSITY VARIABILITY USING DATA FROM SHUTTLE ORBITER

by

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ABSTRACT

Current analyses of control systems for large space structures have shown that the available models of the earth's upper atmosphere are inadequate for accurately establishing their capability requirements. These control system concepts require instantaneous values of atmospheric density which create the forces that must be neutralized. The density values in current models are averaged in both time and space and are, therefore, not applicable to the current problem studies. An improved knowledge on atmospheric density structure is needed for applications to control systems design for large space structures, i.e., Space Station, Platforms, Space Telescope, Tether Satellite, and for aerodynamic braking for the Orbital Transfer Vehicle. Future space technology will also require more precise knowledge of the aerodynamic properties of the orbiting body. Data from the STS-11 target rendezvous system's test offers at low cost a demonstration that atmospheric density structure can be derived and experimental data can be obtained to verify theoretical rarefied gas aerodynamic models of the simple (spherical) target.

BACKGROUND

JSC has plans to conduct a Shuttle orbiter rendezvous systems and sensors performance test on the STS-11 mission (scheduled January 1984) using a passive target ejected in orbit for this purpose. The target is to be an inflatable, 2-meter-diameter aluminized mylar sphere with ballast to yield a mass of approximately 84 kg. The center of gravity will not be at the center of the sphere. The target will be made to spin at a low rate, 3-10 rpm, at ejection. The target will be tracked from the orbiter by a high precision (Ku-band) radar and star tracker system. Optical (photographic) observations will also be made. For an initial altitude of 160 n miles, this target (satellite) will have an estimated lifetime of 3-5 days.

A. Research Objectives:

It was recognized that the JSC STS-11 orbiter rendezvous test data could provide an excellent opportunity at low cost to derive aerodynamic effects on the target and to derive atmospheric density structure within an orbit. To perform these investigations, an in-house task team and a new initiative project have recently been established. For the ADDS (Atmospheric Drag/Density Studies), the following research objectives have been established.

1. To derive atmospheric density structure within a target (satellite) orbit using the on-orbit radar tracking data.
2. To derive relative drag and lift parameters between a simple (spherical) body and the orbiter in rarefied gas flow.
3. To obtain data on gas-surface interactions in rarefied gas flow from the spin decay using movie film or video recordings.
4. To derive aerodynamics torque effects on the target using movie film or video recordings.

5. To derive mean atmospheric density over the target's orbit at low and near circular earth orbital altitudes using onboard tracking and ground-based tracking data.

6. To study the life decay of a simple (spherical) body using ground-based tracking data.

These studies have important applications in verifying theoretical aerodynamic models. There is a need for improved knowledge of the atmospheric density structure at orbital altitudes for control systems design of large space structures.

To accomplish this work the Systems Dynamics Laboratory of the NASA/MSFC has established a special project entitled "Atmospheric Drag/Density Studies" (ADDS). The ADDS task team members are:

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Formulation of Force Equations

The predominant forces considered for the orbiter and the sphere are aerodynamic drag and gravitation. These lead to the governing equations

$$\ddot{\vec{r}} = \frac{-\mu \vec{r}}{r^3} - \frac{\rho |V| \vec{V}}{2B}$$

The first term on the right is the gravity contribution and the second is the aerodynamic drag. μ is the gravitation constant for the earth. $\vec{r}$ and $\vec{v}$ are the position and velocity vectors, respectively. ρ is the atmospheric density at altitude and $B = m/C_D A$ is the ballistic factor. C_D is the drag coefficient, A is the cross sectional area along the velocity vector and m is the mass.

Equation (I) was used for the parametric studies on ρ and B. Solutions were obtained numerically for the orbiter and the sphere simultaneously. Separation range, range rate and altitude drop, etc. could then be determined. Some of the results are shown in figures 1, 2, and 3. Here the ballistic factor for the orbiter B_0, is taken as 300 kg/m^2 and for the spherical satellite, B_s is 10 kg/m^2. The ballistic factor for the orbiter can vary from 125 to 525 kg/m^2.

Results

Figure 1 is a plot of the range (separation distance)

$$R = (\vec{r}_0^{\,2} - \vec{r}_s^{\,2})^{\frac{1}{2}}$$

vs. time in minutes. $\vec{r}_0$ and $\vec{r}_s$ is the position vector of the orbiter and the sphere respectively.

Figure 2 is a plot of the range rate (separation rate) vs. time in minutes. Curve 2 is the range rate using an oscillating exponential atmosphere with a 25% oscillation about a nominal exponential standard 1962 model atmosphere from 120 to 296 km of the sphere. Curve 1 is the range rate using an exponential atmosphere.

Note the regular variation at the orbital period ~ 90 minutes due to the non-circular orbits. This is a combined gravitation and drag effect since the velocities increase at perigee due to gravity but the atmospheric density increases here due to the lower altitudes.

From the simple formulation of the drag force, it is concluded that the onboard orbiter radar accuracies are sufficient to derive the density structure within the target (satellite) orbit.

Satellite Drag and Torque

At the ejection altitude of the satellite, the aerodynamic flow regime can be classified as "free-molecular" because the mean free path of the gas molecules is large compared to the size of the satellite. In free-molecular flow, the gas molecules can be considered to undergo interaction with the satellite surface resulting in momentum and energy exchange directly with the surface rather than through pressure and shear forces which are due to the interaction between the gas molecules. The interaction of the atmospheric gas molecules with the surface give rise to net drag, lift, and torque on the satellite. These forces and torques are directly proportional to the atmospheric density through equations of the form

$$\text{Drag} = 1/2\ \rho V^2 C_D \bar{A} \qquad (1)$$

$$\text{Lift} = 1/2\ \rho V^2 C_L \bar{A} \qquad (2)$$

$$\text{Torque} = 1/2\ \rho V^2 C_T \bar{A}\bar{r} \qquad (3)$$

where ρ is the atmospheric density, V is the velocity of the satellite with respect to the atmosphere, $\bar{A}$ is a reference area, and $\bar{r}$ is a reference length. The quantities C_D, C_L, C_T are termed the drag coefficient, lift coefficient, and torque coefficient respectively. The force and torque coefficients are a function of the nature of the gas surface interaction. For a sphere, for example, one representation of the gas surface interaction gives the following expression for the drag coefficient

$$C_D = 2 + 4/3\ \alpha_d \sqrt{1-\alpha_T} \qquad (4)$$

where α_d is a parameter concerning the nature of the gas surface intraction. The quantity α_d is termed the "momentum accommodation coefficient" and represents the fraction of incident molecules which are reflected diffusely with the remaining fraction being reflected specularly. The quantity α_T is an energy accommodation coefficient. This model is termed a "Maxwell reflection model" (Figure 3) and is one of a number of gas surface interaction models that could be investigated.

The instantaneous torque acting on a sphere spinning in free molecular flow is a function of the orientation of the satellite spin axes with respect to the orbit plane. Integrated over a circular orbit, the average torque is found to give rise to a spin decay per orbit of the following:

$$\frac{\Delta\Omega}{\Omega} = -\alpha_d \sqrt{1-\alpha_T} \; \frac{15\pi}{64} \; \frac{\rho}{\rho_s} \; \frac{R_0}{R} \; (5 + \cos^2\theta_s) \qquad (5)$$

where θ_s is the angle between the satellite spin axis and the normal to the orbit, is the atmospheric density, ρ_s is the density of the sphere, R_0 is the radius of the orbit, R is the radius of the sphere and Ω is the spin rate of the satellite.

The effect of drag on a circular orbit can be shown to cause a decay in orbital radius per orbit given approximately by

$$\frac{\Delta R_0}{R_0} = -2\pi C_D \frac{\rho R_0}{\rho_s R} = -2\pi \frac{\rho R_0}{\rho_s R} \left(2 + 4/3\, \alpha_d \sqrt{1-\alpha_T}\right) \qquad (6)$$

Equations 5 and 6 form a set of two equations in two unknowns, α_d and ρ, which are solved simultaneously giving

$$\rho = \frac{\rho_s R}{4\pi R_0} \left[\frac{520}{45(5+\cos^2\theta)} \frac{\Delta\Omega}{\Omega} - \frac{\Delta R_0}{R_0} \right] \qquad (7)$$

$$\alpha_d \sqrt{1-\alpha_T} = \left[\frac{-\dfrac{64}{15(5+\cos^2\theta_s)} \dfrac{\Delta\Omega}{\Omega}}{\dfrac{520}{45(5+\cos^2\theta_s)} \dfrac{\Delta\Omega}{\Omega} - \dfrac{\Delta R_0}{R_0}} \right] \qquad (8)$$

The above illustrates in principle the method being proposed. The actual data analysis will be complicated by many factors which will be studied as part of the effort proposed. These factors include:

1. Orbit perturbations caused by effects other than atmospheric drag, such as the earth's oblateness, must be identified and accounted for in the data analysis.

2. The structure of the upper atmosphere must be properly modeled to take into consideration the variation in density and the existence of winds. This will be of particular importance as the satellite decays through regions of the atmosphere for which little data exist.

3. The gyroscopic motions of the spinning satellite must be analyzed to include the effects of non-symmetry and initial alignment of the spin axis.

4. The data to be obtained on the motion of the satellite relative to the shuttle must be carefully analyzed to include the effect of shuttle thrustings and the atmospheric drag and lift forces acting on the shuttle.

5. Since the data to be obtained on the satellite spin decay will not be of the same quality as the drag force data, the accuracy of the determination of the gas surface interaction must be assessed.

RECOMMENDATION FOR NEW RESEARCH

Perform studies for future similar missions. Establish what could be achieved using STS present and future technology with:

a. A new target systems design,

b. An active target,

c. Multiple targets with self-contained tracking,

d. Instrumented satellites, e.g., triaxial accelerometer and mass spectrometer,

e. Near real-time (after one orbit) data reduction for density for space technology operations,

f. And at what cost--consider low cost expendable satellites ejected from the orbiter or a space platform to obtain measurements of atmospheric properties in the 120-300 km altitude range.

The above concepts are not entirely original. Some are contained in NASA CR 61313, "Evaluation of Odyssey-I Orbital Aerodynamic Experiment Package" by W. P. Walters, July 1969. This is a summary report on related studies before the event of the STS.

ACKNOWLEDGMENTS:

Recognition is made to other ADDS team members.

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