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VI.3(G)

The Stanford Relativity Gyroscope Experiment (G): Translation and Orientation Control

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1. NEAR ZERO IN ENGINEERING

The nineteenth-century frontier in engineering was the challenge of bigness. The canals, La Tour Eiffel, and the railroads pushed attention on the limits of what could be achieved in size. It was not until the middle of this century that the advantages of making things small were appreciated. Before then the principle followed in gyroscope design was to overcome the effects of disturbance torques by increasing the momentum, *i.e.,* the size of the gyroscope. But in the 1950's it began to be recognized that a reduction in size of the gyroscope could, with good design, reduce the torques even more than the momentum, and hence actually lead to an improvement in performance as well as the advantages of reduced weight, increased ruggedness, greater stiffness and lower temperature gradients. The philosophy of near zero applies in engineering, too. Here are some examples in the pursuit of near zero g and near zero pointing errors.

A low g environment is essential for gyroscopes to perform the general relativity test. Space is a step in that direction. Yet small as the drag forces on the satellite may be, they still produce an acceleration environment of say 10^{-8} g due to radiation pressure for the instruments, which is large compared to the 10^{-10} g environment needed to reach the milliarc-sec performance level required. The pointing requirement for the experiment is also challenging. The telescope has to be kept within its 50 milliarc-sec linear range, which was considered well beyond the state of the art when the experiment was conceived.

2. TRANSLATION

At a conference held at Stanford in 1961 to explore the use of space for tests of relativity, Ben Lange independently conceived the idea of a drag-free satellite [1], first suggested by George Pugh [2] as indicated in section (A)2.2. An internal unsupported proof mass within a satellite would be shielded by the satellite from external disturbances. The satellite could be made to follow the proof mass by applying control authority through a propulsion system referenced to a measurement of the position of the satellite relative to this undisturbed proof mass. Hence the satellite would have an undisturbed trajectory as well. Lange did the first definitive error analysis which made it possible to evaluate the concept applied to a number of different experiments—some in which freedom from disturbance to the orbit was important, *e.g.*, in geodesy, and others in which the low g environment produced in the satellite was the purpose, *e.g.*, the relativity gyroscope. Lange [1] and his students developed the concept and built an air-bearing table simulator which permitted the evaluation of the system including its nonlinearities.

In 1968 Stanford began a collaboration with the Johns Hopkins Applied Physics Laboratory which culminated in 1972 with the flight of the TRIAD satellite of the Transit Navigation System (figure 1). Navigation satellites must broadcast their position in orbit in order for navigators to know their position with respect to the earth as well as with respect to the satellite. The uncertainties in drag limited the validity of the on-board ephemeris to about 12 hours. By canceling the drag, the residual acceleration of 5×10^{-12} g was made more than two orders of magnitude smaller than the drag uncertainty. The principal limitation is the mass attraction of the satellite on the proof mass. Approaching zero in this sense gets difficult below 10^{-10} g. Electric charge, magnetic gradients and other disturbances influence the engineering, but not as strongly. With drag-free control (DISCOS) the ephemeris updates in the transit satellite could be made as infrequently as every two weeks. The year and one-half of successful operation [3] until propellant was depleted provided confidence in the technology for making subsequent Transit Satellites drag-free.

The success of DISCOS and of the laboratory simulator with rotation gave a firm basis for design applied to the relativity experiment. To provide static stability the bandwidth of the control needs only to be larger than

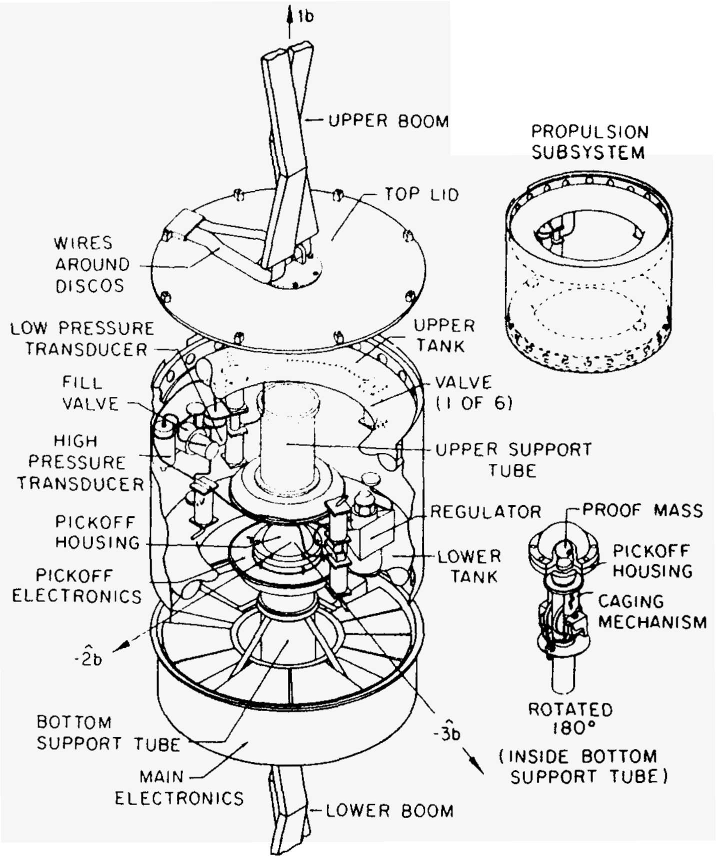

FIGURE 1. Disturbance compensation system (DISCOS) on TRIAD.

the rotation rate. Thus a roll of the relativity experiment about the line of sight to the star to separate the relativity information from the low frequency biases and noise in the instruments sets an easily achieved lower limit for the translation control system bandwidth at 0.01 rad/sec.

Translation control requires propulsion. The propellant was clearly available from the boiloff gas of the helium, once we recognized that if not utilized this gas would be the principal disturbance in both attitude and translation.

3. ORIENTATION

The precision pointing requirements to stay within the linear range of the telescope must be met in the presence of any flexibility of the vehicle, atmospheric drag torques which are not well understood, and possibly thruster noise rising from the very low Reynolds number associated with the helium flow through the thruster nozzles. In the original design for a dewar which would provide refrigeration for a year or longer, we had concluded that a very compliant coupling between the vehicle and the experiment package was necessary to ensure adequate thermal insulation. This led to a very low natural frequency between the experiment package and the satellite. The thrusters being on the outside of the satellite were remote from and only loosely connected with the angle sensors, *i.e.*, the telescope and gyroscope inside the dewar. We studied several possible solutions to the consequent stability problems. The best choice proved to be to add an inner actuator which controlled the experiment package with respect to the dewar.

An inner actuator provides a way of precisely pointing the experiment package in spite of small changes in the orientation of the rest of the vehicle, maintaining high bandwidth in pointing the experiment package while allowing a much more relaxed requirement for the rest of the satellite. Besides getting around the stability problems associated with a very elastic vehicle with noncolocated sensor and actuator, this approach with an inner actuator provides a high degree of isolation from external disturbances. Thus variation in atmospheric drag would not have to be understood well, and even thruster noise of more than 10 percent would be tolerable.

Impressive as these advantages of the inner actuator are, it so happens that in the current design of the experiment the inner actuator is not needed. In the first place, work by John Bull [4] and Jeng-Heng Chen [5]

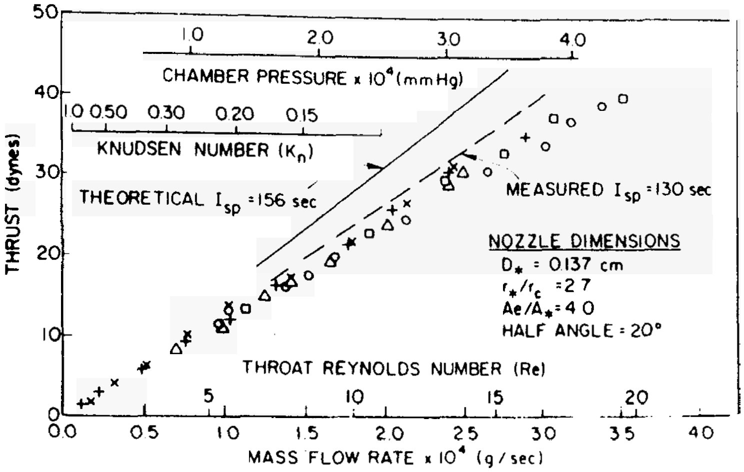

FIGURE 2. Helium specific impulse. Helium specific impulse was experimentally measured to be 130 seconds, giving a maximum thrust of 70 dynes for nominal mass flow.

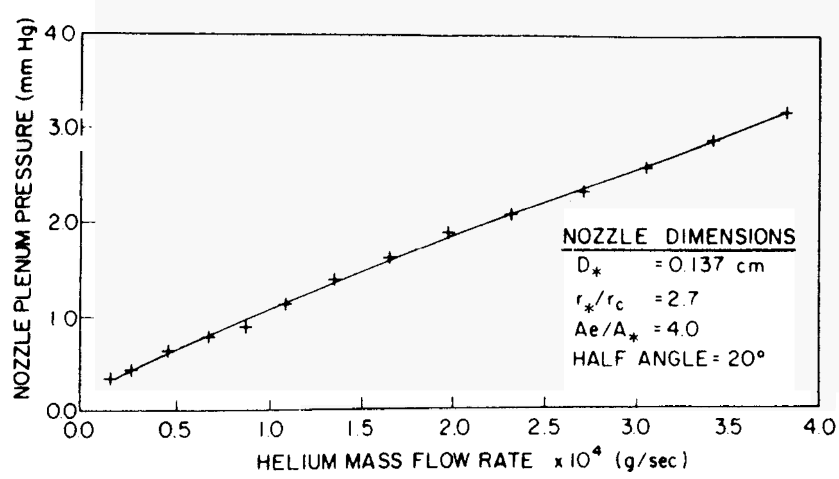

FIGURE 3. Nozzle plenum pressure *versus* helium mass flow

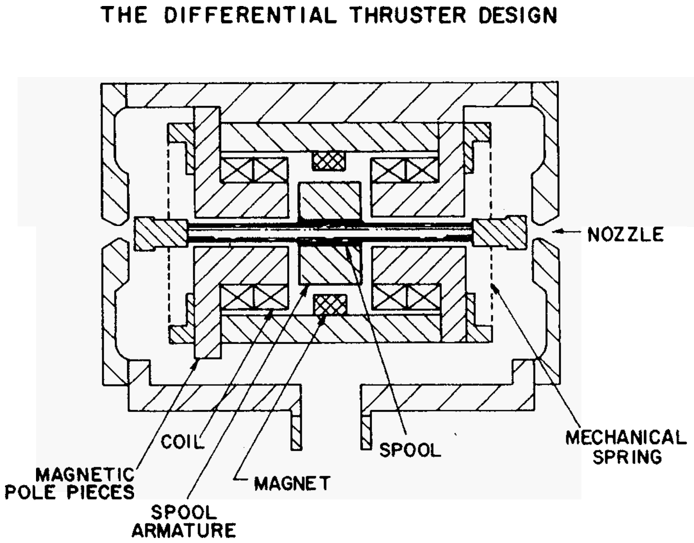

FIGURE 4. Cross section of magnetically actuated differential thruster.

evaluating the thrusters has shown that thruster noise is completely negligible. The only fluctuations they could detect were traceable to uneven pumping capability in the vacuum chambers used in evaluating the thrusters, a condition that would not exist in space. Second, although the variations in drag on the satellite are still not well understood [6,7], the dewar now being designed for the experiment has much greater stiffness

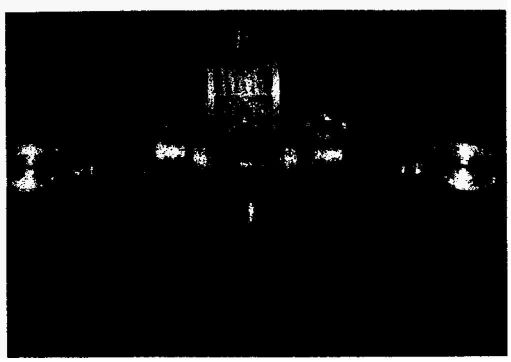

FIGURE 5. "Exploded" view of piece parts for disassembled thruster

between inside and outside than we had originally supposed (35 Hz resonant frequency as compared with about 1 Hz), and the increased stiffness solves the stability problem. Even if one were to assume that high-frequency fluctuations in drag occur, with amplitude as much as 10% of the average drag and frequency as high as 0.1 rad/sec, it would still be possible to achieve acceptable pointing performance without the benefit of the inner actuator. Removing the inner actuator greatly simplifies the design of the cryogenic portion of the experiment.

One might ask whether the helium gas is an appropriate means for applying control. A possible alternative would be to use momentum exchange devices. However, such devices must work in combination with torquers (magnetic or other) to provide a means for getting rid of angular momentum accumulated in fighting off the external torques. Furthermore, momentum storage devices are a possible source of vibration disturbance to the experiment package. Accordingly, we decided that it would be preferable to maintain an adequate altitude so the helium thrusters alone could provide the necessary control. Since the center-of-pressure/mass-center offset is always less than the moment arms provided to the thrusters, most of the gas is used for translation control rather than for pointing control. This in turn means that during an unusually high transient in atmospheric density (due to a solar storm, for example) one may if one wishes momentarily relax the translation control and still have enough authority to perform attitude control alone.

Most satellites which require propulsion do not have a built-in continuously flowing source of propellant. The emphasis is on efficient use and assurance that thrusters are off when they are not needed. On-off valves developed as the best solution for these requirements, and it took a concentrated effort to change our mindset to embrace the advantages of an open

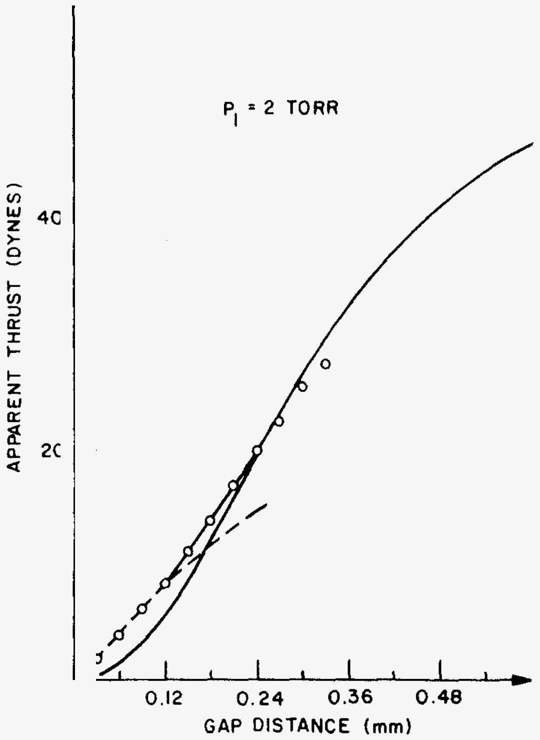

FIGURE 6. Apparent thrust *versus* gap distance for a fixed thruster plenum pressure p_1 for one nozzle. The data are indicated by circles. The solid and dashed lines were obtained from the models.

center valve arrangement which is never closed but which only modulates differentially the relative amount of flow going out of each of two opposed thrusters.

The development work was started by Bull [4], who established the specific impulse of helium at a pressure of 3 torr (figures 2 and 3) and did an early design of a thruster. The work was continued by Jeng-Heng Chen [5] in cooperation with Russell Hacker, who designed a compact valve with a linear spring and very efficient differential solenoid (figures 4 and 5). Chen analyzed the flow characteristics from the dewar to the thruster including regions of continuum flow, slip flow, and finally free molecular flow in the nozzle itself, as shown in figure 6.

With proper choice of the geometry of the thruster, the net flow through a differential thruster can be kept constant in spite of the movement of a spool to unbalance the flow to the two nozzles (figure 7). If the nominal gap

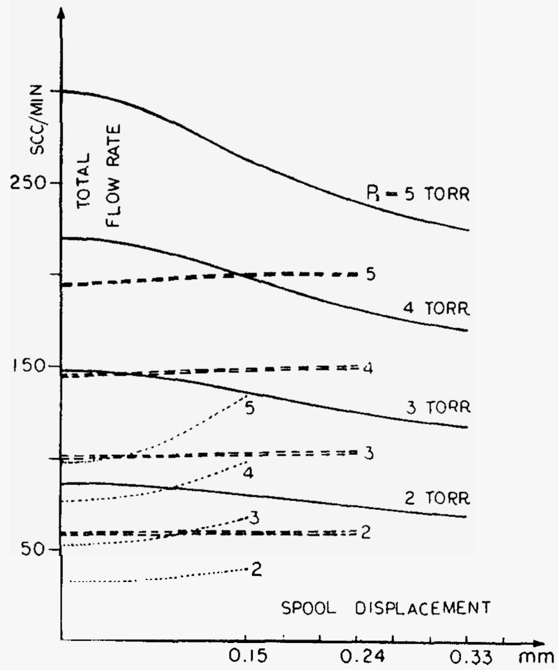

FIGURE 7. Total flow rate through the thruster *versus* spool displacement for different thruster plenum pressure p_1. The flow rate is not sensitive to spool movement for a nominal gap distance of 0.24 mm.

between the spool and the thruster is too great then the flow is essentially constant in one of the nozzles when it is shut off in the other. Alternatively, when the spacing is too small, the flow characteristic is dominated by the valve spool restriction. Between these extremes one can choose a spacing such that the flow resistance in the throat of the nozzle and the spool restriction are balanced, and increased flow on one side is equal to decreased flow on the other. This ensures that there are no temperature fluctuations inside the dewar due to thruster activity.

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