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VERY LOW ALTITUDE DRAG-FREE SATELLITES

Triad demonstrated the practicality of the drag-free satellite subsystem DISCOS, which provided control propulsion to precisely counteract the effects of drag and solar radiation pressure, and results in a pure ballistic trajectory. The advent of Space Shuttle, which is ideally suited to launching extremely heavy satellites into very low altitude orbits, now makes attractive the use of DISCOS to carry out space missions of increasing capability and sophistication.

The geometric advantages of high altitude — even synchronous — satellites, particularly for communications relay, are widely recognized. It is less well recognized that there are frequently good reasons for orbiting satellites at altitudes as low as practicable. In this article we discuss the use and advantages of the drag-free technique for substantially lowering the altitude of a satellite to the minimum that can be considered practicable.

THE USE OF LOW ALTITUDE SATELLITES

There are two quite different reasons for using very low altitude satellites. One is to minimize launch costs; other things being equal, the lowest launch costs result from the lowest practicable altitude. Phrased differently, with a given launch vehicle the maximum satellite weight results from the choice of the lowest practicable altitude. It was for this reason that the early manned suborbital and orbital flights were at very low altitudes. The same consideration led to the choice of a very low altitude for Skylab. The Small Astronomy Satellites (SAS) were put in very low orbits to maximize the weight launchable by the least costly launch vehicle — the Scout. These considerations will be even more compelling in the future with Space Shuttle as the primary launch vehicle. Shuttle is ideally suited to putting very large satellites into orbits up to about 320 km at a low cost per pound. High orbits achieved from Shuttle, no matter how small the satellite, require additional upper stages, with a considerable increase in launch costs.

The second reason for placing satellites in extremely low orbits is that the observations to be made by the satellites concern the earth's surface or things in close proximity to the earth's surface (e.g., the atmosphere or the earth's crust). Thus the Air Force's classified surveillance satellites, which are concerned with photographic observation of the earth's surface, are flown at very low altitudes.

Primary contributions to the current knowledge of the earth's gravity field were obtained by observation of the motion of satellites at altitudes below about 950 km. A still higher order of detail has been obtained, at least over the ocean areas, by the use of radar altimetry from Geos-3, a low altitude satellite. It is generally recognized that further progress in determining the higher-order (short wavelength) gravity field terms requires the observation of satellites at the lowest practicable altitude. The reason for this is that these higher order terms arise from inhomogeneities in density in or near the crust, and hence their gravitational effect on the satellite falls off with the inverse square of the satellite altitude. Similarly, improved magnetic field measurements require extremely low altitude orbits to identify the presence of magnetic anomalies that are crustal in origin (e.g., from magnetic ore bodies).

The recent short-lived Seasat showed that a wealth of observational data concerning the ocean surface, sea state, wind velocity, surface temperature, etc. could be obtained from low altitude satellites. Lowering the altitude of such a satellite improves the resolution of the instrument by increasing the signal strength and reducing the footprint for a given power and antenna size.

Direct observation or remote sampling of the atmosphere, whether for meteorological purposes, environmental monitoring (pollutants, ozone), or atmospheric science, is clearly aided by the use of very low altitude satellites, opening up the possibility of *in situ* measurements in some cases. By measuring along the line of sight between two very low altitude satellites in the same orbit but displaced in phase, the measurement can be brought down to sea level. Finally the use of a phase-displaced pair of satellites opens up interesting possibilities for stereoscopic observation of clouds and surface features.

Table 1 summarizes some of the potential applications for satellites at very low altitudes.

Table 1

APPLICATIONS OF VERY LOW ALTITUDE SATELLITES

Discipline	*Some Objectives*
Geodesy	Improved gravity field model
	Refined gravity anomaly measurement
Oceanography	Sea surface topography
Geomagnetism	Improved geomagnetic field model
	Refined magnetic anomaly measurement
	Updated and improved magnetic charts
Aeronomy	Upper atmosphere and ionosphere density and composition
	Ozone measurements (drag mechanisms)
Meteorology	Cloud height measurements
Geology	Stereoscopic photography

HOW LOW IS PRACTICABLE?

Generally, the lowest practicable altitude for a satellite is determined by atmospheric drag effects. Depending on its ballistic coefficient, a satellite at an altitude below 200 km is doomed to reenter and terminate its mission within a few days. In fact, reconnaissance satellites at very low altitudes require occasional applications of thrust to prevent premature reentry.

Assuming that reentry is avoided either by the choice of a sufficiently high altitude or the application of thrusting, the next problem that seriously complicates the use of low altitude satellites is precision tracking. Generally speaking, the very considerations that suggested the use of low altitude also require precision tracking of the satellite. In mapping the magnetic field, it does little good to improve the accuracy of determination of the magnetic field vector unless the position in space at which the measurement was made is known with corresponding accuracy. Similar arguments apply to almost all the suggested applications of low altitude satellites. The desired data accuracy requires the highest possible tracking accuracy.

Unfortunately, very low altitude satellites are particularly difficult to track with precision. The current knowledge of the gravity field of the earth is quite adequate for superb tracking (to a few meters) of satellites as low as 1000 km. But the still undetermined higher order (short wavelength) terms of the gravity field have an increasing effect on orbit determination as the orbit altitude is reduced. More importantly, the effect of drag on satellite position increases very markedly as the altitude is reduced. The satellites that are routinely tracked with the greatest precision today are those constituting the Navy Navigation Satellite System. These satellites continuously announce their current position based on a 12 hour prediction. Even at their relatively high altitude of 1000 km, the error in the 12 hour prediction is dominated by the uncertainty in drag prediction. The reason for this is that current drag models are quite inadequate for precision tracking. Both the composition and density of the high altitude atmosphere are uncertain and vary markedly with time of day, recent solar activity, and other variables.

Even the mechanism of drag at certain altitudes is uncertain. If the altitude is so low that intermittent thrust is required to prevent premature reentry (as is the case with reconnaissance satellites), the uncertainty of these impulses further complicates the determination of accurate tracking. Thus, up to now the lowest practicable altitude for a satellite has almost always been the lowest altitude at which it was possible to meet the tracking accuracy required by the mission.

DISCOS — THE DRAG-FREE CONCEPT

A design concept that completely eliminates the difficulties caused by drag and makeup impulses in the tracking of low altitude satellites actually dates from the pre-Sputnik era; it was originally suggested for application to ballistic missiles rather than satellites. It appears to have been invented independently by a number of people in the 1950's but most vigorously pursued by Stanford University. It was first demonstrated in a spacecraft called Triad (Fig. 1), which was designed and built by the APL Space Department, with substantial assistance from the Aeronautics and Astronautics Department of Stanford University. APL has used the name DISCOS (for DIsturbance COmpensation System) rather than "drag-free" since this device provides automatic and precise compensation for all external (nongravitational) forces, including radiation pressure, and not just drag. The DISCOS device is illustrated in Fig. 2.

A small proof mass is located in a hollow cavity within the satellite. Means are provided for detecting the position of the proof mass within the cavity; in the Triad satellite this measurement was made by capacitive coupling. Six jets supply both positive and negative thrust impulses along three orthogonal axes. Figure 2 shows only that single axis along which drag acts. The proof mass is caged during launch and uncaged after the satellite achieves orbit. At this point, external forces (e.g., drag acting on the satellite) apply a backward force, but the proof mass, being housed in a solid walled cavity, is completely shielded from this force. Hence the satellite moves backward relative to the proof mass. This motion is sensed and the error signal is used to fire the aft thruster, thus providing a forward force that partially compensates for the drag force. The closed-

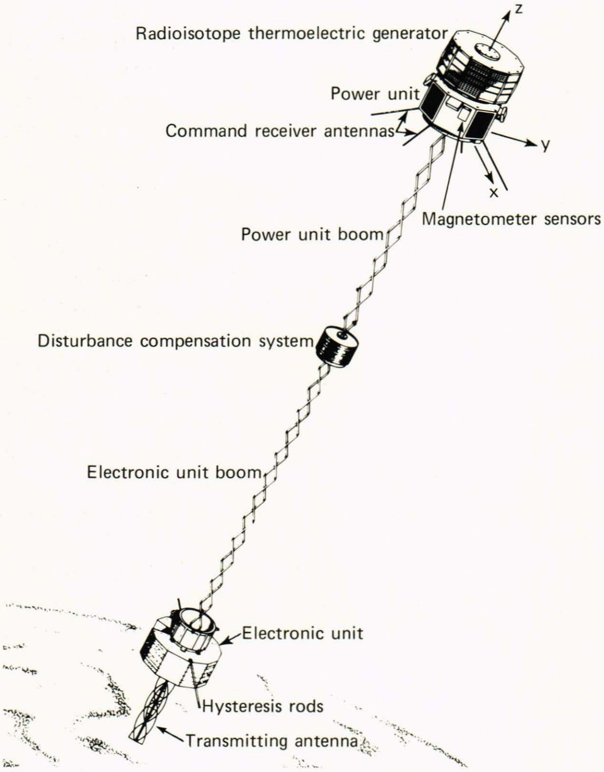

Fig. 1—Triad oriented by gravity gradient.

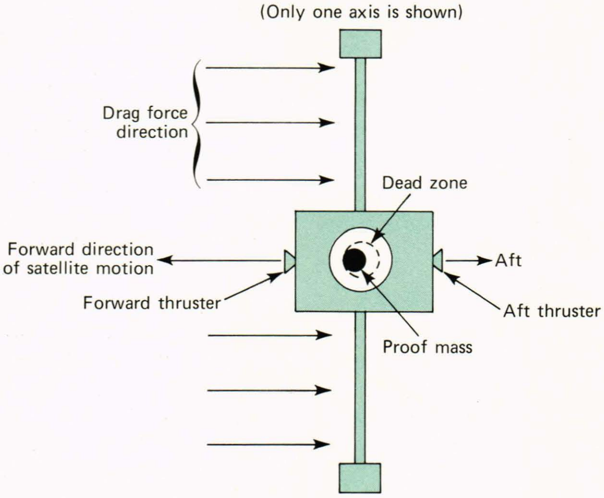

Fig. 2—Illustration of DISCOS as used on the Triad satellite.

loop control system that relates proof mass position to thruster firing is essentially a simple collision-avoidance system that prevents the proof mass from reaching the walls of the cavity.

To see that the system will automatically meter the applied thrust impulses and precisely counter the applied external forces, it is only necessary to consider the behavior of the proof mass. Because the proof mass never reaches the cavity walls, no force is applied to the proof mass by the main satellite. Being shielded from external forces (drag and radiation pressure), the proof mass follows a trajectory determined by the only force from which it cannot be shielded — the gravity field. Thus the proof mass follows a true ballistic trajectory. But the collision-avoidance servo system constrains the main satellite to follow precisely the same trajectory. Thus the simple collision-avoidance system results in metering the thrust impulses to precisely compensate external disturbing forces. In Triad the thrust impulses were of a fixed level and duration, with metering accomplished by varying the interval between the standard impulses. This approach makes it possible to operate over a very large dynamic range of disturbing forces.

The Triad satellite was launched in September 1972. Figure 3 shows a typical 12 min period of operation with respect to the along-track axis. Between thruster impulses there is a continuous force acting on the satellite but not on the proof mass, resulting in a parabolic relative displacement curve. The thruster was set to fire when the relative displacement reached 1 mm (a 1 mm dead band). The proof mass remained in the dead band throughout 18 months of operation until the fuel (cold gas) was exhausted.

Of course the compensation of external forces is not quite perfect. There is a small bias force, principally due to the gravitational attraction of the main satellite on the proof mass. This bias can be determined by comparing long-term prediction of along-track position with the position actually achieved. For the Triad satellite, along-track position showed an error of approximately 75 m in a 53 day prediction. This corresponds to an along-track bias force of 5.5×10^{-12} g (see Fig. 4). However, this does not represent the ultimate attainable accuracy. In fact it is easy to design a system for applying forces of this level on the proof mass (e.g., with magnetic or electrostatic forces) and, by command, canceling the bias force once it is calibrated in orbit. Thus there is literally no limit to the accuracy achievable with DISCOS, and the lowest practicable altitude is no longer set by tracking accuracy requirements.

DISCOS WITH COMMANDABLE BIAS

A DISCOS-type satellite having a commandable bias can be used not only to cancel the inevitable small bias observed in orbit but, by providing for larger bias capability, to provide a satellite that can be purposely accelerated or decelerated with respect to a drag-free orbit and thus be purposely driven into a higher or lower orbit as desired. If two satellites with DISCOS are placed together in identical orbits (e.g., by

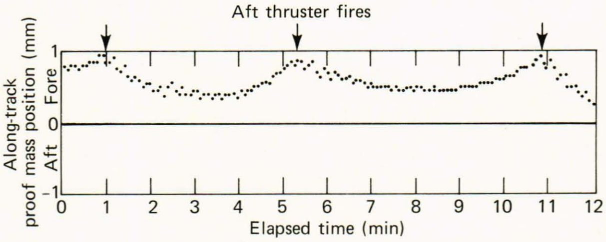

Fig. 3—DISCOS proof mass motion.

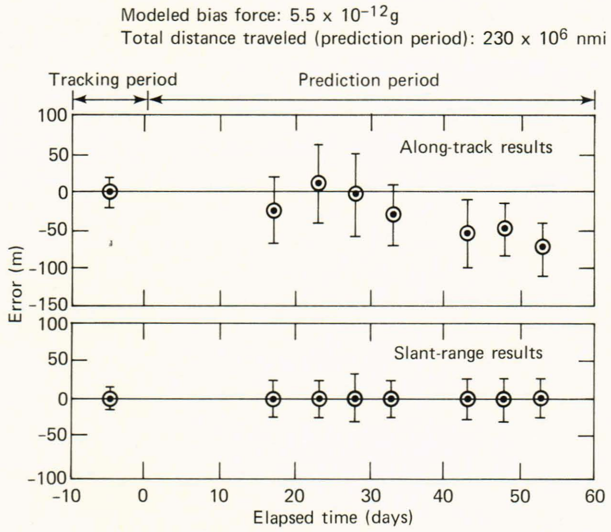

Fig. 4—Tracking results from Triad satellite using DISCOS.

Shuttle), an accelerating bias followed by a decelerating bias to one of the two satellites will return the biased satellite to its original orbit with a change in phase. Thus, a pair of satellites in the same orbit can have their phase difference (spacing) altered at will during the mission. This is very useful for many scientific missions such as aeronomy. Varying the phase between a pair of co-orbiting satellites makes it possible to vary the altitude at which the atmosphere is viewed along the line of sight (Fig. 5). Varying the relative phase is particularly important for the so-called low-low approach to dynamic geodesy. APL is currently analyzing the low-low approach to geodesy under a NASA contract, but enough work has been done to make it clear that the ability to vary in a controlled manner the orbit spacing of two DISCOS-type satellites is very useful in distinguishing gravity terms of different wavelengths.

THE SHUTTLE AND LOW ALTITUDE DISCOS

In the pre-Shuttle era, the use of DISCOS to make possible a great reduction in the practicable altitude of low altitude satellites was not considered, simply because of the rather large propellant weights necessary to counteract the substantial drag forces and the corresponding very high launch costs with available boosters. But Shuttle provides a totally changed economic base. It is ideally suited to carry large weights into low orbits economically.

With DISCOS making possible accurate tracking at any altitude, the lowest practicable altitude would appear to be set by thermal considerations. Figure 6 shows as a function of altitude the stagnation temperature that would have to be withstood by a heat shield for prolonged periods. It appears that an altitude of 125 km would result in stagnation temperatures of about 300°C at the air density resulting from solar maximum. It might not be too difficult to design an appropriate heat shield to make 125 km practicable. Increasing the altitude to 150 km reduces this temperature to the neighborhood of a relatively comfortable 100°C, which is unquestionably practicable. Thus the feasibility of a DISCOS is considered for operation at the low altitude limits of 125 to 150 km. From Figs. 7 and 8 it is seen that the propellant weight (hydrazine) lies in the range of 200 to 1000 kg per month per square meter of satellite frontal cross

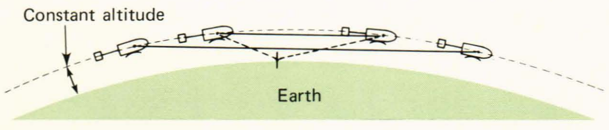

Fig. 5—Line-of-sight and reflection communication geometry.

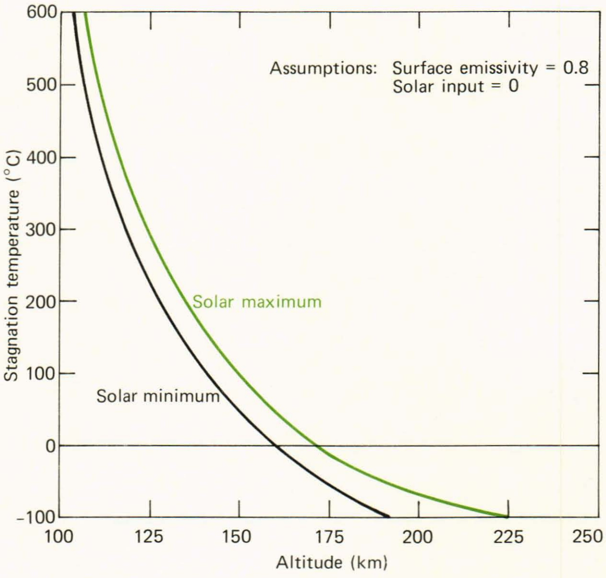

Fig. 6—Effect of altitude on stagnation temperature.

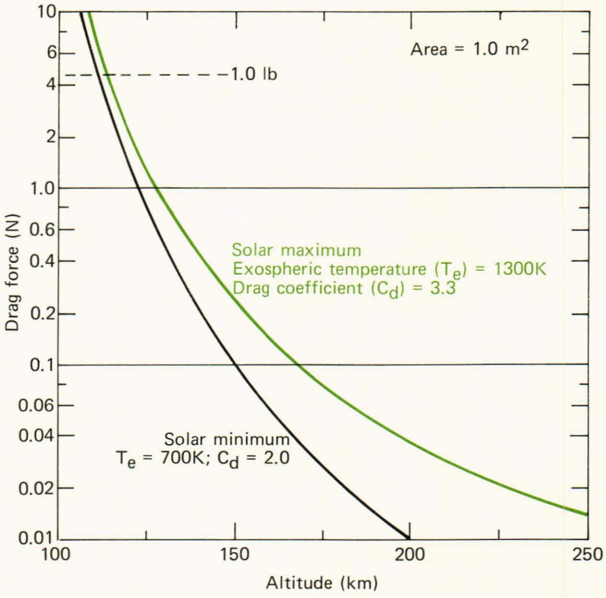

Fig. 7—Drag force for satellites at very low altitudes.

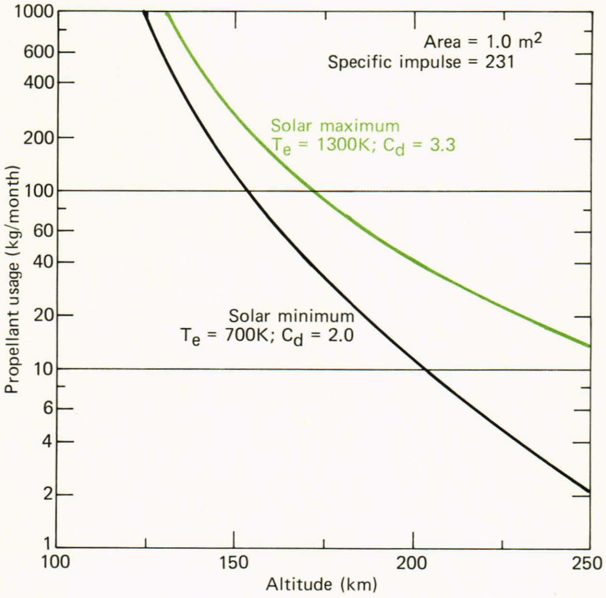

Fig. 8—Propellant usage for satellites at very low altitude.

section. Selection of a preferred configuration would, of course, require a detailed design study that we have not yet carried out, but a conceptual design of a Shuttle-compatible low altitude DISCOS satellite clearly indicates its feasibility.

Attitude stabilization has been chosen to be earth-pointing because the primary reason for using a very low altitude orbit is observation of the earth or something closely tied to the earth (e.g., the magnetic field). However, gravity gradient stabilization, which is frequently preferred for earth-pointing satellites, has not been adopted because it usually results in a high drag configuration. Instead we assume the type of momentum wheel stabilization used in the earth-pointing mode of SAS-3 and adopted for Magsat. This allows the spacecraft to be flown horizontally to achieve minimum drag.

The conceptual design (Fig. 9) shows two fuel tanks symmetrically displaced with respect to the DISCOS sensor. This makes it possible for the DISCOS sensor to remain at the center of gravity of the spacecraft as the fuel is used in equal quantities from each tank. Provision is made for an altimeter dish to provide a follow-on for Seasat and for an extendable boom to carry instruments (such as magnetometers) that must be distant from the main spacecraft (follow-on Magsat mission). The configuration shown has provision for 2000 kg of hydrazine for 2½ months of performance at 125 km altitude or 20 months at 150 km. The spacecraft could also be designed to permit refueling from later Shuttle flights. As seen in Figs. 10 and 11, a pair of such satellites would constitute only a modest fraction of a Shuttle payload.

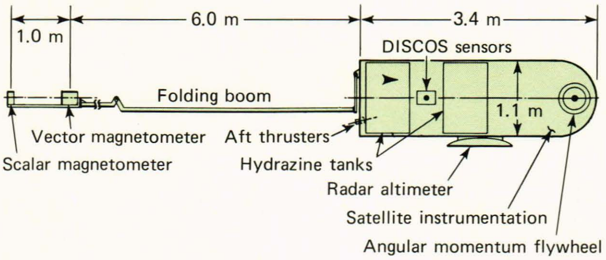

Fig. 9—Conceptual design of low altitude DISCOS satellite.

CONCLUSION

The Shuttle capability appears to open up the possibility of orbiting DISCOS (drag-free) satellites that can operate at extremely low altitudes (as low as thermal considerations permit). Such satellites have many applications and can perform many scientific missions. The possibilities appear sufficiently attractive to warrant a more detailed design and cost study would seem to be warranted so that this specific alternative can be considered in future mission planning.

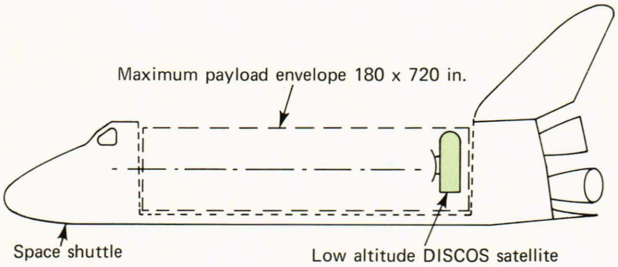

Fig. 10.—Shuttle launch configuration for low altitude DISCOS satellite.

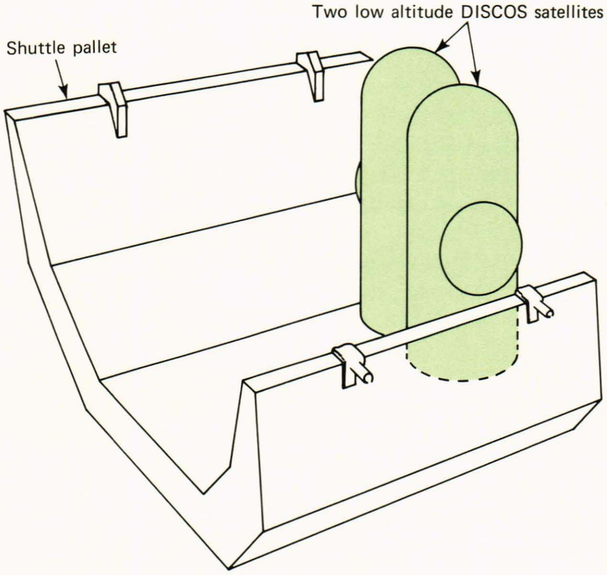

Fig. 11—DISCOS on Shuttle pallet.