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Apr 1st, 8:00 AM

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# THE EXPENDABLE VEHICLE AND SATELLITE DEVELOPMENT

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## ABSTRACT

The role of the expendable launch vehicle (ELV) in the development of satellite systems is explored. Essentially an outgrowth of the ballistic missile which was first used for military applications 4 decades ago, the ELV is used for a wide spectrum of peacetime applications including the launching of earth orbiting satellites which provide inter- and intra-national communications, large area photography for weather analysis and prediction, and high resolution imagery capability for earth resources evaluation. The launch constraints and considerations which the satellite designer must address are reviewed.

A survey of three payloads developed by Hughes Aircraft Company for launch by expendable boosters is included. The HS 376 series of communications satellites are capable of transmitting digital data, digital and analog voice, and television in a typical geosynchronous orbit application. The Geostationary Meteorological Satellite (GMS) records and transmits visual and IR images of the entire earth. The multispectral scanner (MSS) is an imagery system used aboard the low altitude LANDSAT spacecraft which creates images in four spectral bands for evaluation of earth resources.

## INTRODUCTION

The development of advanced electronics and materials technology since an expendable launch vehicle successfully placed a satellite into earth orbit over 2 decades ago, has given rise to a vast array of spacecraft missions designed to benefit mankind. The objectives of these peaceful missions fall into two general categories: science exploration and earth applications. Scientific missions deal with the uncovering of new knowledge of the earth and its environment, the solar system, and the stars that cannot be obtained via earth-bound instruments. Earth applications

missions are those which avail themselves of the satellite's stationary or sweeping view of the earth to economically get a global look at portions of, or the entire, earth's surface. Definite advantages are thus afforded for vital earth tasks such as: communications of wideband information via high frequency line-of-sight radio links, large area photographic observations applicable to meteorology, high resolution photography for assessment of visible earth resources, and navigation aid for aircraft and ships.

It is possible to define any of the above missions in terms of a generic spacecraft configuration, as depicted in Figure 1, which consists of a basic spacecraft bus and mission payload. The spacecraft bus functions to: 1) establish and maintain a desired orbit and attitude following insertion into an approximate orbit by the expendable launch vehicle, 2) command and control the spacecraft and retrieve bus status and payload data via radio link, and 3) provide power, thermal control, and mechanical support for the payload.

Communications payloads typically consist of any up- and downlink radio system wherein wideband information transmitted via radio waves from an earth terminal is received, amplified, and routed to a distant earth terminal. There it enters into the local ground communication network. Information transfer occurs in near real time. Payloads for non-communications type spacecraft receive imaging or field/particles information and transmit this data to mission control. This information may be stored on board the spacecraft bus and transmitted at an appropriate time.

The expendable launch vehicle (ELV) is a key element in the design evolution of every spacecraft system. It dictates the shape and volume within which the spacecraft must fit and the maximum allowable weight which can be lofted into the desired trajectory. The acoustic noise and mechanical vibration envi-

ronment produced by the launch vehicle largely establishes the design criteria for the spacecraft structure.

This paper is confined to the earth orbiting satellite and its interplay with the expendable launch vehicle. Due to its broad use and application, the geosynchronous orbiting satellite mission will be used as an example in developing the role of the ELV and its impact on the spacecraft design. The discussion and methodology, however, can be easily extended to nongeosynchronous missions. A survey of three satellites is provided in the hope that the reader will develop an appreciation for the wide range of applications afforded by satellite technology.

## LAUNCH VEHICLE INTERFACES

The mechanical interface between the spacecraft and the launch vehicle represents the single most important constraint on the spacecraft design. The interface is depicted for a three stage Delta launch vehicle in Figure 2. For every launch vehicle and fairing, a payload dynamic envelope is defined by the launch vehicle supplier. The dynamic envelope is the volume in the fairing within which the dynamic motions of the spacecraft must be contained while the fairing is attached during the boost phase. The launch vehicle supplier must calculate the maximum excursions of the fairing in order to define this volume. Snubbers against the fairing may be required to hold these excursions to acceptable levels. Various windows, some removable, are required in the fairing for access to and inspection of the spacecraft. The spacecraft designer must use the launch vehicle dynamics flight environment to calculate the dynamic motions of the spacecraft.

The importance of understanding this interface can not be emphasized strongly enough. It relates, for example, directly to the allowable solar panel area of the spacecraft and hence, its power-producing capability. Available power is directly related to system performance for many mission payloads. The designer must be aware at the inception of the design process whether or not deployments of antennas, solar panels, or scientific instruments are required to mitigate the size and shape constraints imposed by the launch vehicle payload envelope.

A payload attach fitting (PAF) attaches the spacecraft to the propulsive third stage, depicted as a solid rocket motor for the Delta application. The PAF also provides a platform for mounting the electrical, mechanical, and ordnance equipment needed for third stage operation. These include a telemetry subsystem, a sequencing subsystem, and the spacecraft separation system. An electrical

harness not only ties together these PAF subsystems, but provides the flow of power and signal transfer between the ground and the spacecraft during prelaunch checkout.

Certain satellite missions require spin stabilization during operation subsequent to separation of the spacecraft from the launch vehicle. This spin rate can be supplied either by a spin table on the launch vehicle's upper stage or by a propulsion system on board the spacecraft bus. Of course, the latter technique adds weight, cost and complexity which the satellite designer must, once again, be cognizant of early in the system development.

## TRAJECTORY PLANNING

Different satellite missions often require different orbit plane orientations and periods. Some examples are shown in the brief survey presented in the later sections of this paper. For purposes of identifying the interrelationship of the expendable vehicle and the spacecraft design for this important mission phase, the earth synchronous, or geostationary, orbit will be used as an example.

The geostationary orbit is one which affords the satellite a stationary position in space as viewed from the earth. The orbit must therefore lie in the equatorial plane. It must be circular to eliminate any retrograde motion. Finally, it must have a 24 hour period. The circular orbit synchronous altitude is approximately 35,800 km.

The launch vehicle is a multistage rocket, and it places the spacecraft into a coast transfer orbit that has an apogee at synchronous altitude. The transfer orbit is inclined relative to the equatorial plane. Perigee velocity is approximately 1524 m/sec and a final boost velocity of 1829 m/sec is required to circularize the orbit and correct inclination due to off-equator launch.

The most weight efficient way to achieve synchronous orbit is to have the spacecraft perform the apogee orbit injection with a high thrust solid rocket engine, often referred to as an apogee kick motor (AKM). This allows the smallest launch vehicle for a given in-orbit spacecraft weight, but the spacecraft must cope with large offset thrust pitching moments produced by the solid rocket. These perturbing forces can be readily attenuated by spinning the spacecraft along an axis parallel to the thrust. In some instances, a liquid propulsion system may be used in place of the solid rocket. The attendant lower thrust results in greatly reduced perturbing forces.

A less efficient method of apogee injection, but one that requires no spacecraft control during the transfer orbit, consists of using a launch vehicle upper stage with multiple burn capability. The first burn is done at perigee to achieve transfer orbit injection and a second burn is performed at apogee for synchronous orbit injection. The upper stage can then be ejected, freeing the satellite for normal mission operations.

Both techniques are illustrated in Figure 3. Since the expendable launch vehicle is the most expensive element of the system and its price increases monotonically with spacecraft weight, most synchronous orbit spacecraft carry their own apogee kick motor. In the entire stable of current expendable launch vehicles, only the Titan IIIC possesses the capability of placing a satellite directly into geostationary orbit. Note from the figure that the spacecraft must be able to reorient its attitude via onboard propulsion independent of the technique used.

### PERFORMANCE CONSIDERATIONS

For every satellite mission, there is a velocity that is characteristic of that mission. This "characteristic velocity" is not single valued, however, and many different missions can have the same characteristic velocity. The importance of this parameter is that it allows the launch vehicle performance to be characterized by a single curve. Such curves are very useful for the spacecraft designer in the preliminary design phases. The definition of characteristic velocity,  $V_{CH}$ , is given as:

$$V_{CH} = V_{PARK} + \Sigma \Delta V$$

where  $V_{PARK}$  is the circular velocity in a given parking orbit and  $\Sigma \Delta V$  is the sum of all the velocity increments required to establish final orbit. For high energy missions (e.g., earth escape trajectories for interplanetary flight) an energy parameter,  $C_3$ , is used. It is related to characteristic velocity by the expression:

$$C_3 = V_{CH}^2 - \frac{2K^2}{R_{PARK}}$$

where  $K$  is the earth's gravitational constant and  $R_{PARK}$  is the parking orbit radius.

Typical expendable launch vehicle performance is shown in Figure 4 where spacecraft weight is plotted against a multiple scale which includes  $C_3$  as well as characteristic velocity. As an example, consider the syn-

chronous transfer and the synchronous equatorial missions. The velocity,  $V_{PARK}$ , of the 185 n.mi. parking orbit is about 7800 m/sec. The velocity increment required to inject from this orbit into the synchronous transfer orbit is about 2440 m/sec, so  $V_{CH}$  for the synchronous transfer orbit is about 10,240 m/sec. For the synchronous equatorial orbit, an additional velocity increment of 1830 m/sec is required to inject from the inclined transfer orbit. Thus the total impulse velocity needed beyond  $V_{PARK}$  is approximately 4270 m/sec for a  $V_{CH}$  of 12,070 m/sec.

Note that for the synchronous equatorial mission,  $C_3$  is 24. For interplanetary missions,  $C_3$  depends heavily on the transit time; the shorter the transit time the greater  $C_3$ . Direct flight to Venus and Mars, for example, requires a  $C_3$  of 9 and 12, respectively, for transit times less than 1 year.

### PAYLOAD WEIGHT OPTIMIZATION

Maximization of in-orbit payload is a critical performance tradeoff analysis which the satellite system designer must conduct. For a geosynchronous mission, this tradeoff involves matching the spacecraft's apogee impulse capability with the launch vehicle capability.

Assume the launch vehicle is required to inject a payload (spacecraft + AKM) into synchronous transfer orbit, relying on the AKM to complete the injection into geosynchronous orbit. The technique for maximizing the payload is illustrated in Figure 5. Synchronous transfer orbit payload is plotted against launch vehicle perigee plane change (or transfer orbit inclination). This performance is easily calculated and is also provided by the launch vehicle supplier. One can also compute the AKM capability translated back to the synchronous transfer orbit payload. As the perigee plane change executed by the launch vehicle increases, the required apogee plane change decreases and, hence, the allowable payload weight increases. If the AKM propellant loading is just right, the AKM and launch vehicle capability curves meet at near zero perigee plane change and the payload weight is maximized. If the AKM is oversized, the velocity increment will inject the spacecraft into the wrong orbit. In such cases, the launch vehicle is required to run an inefficient boost trajectory to effectively expend the excess energy. If the AKM is undersized, the proper orbit can only be obtained by reducing the payload weight and the launch vehicle must be programmed to supply the matching perigee plane change. As one might expect, AKMs are rarely perfectly matched because of the cost of developing new motors and changing launch vehicle capabilities.

Since every extra pound that can be put in orbit can reap substantial rewards in system performance, the payload weight optimization process is critical. The satellite system designer must thoroughly understand the launch vehicle performance capability in order to carry out the optimization process.

### SATELLITE SYSTEM SURVEY

The three satellites discussed are representative of the various payloads developed by Hughes Aircraft Company for launch by expendable launch vehicles. In each case the satellite designer has had to confront and solve the problems discussed earlier. He has had to constrain critical satellite dimensions to fit within the launch vehicle payload envelope, sometimes incurring increased cost and complexity as a result of the need for deployments and improved solar cell efficiency. He has had to optimize the boost trajectory to eke out every last ounce of available payload weight and still, in some cases, suffer reduced lifetimes or have to develop new, light materials. He has had to construct complex spacecraft structural math models to ensure that the spacecraft will survive the severe loading produced by the boost environment. All these efforts are recurring themes in the development of a satellite system.

To discuss the design process as it relates to the impact of launch vehicle constraints on any one of these satellites would be beyond the scope of this paper. Instead, the designs are presented simply to expose the reader to the diverse applications of satellite systems.

#### HS 376 Communications Satellite

Hughes' newest spacecraft for satellite communications, designated the HS 376, is shown in Figure 6. Its concept developed out of a need for more powerful satellites for which a choice of launch vehicles could be made. While most HS 376s currently developed are destined for launch aboard the Delta 3910/3920, the spacecraft can also be launched on the Space Shuttle. An outer solar panel that telescopes in space to nearly double the solar power generating capacity and a folding, space saving antenna system afford cost-effective launch flexibility.

A wide variety of payloads have been ordered for both C band and K band communications tasks including: Anik C and D, covering the most populated areas and all of Canada for TelSat Canada; SBS, offering K band communications to business customers in the continental United States with weighted beams for the most densely populated areas; Westar IV, V, and VI, with which Western Union will serve customers in the continental United States, Hawaii, and Puerto Rico; Palapa B, providing

electronic links between the many islands of Indonesia and ASEAN countries by Perumtel; TELSTAR 3, American Telephone and Telegraph's new long distance high speed digital and video communications satellite system; and Galaxy, dedicated to the distribution of cable television for Hughes Communications, Incorporated. Satellite system lifetimes range from 7 to 10 years.

The basic HS 376 communications payload consists of two polarization selective reflectors which share a common aperture and a channelized, single conversion repeater. Incoming (uplink) signals are collected and amplified by the antenna where they are routed to wide-band receivers that supply additional gain and downconvert to the desired transmit frequency. The signals are then channelized by an input multiplexer. Each channel provides phase and amplitude equalization, gain control, and high power signal amplification. The signals are then recombined in an output multiplexer prior to transmission via the downlink antenna.

Shaped transmit and receive antenna coverage is achieved through multiple feed horn techniques. The front reflecting surface is horizontally polarized and is RF transparent to vertically polarized beams which are bounced off the rear reflector. Frequency reuse is afforded via polarization and/or spatial diversity.

Although the main part of the HS 376 spacecraft body spins in space to maintain gyroscopic stability, the antenna and communications equipment shelf are despun to permit the antenna to point consistently toward its target on earth.

Every HS 376 has its own solid propellant apogee motor. Originally matched for launch aboard the Delta 3914, subsequent growth in capability of the Delta family has resulted in an undersized apogee motor for most current missions.

The HS 376 spacecraft is a classic example of design innovation that has sought to mitigate the constraints imposed by the launch vehicle. The use of deployments, light and strong composite structures, and increased solar cell efficiency has afforded the HS 376 a communications capability exceeding that of earlier spacecraft launched from larger, more expensive expendable vehicles.

#### Geostationary Meteorological Satellite

Designed to pinpoint and photograph dynamic weather patterns over the Pacific Ocean, the Geostationary Meteorological Satellite (GMS), shown in Figure 7, operates at 140°E longitude over the equator, directly south of Tokyo,

Japan. The satellite has a key role in the World Weather Watch program, described by meteorologists as the most detailed study of the earth's atmosphere ever attempted. The effort involves the United States, Japan, the European Space Agency, the Soviet Union, the United Nations, the World Meteorological Organization, the Internal Council of Scientific Unions, aerospace industries, and about 145 nations that contribute daily surface and atmospheric measurements.

Many conditions of weather that daily affect the lives of people in various parts of the world exist for such relatively short periods that polar-orbit weather satellites fail to observe them. However, the synchronous orbit GMS, from its stationary vantage point approximately 35,800 km above the equator, has the operational capability to keep a third of the earth's surface under constant observation and to acquire almost instantaneous information on rapidly changing weather patterns.

An instrument developed by Hughes' Santa Barbara Research Center for making pictures of the earth's cloud cover in daylight and darkness is carried aboard the spin stabilized GMS-1. This instrument, called a visible and infrared spin scan radiometer (VISSR), senses radiation from the earth and its atmosphere. The optical telescope consists of a scan mirror and primary and secondary mirrors. It is mounted on the spinning portion of the spacecraft and scans the earth using a combination of the natural spin motion of the spacecraft (100 rpm) for east-west scan, and a mirror which steps 0.2 m every revolution for north-south scan. The telescope uses folded optics and images the scene onto eight visible and two IR detectors via fiber optics. The visible detectors are photomultiplier tubes and provide 1.25 km resolution while the IR detectors are mercury-cadmium telluride and are sized to provide 5 km resolution. The camera has the capability to send back black and white, television-like images of one-third of the earth every 30 minutes, day or night, enabling meteorologists to identify, monitor, and track severe windstorms, heavy rainfall, and typhoons.

Picture data gathered by the VISSR is formatted in a multiplexer/modulator and transmitted to the ground through S band electronics and antenna. The same S band system is used as a repeater to relay ground processed imaging data for facsimile reproduction at distribution points in the Western Pacific area. In addition, meteorological observation data from surface collection points (ships, buoys, and weather stations) can be relayed to the central processing center at the NASDA Tsukuba Space Center in Japan.

Also carried on GMS-1 is a space environmental monitor (SEM), developed by Nippon Electric

Company, which is used to investigate energetic particle activity emanated by the sun and assist in studying the effect of extreme solar activity on earth's telecommunications systems. The SEM detects solar protons, alpha particles, and solar electrons.

The first GMS was launched from Cape Canaveral in July 1977 by NASA; the new generation (GMS-2) was launched in August 1981 by Japan's National Space Development Agency (NASDA), from their Tanegashima Space Center, using a Japanese N-II rocket. To match the payload capacity of the N-II launch vehicle, a spacecraft weight reduction of 36 kg was required. This was accomplished by using lighter materials and fewer but more efficient solar cells.

#### LANDSAT and the Multispectral Scanner

Remote sensing from space for earth resource management constitutes one of the most practical applications of space technology. With the Earth Resources Survey Program inaugurated in 1972 by the highly successful LANDSAT (originally named the Earth Resources Technology Satellite, or ERTS), the user community is provided data that are unique and useful in many resource management fields.

LANDSAT circles earth from a sun synchronous 919 km circular orbit every 103 minutes or 14 times a day. The pass is from north to south at an angle of 99° retrograde to the equator. On each north to south pass the satellite crosses the equator at 9:30 a.m. local time. Each pass covers a region 185 km wide with some overlap between passes. After 18 days, or about 252 passes, the satellite returns to the same overhead position. The sun synchronous orbit ensures that lighting angles are little changed for contiguous areas imaged and for subsequent images of the same area.

Hughes designed and built the Multispectral Scanner (MSS) which performs the actual imaging on LANDSAT. MSS is designed to scan a 185 km swath on earth. An oscillating mirror provides the cross-track scan while the satellite's orbit motion provides the in-track scan. This mirror, together with a two element all reflective optical system (telescope) and a bank of 24 detectors, produce collocated images in four spectral bands; one image is in the green spectral region, one is in the red, and the other two are in the near infrared. A single image is approximately square (about 185 km on a side) and is made up of 7-1/2 million pixels (picture elements), each 80 meters square. Each pixel is quantized into

one of 64 intensity levels, and the values are multiplexed into a single 15 Mbps data stream on board the spacecraft and transmitted to receiving sites. The received data are recovered and demultiplexed into the original channels and formatted for binary recording on multitrack tapes.

Thus by looking down from its near polar orbit, the MSS aboard LANDSAT can transmit nearly 9000 highly detailed pictures a week for processing, analyzing, recording, and establishing standards tables for use by 300 principal investigators in 50 nations.

From Brazil comes reports that satellite data show marked differences in Amazon tributary positions from other recent maps. Some of these discrepancies are by as much as 19 km and 90° in direction.

Across the South Atlantic Ocean, Ghana reports MSS information is being used experimentally to control locusts by spotting the breeding grounds. Reports from the African nation of Mali indicate that MSS data are being used to make maps of remote areas, for the routing of new roads, for water exploration, and for many other vital guidelines.

A half a world away, uncharted reefs have been detected off Australia. By swinging over the Bahama Islands, MSS information has produced maps more accurately than any current navigation charts. Area acreages for Texas and Oklahoma have been categorized as to range and pasture, forest, and water by using satellite information. In Nebraska, Illinois and New York, shallow substrate, water-bearing rocks were detected. Polluted water drift was charted off the coast of New Jersey.

MSS data has enabled geologists to identify alternative sources for oil, gas, and other minerals in Alaska. In land use mapping, maps were obsolete before they were completed, often taking 1 to 2 years. An equivalent or better MSS picture can be rendered in 30 to 40 hours.

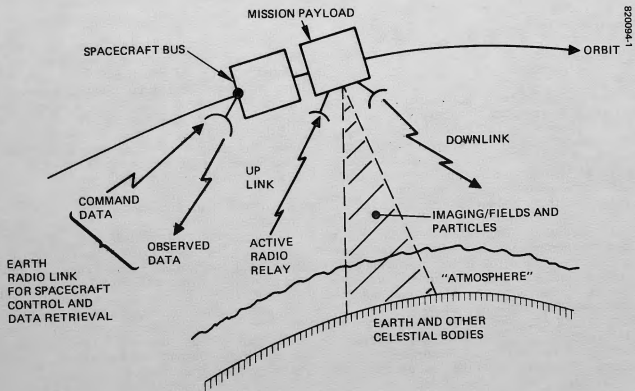
Three weeks of poor grazing can cost 113 kg of beef per animal, therefore MSS pictures were

used to map dynamic changes in foraging areas and resulted in great cattle savings in California and New Mexico. Icelanders have been able to direct their sheep to clear pastures and to avoid ice damaged ranges. MSS ocean ice information also permits the Icelanders to ship their sheep at the premium spring age.

The list goes on and on, with long term benefits in geology, hydrology, cartography, oceanography, agriculture, and urban development. Equally significant is that the data is not only fast, with excellent ground resolution; it is obtained at substantial savings over the more conventional methods.

The MSS has also felt the impact of expendable launch vehicle performance constraints. The latest version of the MSS will fly on the new Multimission Modular Spacecraft (LANDSAT D), shown in Figure 8. Due to a heavier payload complement, the circular orbit altitude is necessarily reduced from 919 to 705 km. In order to maintain similar area coverages and data rates, significant modifications to the MSS had to be incorporated.

The spectacular achievements of MSS in carrying out the Earth Resources Remote Sensing Mission have prompted NASA and the user community to set even broader goals, requiring increased instrument capability. To satisfy these new requirements, Hughes is developing and building a sensor called Thematic Mapper which has major performance improvements over the MSS. First, its resolution is 30 meters - 2.5 times better than the 80 meters currently obtainable. Second, it has seven spectral bands versus four for the MSS. In addition, the spectral separation of these bands is especially tuned to established user needs. Its radiometric precision is 256 levels - four times better than the 64 levels of the MSS. The Thematic Mapper will fly with MSS-D on the LANDSAT-D spacecraft. Together, they promise to provide still new and ever changing information on the quality of life on this planet.



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FIGURE 1. GENERIC SPACECRAFT MISSION



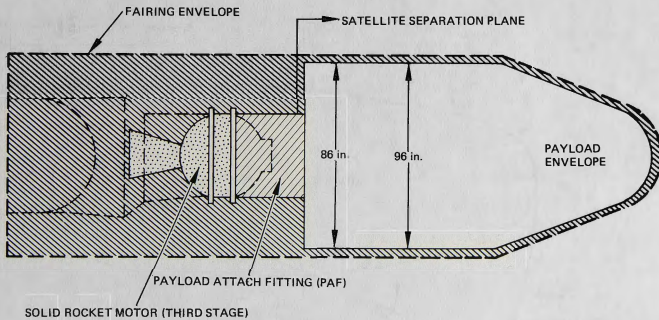


FIGURE 2. THREE-STAGE DELTA LAUNCH VEHICLE PAYLOAD ENVELOPE

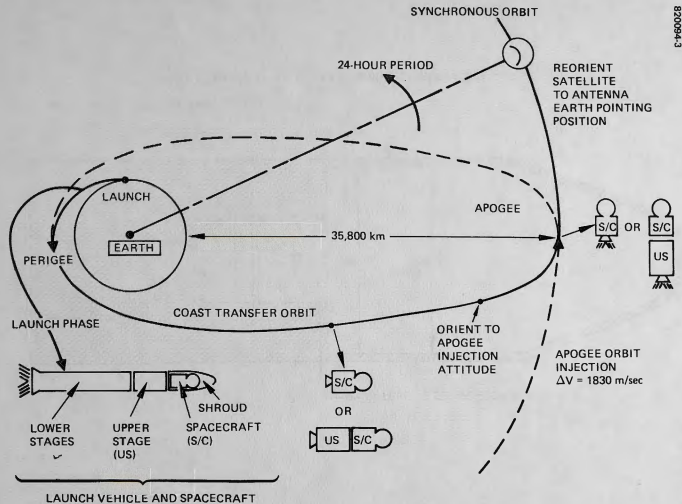


FIGURE 3. SPACECRAFT PLACEMENT IN EARTH SYNCHRONOUS ORBIT

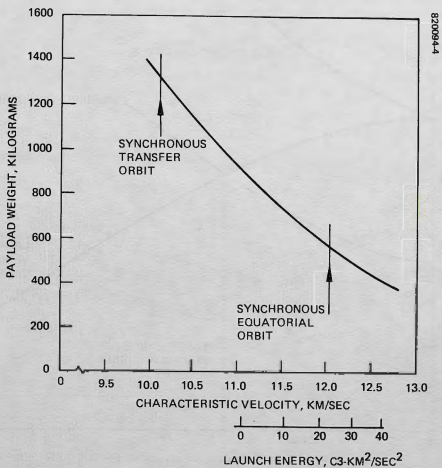


FIGURE 4. EXPENDABLE LAUNCH VEHICLE PERFORMANCE

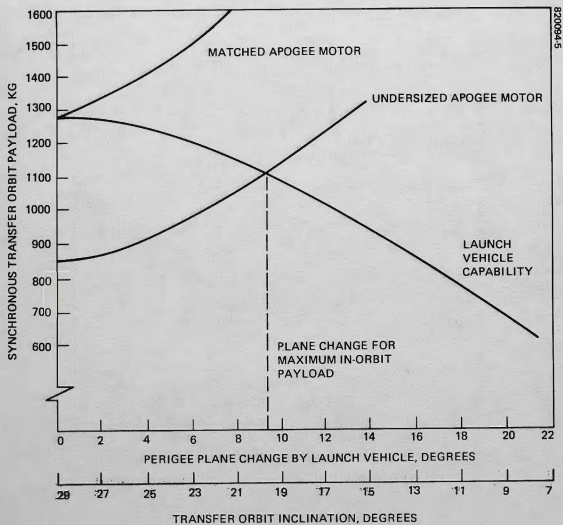


FIGURE 5. LAUNCH VEHICLE/AKM OPTIMIZATION

3

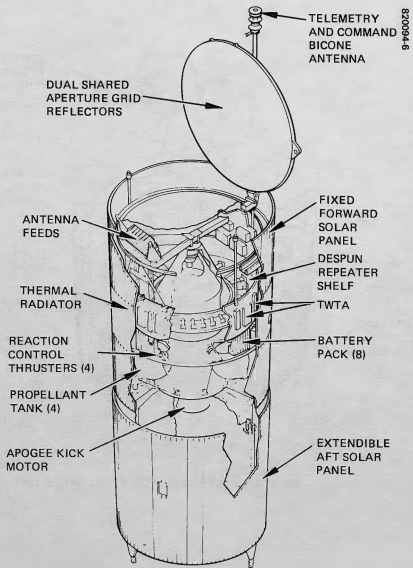


FIGURE 6. HS 376 COMMUNICATIONS SATELLITE

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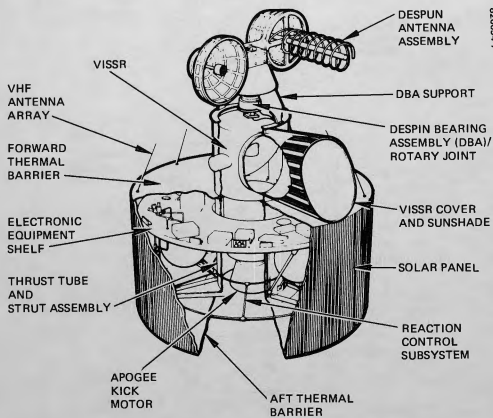


FIGURE 7. GEOSTATIONARY METEOROLOGICAL SATELLITE

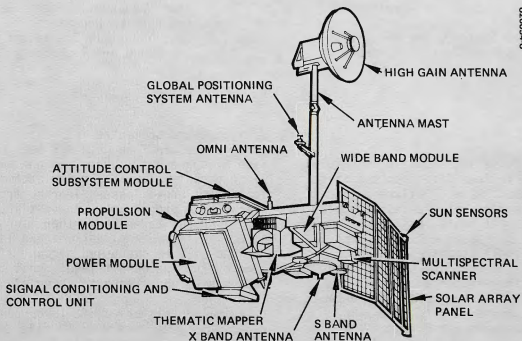


FIGURE 8. LANDSAT-D SPACECRAFT