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The DODGE

The primary mission of the Department of Defense Gravity Experiment (DODGE) satellite is to study the characteristics of gravity-gradient stabilization at synchronous or near synchronous altitudes. A satellite in a synchronous orbit rotates about the earth at the same rate and in the same direction as the earth turns. Therefore, to an earth observer the satellite appears to be fixed in space. The altitude at which synchronism is achieved is approximately 19,300 nautical miles. At lower or higher altitudes the satellite rotates more or less rapidly than the earth resulting in motion relative to an earth observer. In the near synchronous region very slow relative motion rates are possible. The DODGE satellite orbit altitude is 18,200 nautical miles. This sub-synchronous orbit is dictated by the requirements of other satellite payloads that are part of the same rocket-launching operation.

An attitude control system is required whenever it is necessary to maintain a specific satellite orientation. Gravity-gradient stabilization is an important means of attitude control. The advantage of this type of attitude control system is that it provides a passive means of satellite orientation which maintains one face pointed toward the earth. This orientation is particularly important for satellite systems requiring earth-pointing sensors or directional antennas. Combining a gravity-gradient stabilization system with a synchronous satellite is clearly desirable. However, at synchronous altitude the gravity-gradient effect is quite small and there are unanswered questions as to the implementation of such a system.

The DODGE satellite has been designed to demonstrate the application of gravity-gradient techniques at high altitudes, and to verify the analytical model used for the system design. The television system will provide a means of attitude measurement for the purpose of evaluating the attitude control system. Figure 1 is an artist's conception of the DODGE satellite, properly stabilized in orbit, showing the two cameras and their picture characteristics. As the orientation of the satellite changes, the relative position of the earth as seen in the picture also changes, thus providing a measure of satellite attitude. The two cameras provide high accuracy attitude data for

The DODGE television system was designed to evaluate the performance of the gravity-gradient stabilization system on the DODGE satellite. This article discusses the system geometry and measurement requirements leading to the television system design. The limits of measurement are presented and the system operation is described.

Television System

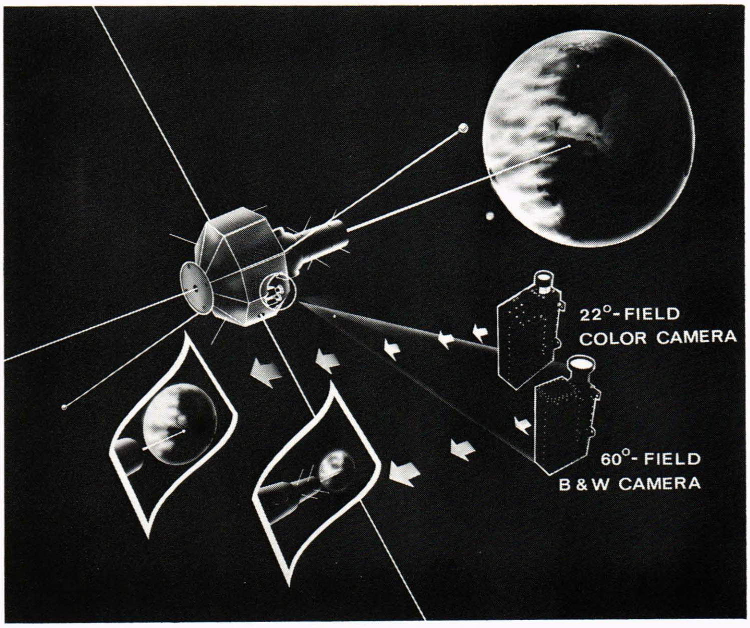

Fig. 1—Artist's conception of the DODGE satellite, showing its two cameras and their picture characteristics.

the near stabilized condition as well as a wide range capability for observation of peak motions. The stabilization booms, which are motorized and deployed after injection into orbit, are shown for one of the two three-axis gravity-gradient configurations. The two booms shown extending from the mast structure are part of the system used to damp satellite librations. The other four booms can be retracted and a second fully independent set of four booms in a different arrangement (not shown in the illustration) can be extended to provide an alternate configuration. The damper booms can be retracted and alternate damping techniques used with either configuration. To provide the experimental data needed to verify or refine the analytical model of the system, all boom lengths and many of the damping parameters are variable by command from the ground station.

The relative orbital motion of the DODGE satellite can best be appreciated in terms of the motion of the sub-satellite point (SSP). In one day the SSP will move eastward about 1700 miles, a ground speed of approximately 70 miles per hour. In terms of the camera picture scale this rate is about two resolution elements per hour for the wide angle camera and six resolution elements per hour for the narrow angle camera. The apparent motion in the scene below due to satellite libration may well override the orbital motion. Since the libration periods are expected to be of the order of 10 hours and the expected stability in pitch and roll roughly ±2 degrees RMS, a libration rate of about one-half degree per hour is anticipated. A libration rate of one-half degree per hour is equivalent to about a 170-mile per hour motion of the SSP.

Basic Concepts

The DODGE television system was designed to meet the measurement requirements for performance evaluation of the attitude control system. With the satellite fully stabilized, a downward looking television camera will see the earth centered in its field of view. For other attitude conditions, measuring the displacement of the earth's image from the center of a picture allows one to determine the satellite pitch and roll angles. Earth edge determination is sufficient for this measurement. In addition, the position of the terminator line can frequently be used for yaw sensing.

The television system was selected on the basis of its versatility. Each picture contains complete attitude information in the sense that a measure of the rotations about each of the body-fixed axes can usually be determined from the picture data. A further advantage of the television system results from its ability to observe the downward pointing stabilization boom, thus providing information on solar and gravitationally induced boom bending. The rate requirements to obtain boom bending dynamics are higher than those required for attitude measuring. One data point per minute will provide the necessary information. The major disadvantage in using a television system for attitude detection is the bandwidth required for picture transmission.

System Geometry

The DODGE satellite will be launched into a circular equatorial orbit at an altitude of 18,200 nautical miles. The period for this orbit is 22.24 hours. The basic geometry is indicated in Fig. 2.

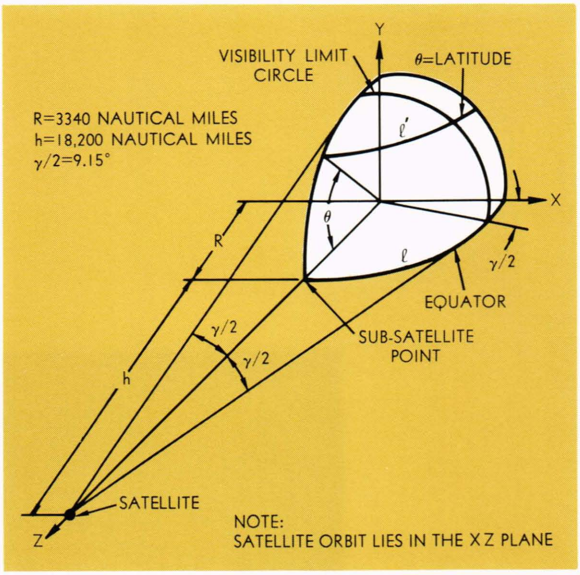

Fig. 2—DODGE visibility geometry.

The angle, γ, subtended by the earth at this altitude is 18.30 degrees. The visibility limit circle as shown includes 161.7 degrees ($\pi - \gamma$) of latitude and longitude. The satellite will move east at the rate of 28.49 degrees of longitude per day. At this rate the orbital period relative to an earth observer is 12.64 days. Since the satellite will be in view to a ground station at the equator for 161.7 degrees of relative rotation, a complete pass will take 5.68 days. At any other latitude θ the duration of a pass is reduced; this relationship is shown in Fig. 3. For the APL station a pass is approximately 5.5 days or about 43 percent of a full period.

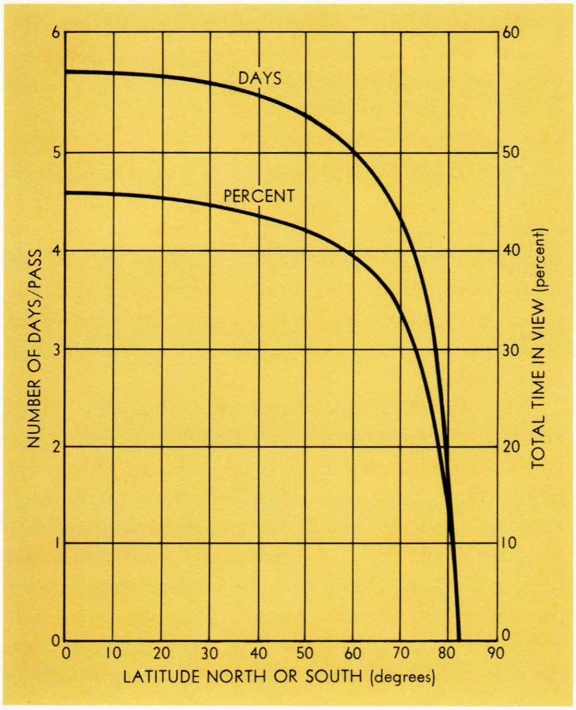

Fig. 3—Pass duration versus latitude.

The illumination condition with the sun at an angle ϕ to the local vertical is indicated in Fig. 4. The angle 2α represents the amount by which the visible edge is less than a half circle. When $\phi \leqq \gamma/2$ the full visible circle edge is illuminated. Such a condition will exist once during each orbit for a period of 1.13 hours provided the sun angle to the equatorial plane is zero. The time duration for which the full visibility limit circle is illuminated each orbit will vary from this maximum as the sun angle to the equatorial plane changes. However, the full edge limit will be illuminated for some part of each orbit whenever the sun angle to the equatorial plane is less than $\gamma/2$. This condition is satisfied between February 25 and April 14, and again between August 27 and October 15, or about three and one-third months per year. The relationship between sun angle and visible circle edge illumination is shown in Fig. 5. From this illustration it is apparent that attitude sensing with this system is not possible for ϕ greater than 170 degrees. For a camera with a lens that views the full earth, attitude sensing may be further restricted to protect the image sensor from exposure to the sun.

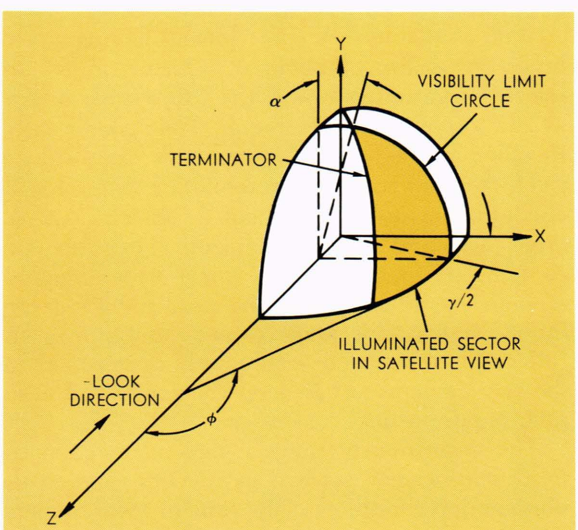

Fig. 4—DODGE illumination geometry.

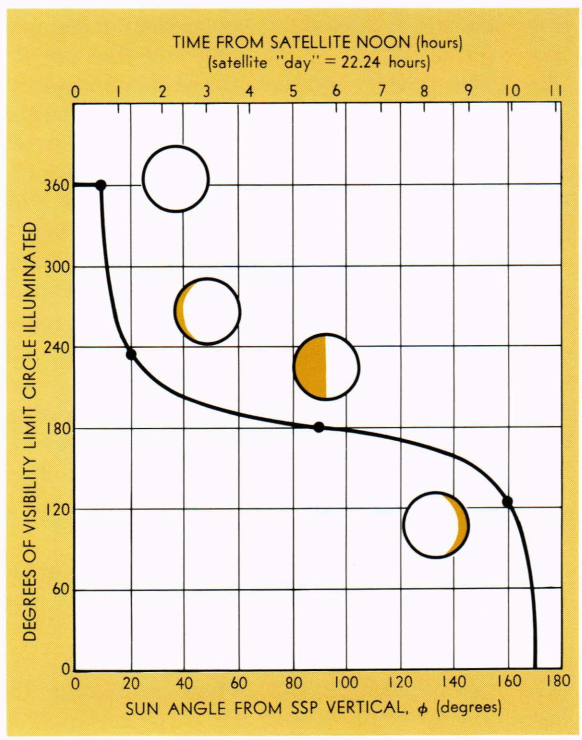

Fig. 5—Earth illumination versus sun angle.

Data Link Considerations

The power required to transmit the television picture is dependent on the camera resolution capability and frame time (time required to complete one picture scan), the independent data link parameters (satellite and ground antenna characteristics, ground receiver characteristics, transmitting frequency, and modulation method), and the orbital geometry. The orbit is fixed by the main mission requirements. The independent data link parameters are either fixed without regard to the specific mission or are optimized independently. The camera resolution is determined by the measurement requirements and limitations in available image tubes. The variables of the system design are frame time and transmitter power with their product a constant. For the DODGE transmission system this product is approximately 2000 watt-seconds.

Consider the requirement of one picture per hour for attitude determination. If a one hour frame time were used the transmitter power required would be less than one watt. At this output level the prime DC power required by the transmitter is small relative to the power requirements of the camera and signal processing elements of the data system. Over broad ranges of frame time the power required for the camera and processing elements is essentially constant and for very short frame times is negligible relative to the transmitter power requirements. If the transmitter efficiency is independent of the required output power, and if the system can be turned off between pictures, the average prime power required for one picture per hour is less for the short frame time case. The actual lower bound on frame time is set by the availability of highly reliable space-qualified transmitters. Other practical considerations are: the time required for the ground equipment to "lock-on" to the transmitter and begin recording, the possibility of using the system directly from the solar array in the event of a battery failure, and the desire to make use of equipment designs completed for earlier satellites.

Sensor

There are two basic methods of television image formation: (a) a storage method, where an image is stored as an electronic charge distribution which is read out with a scanning beam, and (b) a real time method, where the output represents the instantaneous brightness at the current scan position. Generally the charge storage device has a large advantage in sensitivity due to its ability to integrate the signal at each element for a full frame time.

However, when slow frame times are required and the illumination levels are high the sensitivity characteristic becomes less important. For the DODGE system either image method could have been applied. However, to obtain the full advantage from the real time device would have required the use of longer frame times, which as noted above would increase the average DC power required by the system. In the limit of a full one hour frame, the continuous nature of the data would be a disadvantage from an operational view. It should be noted that a real time camera is not subject to image smear unless motion is fast relative to an element dwell time. Motion over a frame is represented as picture distortion which frequently can be useful for measuring systems in motion. Within the time scale selected for the DODGE satellite a vidicon camera system represented the best choice. Flight-proven tubes with good resolution capability were available and all the measurement requirements could be realized.

The vidicon is an image tube that uses a semiconductor target with photoconductive characteristics. An electron gun is used to focus an electron beam onto the target area. Deflection of the beam can be accomplished either electrostatically or electromagnetically. A thin transparent conductive film is used on the glass side (light input side) of the target to act as a signal electrode. A positive voltage is applied at this electrode through a load resistor. In the absence of light the target will act as a capacitor and the scan beam will charge it to the target potential, the cathode being at ground potential (charge cycle). When a light pattern is imaged on the target it will selectively discharge. After an appropriate exposure interval the shutter is closed and the image is stored in the form of a charge pattern. Upon scanning the target a signal output results from the recharging of each picture element (read cycle). The signal output is proportional to the degree of discharge, and hence to the illumination level.

Measurement Limits

With available slow scan vidicons having a resolution capability of about 500 lines and for the selected transmitter power the frame time was set at 200 seconds. This resolution, while good relative to other image tubes of comparable size, will not yield the desired angular resolution over a wide enough field to allow detailed observations for large pitch and roll displacements. Therefore, two cameras are used; a narrow angle camera capable of high accuracy data in the near stabilized condition, and a wide angle camera usable over the full range at reduced accuracy. Lens selection for the two cameras is based on the range and accuracy requirements.

The measurement range is dependent upon the fixed field of view, set by lens selection, and on the illumination condition at the time of measurement. The maximum range of measurement is determined by assuming the entire region of the earth within the visibility limit circle is illuminated. For this case an attitude measurement can be made with any part of the earth within the picture area. The minimum pitch and roll measurement range for worst-case conditions (i.e., a small crescent of illuminated earth and the satellite motion directed away from the illuminated area) is based on the condition that the visibility limit circle is within the picture area.

The time limit on attitude sensing is set by the sun-in-field condition. A separate sun sensor protects the camera when the sun is in the field of view by preventing the shutter from opening. The times when the sun is eclipsed by the earth is relatively unimportant as a limit on attitude measurement since it represents such a small part of the total mission time. However, pictures taken during the eclipse may provide attitude data from air glow or auroral phenomena. Pictures taken during the eclipse may prove to be one of the more interesting side products of the DODGE camera system.

For some periods of time the moon will also be in view of the DODGE cameras. It will be possible to take pictures of the moon during each satellite orbit provided it is not necessary for the cameras to look into the sun. This condition exists only during the phase of the new moon and represents a relatively small part of the moon's orbital period. The restricted period, as for the sun-in-field limit, is directly proportional to the camera field of view. The moon-viewing characteristics for the satellite cameras are very similar to those of an earth observer. The distances to the moon from the satellite and from an earth observer are about the same. The major difference results from the fact that the satellite cameras are always pointing earthward. Therefore, both the earth and moon will be within the field of view and the earth will eclipse the moon each satellite orbit.

The 200-second frame time is not compatible with the rate information needed for dynamic boom-bending measurements. To overcome this difficulty, a fast scan mode was included. With the bandwidth restricted by the data link, this speed-up would normally produce a corresponding reduction in resolution. Since the boom end mass will be found most frequently in the central region of the picture, the resolution degradation can be partially overcome by reducing the scan area. Reducing the scan area by a factor of four allows for boom end mass measurements over half the field, and a speed-up of four can be achieved with no reduction in resolution. A factor of eight speed-up was required and the additional factor of two was obtained at the expense of resolution degradation in the horizontal scan direction.

Camera Configuration

To allow accurate measurements in the near stabilized condition and to provide information over a wide angular range two cameras are employed. A wide angle 60° x 60° field of view camera (60° camera) and a narrower 22° x 22° field of view camera (22° camera) have been selected. The picture geometry is shown in Fig. 6 for both cameras. Indicated in the illustration are

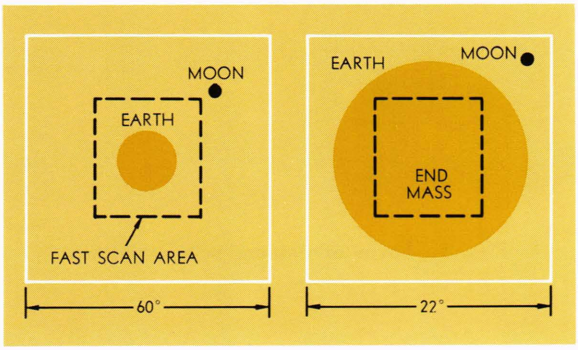

Fig. 6—DODGE picture geometry.

the fast scan areas, the relative size of the moon, and a 10-inch boom end mass 120 feet from the 22° camera. The relationship between camera angle and the earth angle measured from the satellite sub point (SSP) to any other point is shown in Fig. 7. Also indicated in the illustration

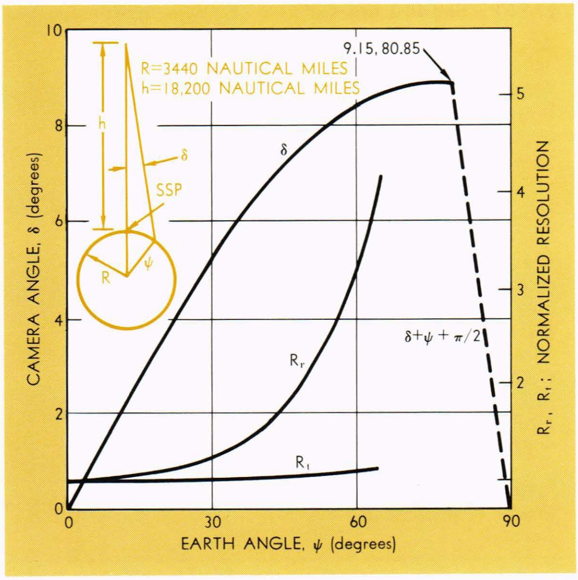

Fig. 7—DODGE resolution characteristics.

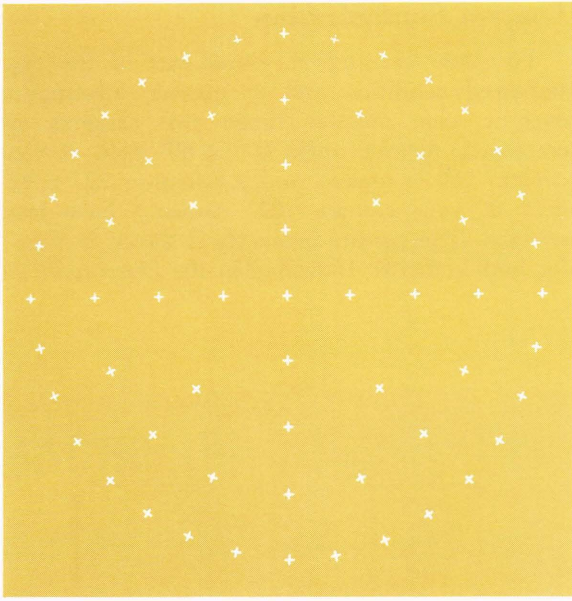

Fig. 8—Form of camera reticle pattern.

TABLE I

TELEVISION SYSTEM CHARACTERISTICS

	Slow Scan		*Fast Scan*	
Frame time (seconds)	200		25	
Field of view (degrees)	60	22	32	11
Angular resolution (degrees)	0.12	0.044	0.12/0.24*	0.044/0.088*
Linear resolution limit at SSP (nautical miles)	36	13	36/72*	13/26*
Angular calibration accuracy (to reticle-degrees)	0.15	0.05		
Sun-in-field (percent of satellite orbit)	22	8.9		
Moon-in-field (percent of satellite orbit)	16.7	3.9		
Moon in sun direction (days/moon orbit)	6.2	2.5		
Maximum usable time as an attitude sensor (percent of orbit)	78	91		
Pitch and roll limit (any illumination-degrees)	±20	±2		
Pitch and roll limit (full illumination-degrees)	±34	±14		
System weight (pounds)	19			
Power requirements (watts)	9			

$* \frac{\text{Vertical resolution}}{\text{Horizontal resolution}}$ = one-half in fast scan

is the limit of visibility and the normalized resolution characteristic. Resolution in this illustration represents the ability of the camera to resolve surface or near surface detail on the earth. The normalized radial resolution, R_r, is defined as the degradation in resolution as one moves radially outward from the SSP in any direction. The normalized tangential resolution, R_t, is defined as the degradation orthogonal to R_r.

Position measurements will be made relative to a reticle pattern fixed on the face plate of the vidicon. This method establishes a mechanical reference for measurement which is independent of electronic scan stability. The form of the reticle pattern is shown in Fig. 8.

A summary of the camera system measurement characteristics is given in Table I.

System Operation

A basic block diagram of the television system is shown in Fig. 9. The normal sequence consists of a 200-second charge cycle, followed by exposure of the 60° camera and a 200-second read cycle, and finally, exposure and a 200-second read cycle of the 22° camera. In continuous operation a 60°

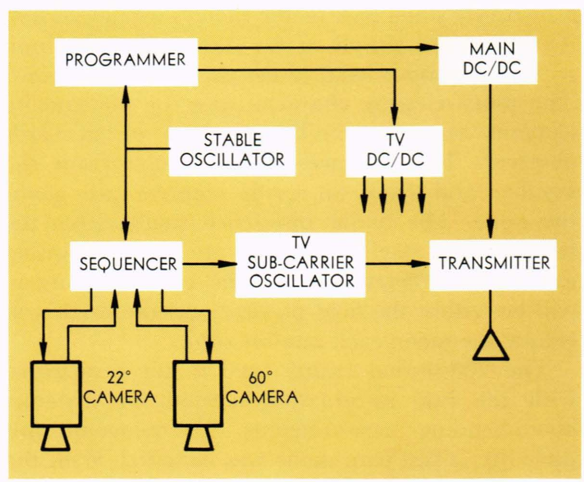

Fig. 9—TV system block diagram.

camera exposure and read cycle will follow immediately. The initial charge cycle is required only at turn on. In the programmed mode of operation the satellite programmer turns the system on every hour on the hour for 10 minutes. In normal operation the camera system will be in the slow scan mode which will provide one picture from each camera every hour. For more specialized camera operations the programmer can be bypassed and the system can be controlled by ground command.