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Cartographic Potential of a Spacecraft Line-Array Camera System: Stereosat

Stereosat would be capable of satisfying accuracy standards for planimetric maps at 1:100,000 scale and contour intervals of 100 metres.

ABSTRACT: *A study of the proposed Stereosat mission reveals the possibilities of acquiring analog/digital stereo image data of cartographic quality with line-array camera systems. Three cameras (fore, vertical, and aft looking), mounted so as to record stereotriplets for a 61.4 km wide swath at a nominal focal plane scale of 1:1,000,000, are considered. The IFOV of 15 m represents a substantial improvement in resolution over other planned satellite missions and should prove adequate for producing thematic and image map products at scales of 1:50,000 to 1:250,000. At present, estimates of RMS pointing accuracies and attitude control rates indicate that X, Y positions can be recovered to within approximately ±100 to 200 m with minimal ground control. With adequate ground control, it may be possible to recover planimetric coordinates to better than the ±30 to 35 m necessary to satisfy the accuracy standards for planimetric maps of 1:100,000 scale. However, the closest contour intervals meeting U.S. National Map Accuracy Standards appear limited to about 100 m, which is compatible with topographic maps of 1:250,000 scale and smaller. In order to achieve these accuracies, it is assumed that sensor attitudes can be recovered to ±5 seconds of arc, satellite rate precision in 10^{-5} deg/sec or better, and timing marks are included in the image data. The challenge of Stereosat type data is in the realm of automated mapping.*

INTRODUCTION

STEREOSAT is a proposed satellite mission capable of producing stereoscopic coverage of the Earth's surface with three linear array camera systems. Initial impetus for the Stereosat mission came from the geologic community but, as the parameters for the mission were refined, support broadened to include disciplines such as cartography, hydrology, and engineering (Henderson and Swann, 1976). Of these disciplines, cartography undoubtedly places the greatest demands on the Stereosat mission parameters. It is argued, for example, that Stereosat can provide X, Y, and Z terrain coordinates for the Earth's surface, and that these data will be available in both analog and digital formats and of sufficient resolution (15 m instantaneous field-of-view) and geometric fidelity to permit the compilation of topographic maps at 1:100,000 scale (JPL, 1979; Goetz, 1980). Since much of the world is poorly mapped at scales

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of 1:100,000 and larger, Stereosat would offer a means of providing maps for developing countries and/or areas where activities such as mineral exploration and agricultural expansion are hampered by the absence of suitable map coverage (United Nations, 1970a; 1970b; 1976) (Figure 1).

The extent to which the cartographic goals can be reached, however, is dependent upon the system design parameters and their relationship to the completeness and accuracy requirements of cartographic products. Colvocoresses (1979), for example, has proposed a Mapsat mission intended to meet topographic mapping requirements, but which requires significantly more stringent performance parameters than those specified for the Stereosat mission. Consequently, Mapsat will be more expensive and difficult to implement. Similarly, the French Centre National d'Etudes Spatiales is developing a satellite program, Système Probatoire d'Observation de la Terre (SPOT), which is designed to produce cross-track stereoscopic coverage with pointable linear array camera systems referred to as the High Resolution Visible (HRV) sensors (Chevrel *et al.*, 1980). Stereosat differs considerably from SPOT and Mapsat (Table 1). Therefore, the objectives of this paper are (1) to provide information on the Stereosat system and mission parameters; (2) to utilize studies associated with Stereosat in order to indicate the nature and scope of problems associated with recording image data of high geometric fidelity from spacecraft equipped with line array sensors; and (3) to assess the possibilities of meeting the completeness and accuracy requirements of cartographic products.

ORBIT CHARACTERISTICS

The Stereosat orbit must provide for repetitive global coverage of the Earth's surface from a nearly constant altitude with orbit stability, predictability, and lighting conditions consistent with the requirements of high-quality imagery. Orbit parameters which best satisfy these conditions are similar to those of Landsat-D (Table 2), and, at present, plans call for a 9:30 A.M. equator crossing at the descending node. A 713-km circular, sun-synchronous, near polar orbit with an inclination of 98.24 degrees and a repeat cycle of 48 days is designed to insure global coverage of the Earth's land masses during the three-year lifetime of the mission. A three-year lifetime is necessary to maximize the chances of obtaining cloud free image data (Figure 2). A westward swathing direction is proposed; however, it must be emphasized that a wide variety of orbit configurations are possible (Figure 3) (JPL, 1979).

After injection and orbit circularization, sufficient tracking time would be allowed to precisely determine the orbit. Onboard propulsion could then be used to refine, orient, and shape the orbit to provide a near-constant altitude of 713 km. This constant altitude is desirable in order to achieve a standard geometry between images and, thereby, ease image interpretation and minimize ground data processing. These adjustments would insure a near-circular orbit with a preferred periapsis orientation.

A planned ground-track spacing between adjacent orbits of 57 km and a swath width of 61.4 km provides approximately 7 percent sidelap at the equator, and is intended to allow an adequate

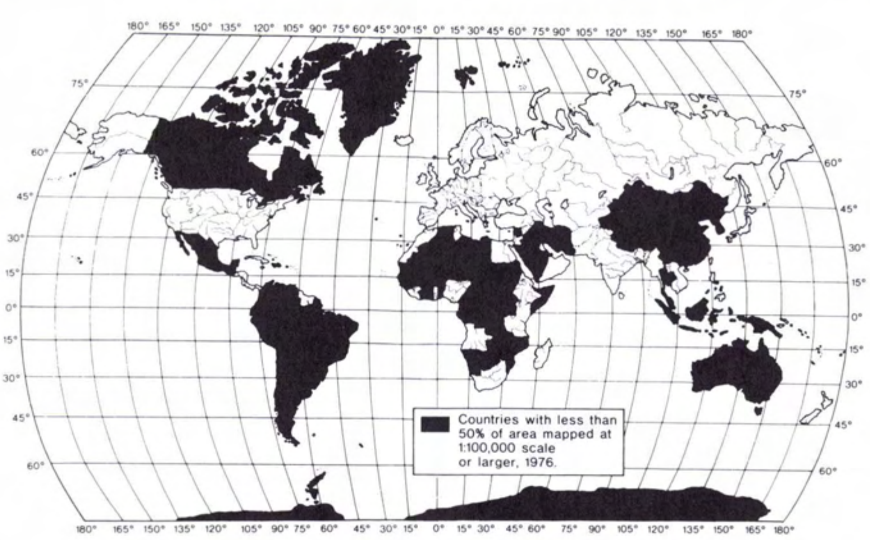


FIG. 1. The shaded areas represent countries or regions with 50 percent or less of their area mapped at 1:100,000 scale or larger in 1976 (United Nations, 1976).

TABLE 1. COMPARISON OF SENSOR PARAMETERS FOR PROPOSED SATELLITE MISSIONS

	Sensor System	IFOV	SWATH	Repeat	Bands	Data	Products
LANDSAT-D (1982)	TM MSS	30m 76m	185km	16-20 dys	7 4	100mb/s TDRSS & DIRECT	IMAGES CCT's
STEREOSAT (1985)	3 camera*	15m	61km	48 dys	1	32mb/s TDRSS	IMAGES* CCT's DTM
SPOT (1985)	HRV(2)*	20m 10m	60km	26 dys*	4	50mb/s DIRECT TAPE	IMAGES* CCT's DTM
MAPSAT (mid-1980's)	3 camera*	10-30m	185km	18 dys	3-4	15-30mb/s TDRSS & DIRECT	IMAGES* CCT's DTM
	LINE* ARRAYS			POINT-* TABLE			STEREO*

margin of error so that sidelap will not be reduced to less than the 100 pixels considered essential for the preparation of image mosaics. A problem with the proposed Landsat-D compatible orbit is the 23-day time lapse between adjacent swaths which reduces the chances of obtaining uniform images of large areas due to seasonal variations in weather patterns.

IMAGING SYSTEM

The proposed imaging system for Stereosat consists of three line-array cameras operating in the pushbroom mode (Thompson, 1979; Welch, 1980) (Figure 4). Two of the cameras will be oriented approximately 24 degrees from the vertical in a convergent arrangement in order to provide fore and aft coverage while the third camera is aligned vertically so as to produce near orthographic coverage of the terrain. This configuration results in potential base-height (B/H) ratios of 1.0 for fore and aft stereopairs and 0.49 when the vertical is employed with either fore or aft coverage. The viewing geometry, which is illustrated in Figure 5, may be described mathematically as follows:

$$\begin{aligned} B/H &= 2 \tan \alpha \\ &= 1.0 \text{ by design.} \end{aligned} \tag{1}$$

To achieve this base-to-height ratio, the camera must be offset from vertical by an angle θ, where

$$\begin{aligned} \theta &= \sin^{-1}\left[\left(\frac{R}{R+H}\right)\frac{(B/H)}{\sqrt{(B/H)^2+4}}\right] \\ &\approx 24^\circ \text{ for the proposed orbit altitude.} \end{aligned} \tag{2}$$

Finally, the slant range, l, to the surface for the oblique cameras is given by

$$l = (R+h)\cos\theta - \sqrt{R^2 - (R+h)^2 \sin^2\theta} \tag{3}$$

Cross-track coverage is determined by the altitude (713 km), the number of photodiode elements in the line array (4096), and the focal lengths of the camera systems. Focal lengths of 705 and 775 mm are proposed for the vertical and oblique cameras, respectively, which produce a

TABLE 2. CHARACTERISTICS OF POSSIBLE STEREOSAT ORBITS. NUMBER 4 IS THE BASELINE ORBIT (SOURCE: JPL, 1979).

No.	Q (rev/day)	ND (days)	NP (orbits/cycle)	Period (min)	ALT (km)	INC (deg)	COV LAT (deg)	FOV (deg)
1	13 ± 1/52	52	676± 1	111	1257	100.7	79.6	1.80
2	14± 1/48	48	672± 1	103	888	99.0	81.3	3.96
3	15± 1/45	45	675± 1	96	561	97.6	82.7	6.27
4	14 25/48	48	697	99.2	713	98.24	82.0	4.93
5*	14 9/16	16	233	98.9	700	98.19	82.1	15.03**
6	14 29/48	48	701	98.6	686	98.13	82.2	5.13

* A proposed Landsat-D orbit.

** Swath width of 185 km. Other FOV's are based on 61 km swath width.

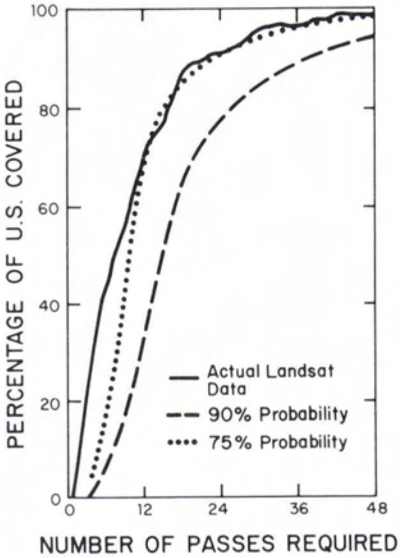


FIG. 2. Percentage of United States with 10 percent or less cloud cover as a function of number of passes based on (1) actual Landsat data (solid line); (2) 75 percent probability (dotted line); and (3) 90 percent probability (dashed line). A repeat cycle of 48 days will provide 22 passes in a three-year lifetime, resulting in a 75 percent probability of obtaining 90 percent of the United States with 0 to 10 percent cloud cover (JPL, 1979).

focal plane image scale of about 1:1,000,000. The field-of-view (FOV) for each camera is five degrees and the instantaneous field-of-view (IFOV) (corresponding to the detector element size of 15 μm) is 15 m. Along-track coverage is generated by the 6.83 km/s forward ground-track velocity of the spacecraft, hence the term "pushbroom" mode (Figure 6). Because along-track coverage is a function of time, any perturbations of the spacecraft or causes for variation in satellite velocity or altitude will be translated into geometric distortions in the imagery, giving rise to planimetric and vertical errors.

A single optimum spectral band from 600 to 900 nm is envisioned. No shutters need be incorporated in the system since the exposure is fixed by the detector IFOV divided by the ground-track velocity and is equal to approximately 2.2 ms. Variations in scene brightness are accommodated through the use of electronic gain control and a sensor dynamic range (1000:1) that far exceeds the six-bit encoding (64 shades of grey). The output from each camera is a data stream of approximately 11 Mb/s (32 Mb/s for all three cameras) representing a continuous strip, or swath, along the ground-track of the spacecraft. Discrete frames can be segmented during the ground processing operation.

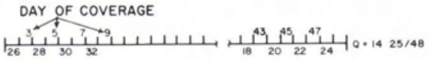


FIG. 3. A proposed Landsat-D compatible orbit pattern for Stereosat. The problem with this pattern is the 23 day interval between adjacent orbits (JPL, 1979).

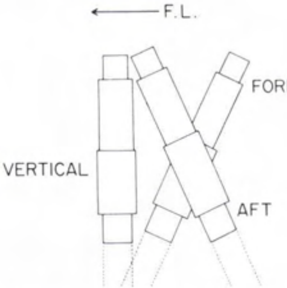


FIG. 4. Arrangement of three line-array cameras oriented so as to provide along-track stereo coverage with vertical and fore and aft looking cameras.

ERROR CONSIDERATIONS

The Stereosat mission must provide essentially error free geometric and radiometric data if accurate map, image enhancement, and classification products are to be developed. In theory, the spacecraft and sensor systems can be controlled so as to preclude any special ground based computer processing (to correct the errors), which is both expensive and subject to delay. On the other hand, if unrealistic requirements are placed on spacecraft and sensor system design engineers, the total cost of the mission may be prohibitive. Consequently, a knowledge of error sources, their magnitudes, and what constitutes an acceptable

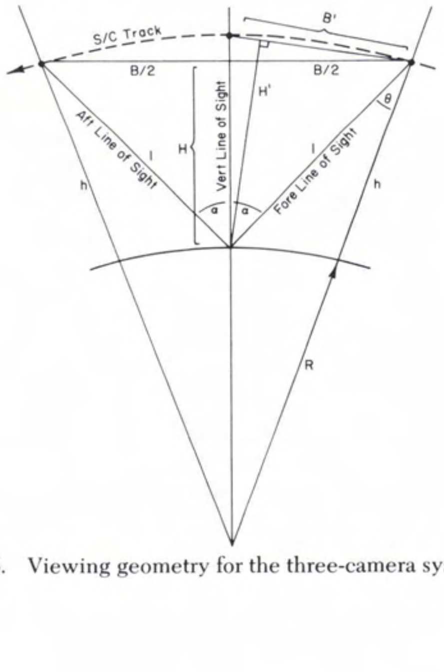


FIG. 5. Viewing geometry for the three-camera system.

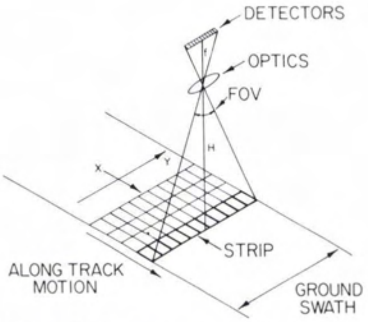


FIG. 6. Schematic diagram of a vertical line-array camera system. Cross-track coverage is determined by the number of detectors in the focal plane and the field-of-view (FOV) of the optics. Along-track coverage is produced by the forward motion of the satellite.

compromise between user requirements and engineering realities is vital to the interests of geologists and cartographers.

The parameters which influence the geometric fidelity of the image data include pointing control (0.1 to 0.01 degree), rate motion stability (10^{-4} to 10^{-6} deg/sec), and jitter (less than 4 arc seconds). In orbit the Stereosat spacecraft may be envisioned as moving along the path represented by the X axis in Figure 6, where

$$\Delta X = \Delta t \cdot V \qquad (4)$$

where Δt = time increment in seconds,
V = ground velocity of spacecraft (6.83 km/s), and
ΔX = along track distance increment in km.

The satellite line-array sensor system (which is recording the terrain as a series of cross-track strips) must be pointed correctly and held stable for the 9 seconds required to cover a 61.4 km square area, and for 92 seconds to produce an error free stereo-triplet. Any perturbation of the sensor system during these recording periods will cause displacements/errors in the data which, in turn, may require geometric correction and resampling at a ground receiving station. Rotation of the spacecraft about the X, Y, and Z axes (roll, pitch, and yaw, respectively), although constrained to 10^{-4} deg/sec or better, will cause deformations of the nominal image format as will changes in spacecraft altitude and oblateness of the Earth. Furthermore, although the concept of producing stereo-triplets from the along-track coverage provided by the three line-array camera systems appears fundamentally sound, the dynamics of Earth rotation preclude the possibilities of obtaining three sets of image data which can be easily registered. The deformations associated with the various motions and perturbations may be classified as intraframe, interframe, and/or swath-to-swath (Driver, 1980).

INTRAFRAME DEFORMATIONS

The image format resulting from a constant roll rate error or from a fixed yaw angle between the camera platform and the satellite ground track is illustrated in Figure 7a. Image lines are parallel but the coverage is skewed. If the yaw angle varies with time, however, the image lines do not remain parallel, thus introducing displacement, *d*, which will deform the image and influence image analysis and measurement (Figure 7b). A similar deformation can occur if the spacecraft does not follow a great circle route on the Earth, even though the camera platform is aligned with the ground track (Figure 7c). A time varying pitch angle will create gaps or overlaps between adjacent scan lines, whereas a fixed pitch error has no effect.

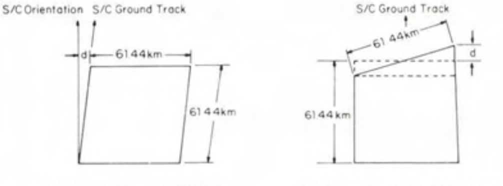
A spacecraft altitude displacement from the nominal value results in a scale error (Figure 7d). Sizable altitude variations can occur from either the geometrical or the gravitational effects of Earth oblateness, or from an incorrect orbit shape or orientation. Scale errors may also result from attitude errors or from variations in satellite velocity.

INTERFRAME DEFORMATIONS

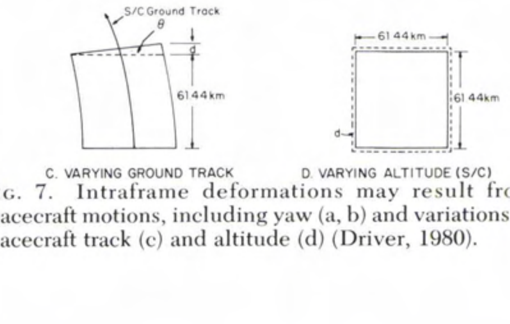
Interframe deformations affect the registration of any two individual frames which comprise a stereo triplet (Figure 8). These deformations are caused by variations in altitude, attitude rate uncertainty, and the yaw mechanization mode used to compensate for Earth rotation as described below. As a result, the overlap area may be reduced and severe model deformations incurred.

SWATH-TO-SWATH DEFORMATIONS

Swath-to-swath deformations influence the sidelap of frames recorded along adjacent orbit paths (Figure 8). A minimum sidelap of 100 pixels (2.5 percent) at the equator is envisioned, and this



A. CONSTANT YAW ANGLE B. TIME-VARYING YAW ANGLE



C. VARYING GROUND TRACK D. VARYING ALTITUDE (S/C)

FIG. 7. Intraframe deformations may result from spacecraft motions, including yaw (a, b) and variations in spacecraft track (c) and altitude (d) (Driver, 1980).

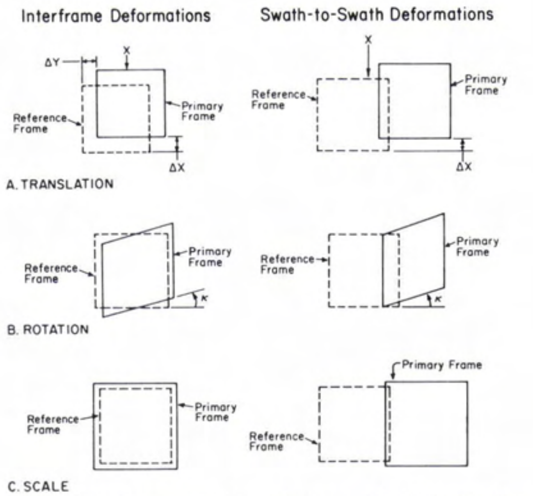


FIG. 8. Interframe and swath-to-swath deformations can reduce overlaps and warp the stereomodel (Driver, 1980).

will increase poleward. Cross-track displacement is of concern only if there is insufficient sidelap for mosaicking. A roll position error will cause cross-track displacements as will a yaw control error or time variations in the corrections for Earth rotation.

In the following sections the problems associated with Earth rotation and oblateness are treated in further detail. Earth rotation is a particularly important consideration for missions designed to produce stereo coverage in the along-track direction.

EARTH ROTATION COMPENSATION

The basic Stereosat imaging concept is straightforward, and it appears at first glance that the stereoscopic coverage can be implemented with a minimum of difficulty. However, because of Earth rotation, the satellite ground track is no longer a simple great-circle route, and the vertical, fore, and aft cameras will not automatically image the same ground area, even with a perfectly stable satellite. In order to obtain ground coverage common to any *two* cameras, a yaw motion must be introduced into the camera/spacecraft. This motion is not constant, but must vary with latitude to maintain image registration. At the equator the rate of Earth rotation is approximately 0.46 km/s which, over the 46 or 92 second intervals required for stereo coverage, results in a 21 or 42 km lateral displacement of the image center, reducing the overlap by approximately 33 or 66 percent, respectively (Figure 9). The vector difference between spacecraft velocity, $V_{S/C}$, and earth rotation, V_E, at the Earth's surface establishes the satellite ground-track velocity, V_G. The angle between the two satellite velocity vectors is the required platform yaw angle, κ.

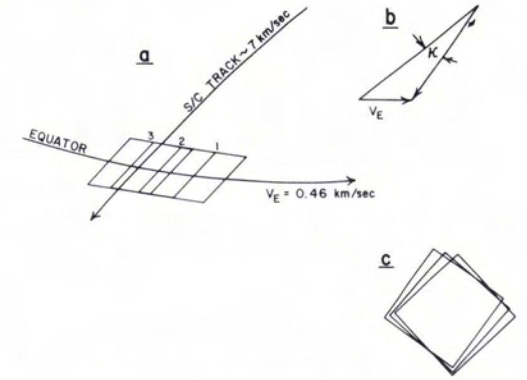


FIG. 9. (a) Earth rotation causes successive fore, vertical, and aft frames to be offset unless a controlled yaw maneuver is introduced; (b) the yaw angle, κ; and (c) stereotriplet registration with controlled yaw.

The baseline yawing algorithm, as simplified from exact form, can be expressed as

$$\kappa = \kappa_{\max} \cos \phi \qquad (5)$$

where ϕ is the satellite angle in orbit past the ascending node equator crossing, and where $\kappa_{\max}$ is equal to 3.89 degrees at the equator. Thus, near the poles the amount of yaw required is essentially zero; however, at high latitudes (because of Earth rotation) the image lines recorded by the different cameras over the previously discussed time interval will not be parallel, resulting in a rotation error between frames of approximately 0.4 degree. This equates to a ΔX value of approximately 200 m at the lateral margins of the second image. At the equator, where a yaw steering rate of near zero is required, the rotation error between frames is essentially zero, but can produce a small sidelap error of approximately 60 m between adjacent orbits (Figure 10). The rotation error between frames should not present a serious problem for analog interpretation or measurements, but may impair digital correlation of image data. A possible alternative to spacecraft yaw is to develop an independent yaw mechanization for each camera which would allow image registration to close tolerances. The cost and reliability of this additional capability, however, needs to be assessed.

OBLATE EARTH EFFECTS

The basic Stereosat imaging concept assumes a spherical Earth and a circular satellite orbit so that a constant satellite altitude is maintained. In practice, however, we must consider an oblate spheroid and an orbit which only approximates to a circle due to variations in the gravitational effect of the Earth. These deviations from the ideal situation create increases in slant range and altitude, l_1, h, and l_3, which in turn cause scale variations as

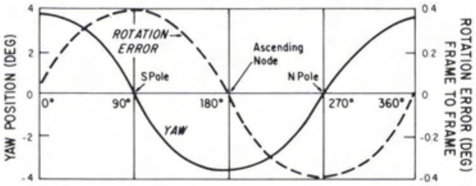


FIG. 10. Yaw required to compensate for Earth rotation and the resultant rotation error between frames.

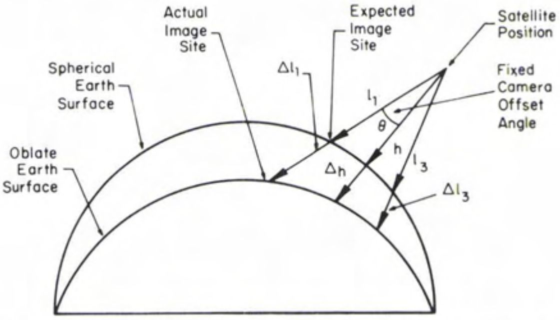


FIG. 11. An oblate Earth creates variations in altitude which influence image scale and area coverage (JPL, 1979).

the satellite increases its distance from the equator (Figure 11). The maximum cross-track increase in ground coverage at the poles is about 100 pixels or 1500 m. Maximum interframe image discrepancies equate to six pixels relative to the central camera and 12 pixels when the fore- and aft-camera images are compared. Again, this may create correlation problems. These displacements are correctable only to the extent the actual satellite altitude is known.

RESAMPLING CONSIDERATIONS

Any image deformations which are not maintained within specified limits must be removed in the ground data processing. The pixels may be resized, reshaped, realigned, and new grey level values determined to provide the necessary image quality. This resampling will require modeling of a large number of parameters, including orbit dynamics, satellite dynamics and orientation, and the impact of yaw. Second order variations in the mechanization may create discrepancies in imaging time, line separation distance, and image integration time. Camera alignment errors and temperature effects must also be considered to provide a basis for data resampling.

SPACECRAFT PERFORMANCE

In order to reach some conclusions regarding the geometric accuracy of Stereosat, it is necessary to consider the pointing, stability, and jitter of the spacecraft and its sensors. Pointing accuracy is the factor most often quoted as a measure of geometric performance. For example, the Multimission Modular Spacecraft (MMS) which will be employed for Landsat-D (and is a candidate for Stereosat) has a pointing accuracy *specification* of ±0.01 degree (one sigma). Thus, by design, the summation of all factors that influence the attitude control subsystem should have a root-sum-square value of less than the design specification. In addition, other factors such as orbit determination, timing, sensor alignment with the attitude control system (including the effects of thermal instabilities), and the torquing motions of a tape recorder (if used) influence the pointing geometry. A representative set of values for a Stereosat type mission are provided in Table 3 and, when combined, produce a root-mean-square error (RMSE) of about ±0.016 deg or ±200 m on the ground. The determination of the orbit emphemeris to ±140 m is based on Seasat A data and represents a worst case condition when compared to the predicted values of 40 to 100 m for the Tracking and Data Relay Satellite System (TDRSS) or the 5 to 70 m obtainable from the NAVSTAR Global Positioning System (GPS). When fully operational in the mid-1980's, the GPS will consist of 18 to 24 satellites in circular orbits at an altitude of approximately 20,000 km (Martin, 1980). These satellites will serve as reference points from which the position of other vehicles, including satellites (such as Stereosat) equipped with appropriate receivers, can be determined.

TABLE 3. STEREOSAT POINTING ACCURACY

Error Source	Pointing Accuracy	
	Degrees	Metres on Ground
Satellite (w/star tracker)	0.01	124
Orbit Ephemeris	0.011	140(10)*
Timing	0.00016	2
Alignment	0.004	50
Tape Recorder	0.0011	14
RMSE	±0.0156	±194(135)

* 140 m represents the estimate for two-day updates, whereas 10 m is based on GPS-Phase II specifications (18-24 satellites).

The GPS specifications provide for user position determination to ±10 m, velocity to 0.1 ms^{-1} and time to ±30 nanoseconds. However, even if the orbit ephemeris value is reduced to ±10 m, the pointing accuracy remains in excess of ±100 m.

Figures on satellite stability are often quickly transformed into geometric errors. Actually, the stability specification of 10^{-6} degs/sec for the MMS refers to the ability of the strap down attitude control system to control desired rates such as those required for yaw correction. It does not represent the capability of the satellite platform to completely eliminate rotations and, therefore, should not be used to predict geometric performance. The controlled yaw necessary for Stereosat requires steering rates up to 0.004 deg/sec, and the MMS system stability of 10^{-6} deg/sec would be adequate to insure registration of stereopairs. However, a stability specification of worse than 10^{-5} deg/sec may cause serious problems.

The third problem is jitter. The satellite will respond to dynamic disturbances caused by antenna or solar panel motions as would a tuning fork. Response is frequency dependent because of structural qualities. Studies based on Landsat-D structure assumptions indicate that the dynamic response caused by jitter is less than one pixel in 2.2 ms. Consequently, jitter does not appear to be a serious problem for Stereosat.

CARTOGRAPHIC POTENTIAL

Cartographic products which could be produced from Stereosat data include topographic, thematic, digital (e.g., DTM's or slope maps), and image maps. The possibilities of deriving these map products by analog and/or computer assisted processes, however, are controlled by spatial resolution, scale, and geometric fidelity of the image data.

SPATIAL RESOLUTION AND SCALE OF THE IMAGE DATA

The Stereosat cameras are designed to record images as a series of cross-track image lines each containing 4096 discrete picture elements (pixels). These pixels have a focal plane dimension of 15 μm, which equates to a 15 m instantaneous field-of-view (IFOV) at the image scale of 1:1,000,000. The IFOV of 15 m represents a five-times improvement over the 76 m IFOV of Landsat MSS data and an approximate two- to three-times improvement over the return beam vidicon (RBV) cameras of Landsat-3 and the Thematic Mapper of Landsat-D (Figure 12) (Slater, 1979; Williams and Salomonson, 1979). However, it is incorrect to assume that the linear improvement in IFOV will yield corresponding increases in cartographic information content (Welch, 1977). For example, in a recent study of the completeness of map information contained in Landsat-3 MSS and RBV images, it was found that about 40 percent of the *basic* planimetric features normally plotted on a 1:250,000 scale map could be *detected* on MSS images when their location and identity were already known (Welch *et al.*, 1980). The RBV images, representing an approximate two-times improvement in spatial resolution, permitted the detection of about 55 percent of the map features. Thus, the increase in detail more closely approximates to the square root of the IFOV improvement factor. Consequently, the Stereosat sensors with a 15 m IFOV may provide about two to three times the map information available from Landsat-3 image data, but this may still be insufficient to produce maps with detail comparable to the 1:250,000 scale cartographic products of the Defense Mapping Agency or U.S. Geological Survey. Despite this apparent limitation, the 15 m IFOV should be adequate for (1) good reconnaissance map products of relatively unexplored areas; (2) thematic maps required for geologic exploration; and (3) image maps to scales of 1:100,000 and 1:50,000. should also permit the detection of changes and to some extent the revision of existing map products. There is a significant need for these data.

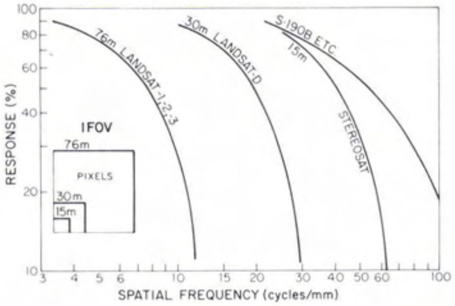


FIG. 12. Representative modulation transfer functions (MTF's) for the MSS, TM, and Stereosat sensors (based on sin *x/x* functions) and the ETC of Skylab (all adjusted to 1:1,000,000 scale) indicate the comparative resolutions of the systems.

GEOMETRIC FIDELITY

From a cartographic viewpoint, the most significant problems with Stereosat data are likely to be of a geometric nature. Consequently, it is desirable to determine the accuracy to which *X*, *Y*, *Z* terrain coordinates can be recovered from image data recorded by the proposed three-camera line-array system.

Major factors which appear to determine the accuracy to which *X*, *Y*, and *Z* terrain coordinates can be recovered from Stereosat data are listed in Table 4. An attempt is made to estimate quantitatively the magnitudes of the first five error sources in terms of root-mean-square error (RMSE). This is the accepted cartographic measure of variation

TABLE 4. SOURCES WHICH INFLUENCE THE CARTOGRAPHIC ACCURACY OF LINE ARRAY IMAGE DATA

Error Sources
(1) Pointing of sensors and attitude control
(2) Satellite velocity
(3) Precision of measurement
(4) Reliability of ground control
(5) Earth curvature, atmospheric refraction, etc.
(6) Processing equipment and procedures
(7) Adjustment Procedures

from the correct coordinate values at the 68 percent (1 σ) level of confidence. The effects of these errors are then considered in relation to map accuracy requirements.

Sensor pointing and attitude control. A sensor pointing error of 0.1 degree (the original Stereosat specification) will cause a planimetric error of approximately 1.2 km from the nominal altitude of 713 km (Figure 13). This is unacceptable to cartographers even though nominal correction values for a constant bias can be determined with the aid of ground control. In many areas of the world, however, ground control is inadequate for mapping tasks, and alternative methods of establishing corrections for pointing errors must be made available. One possibility is to utilize the NAVSTAR GPS. To be fully effective, however, the satellite position must be correlated with attitude information provided by the star tracker on board the satellite. At present, the GPS is not included in the Stereosat package and, as previously mentioned, it appears that RMS pointing errors of approximately ±0.016 degree can be expected. This equates to about ±200 m on the ground.

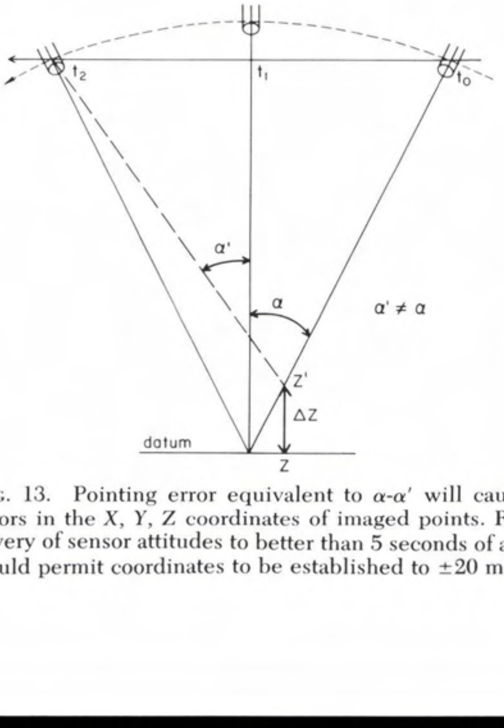


FIG. 13. Pointing error equivalent to α-α' will cause errors in the X, Y, Z coordinates of imaged points. Recovery of sensor attitudes to better than 5 seconds of arc would permit coordinates to be established to ±20 m.

Attitude stability and maintenance of controlled yaw are critical parameters. In order to achieve acceptable coordinate values with reasonable consistency, a worst-case correction rate value of 10^{-5} deg/sec at one sigma level of confidence is required. This equates to ±12 m (approximately 1 pixel) over the 92-second interval needed to record image data for the same area with the fore and aft cameras. For all practical purposes this error is negligible. If the MSS specification of 10^{-6} deg/sec can be achieved, attitude stability should not influence cartographic accuracy. An attitude correction rate of less than 10^{-5} deg/sec, however, may result in unacceptable y-parallax values. The y-parallax must be eliminated from a stereopair before height measurements or correlations can be obtained. Normally, this is easily accomplished in a manual mode, but is much more complicated if automatic correlation devices are used to derive height measurements (Panton, 1978).

Satellite velocity. Provided that ground control is available, the satellite image data can be transformed into the ground coordinate system; however, many of the rugged and/or remote areas of the world are poorly surveyed and contain few identifiable features that can serve as control points. Consequently, the image data must contain a framework of reference marks which, in the absence of ground control, can be used to insure reasonable geometric accuracies for measurements of distance and elevation. Therefore, it is anticipated that a series of timing marks (in the form of crosses, squares, or dots with an image dimension of approximately 30 to 50 μm) can be incorporated along the image track of the satellite and at the along-track margins of the image data. For the nominal scene coverage of 61.4 by 61.4 km, the timing marks could be spaced at constant object space intervals of 10 km, as shown in Figure 14 (or nominally every 10 mm in the focal plane of the vertical camera). In order to make efficient use of these timing marks and incur X, Y, Z coordinate errors of less than ±30 m (2 pixels) across the frame, the velocity of the satellite must be recoverable to about 0.002 km per sec and the time to about 0.0025 sec relative to a point of origin at the leading edge of the frame. Corrections to image coordinates can be determined by plotting the measured x-coordinates of the timing marks against their respective time values (Figure 15). The GPS could meet these requirements and facilitate the mapping of remote areas.

Measurement precision. The basic "heighting" equation for convergent line-array image stereopairs recorded with the proposed Stereosat configuration is (Welch, 1980)

$$\Delta h = \frac{\Delta p}{2 \tan \alpha} (SF) \qquad (6)$$

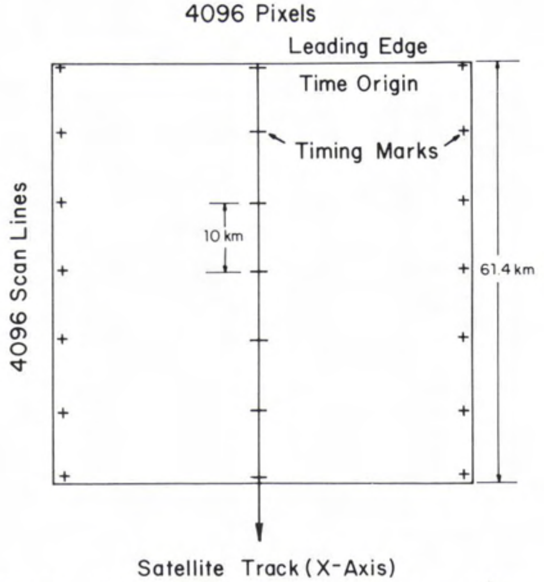


FIG. 14. Timing marks that could serve as reference marks would help to establish the internal geometric consistency of linear array image data.

where

- Δh is the difference in elevation between two objects,
- Δp is the difference in x-parallax between the two objects,
- SF is the image scale factor, and
- α is the angle of emission (26.57° as represented in Figure 5)

In the equation, the critical elements are α and Δp. For Stereosat, $\alpha = 26.57°$ and $2 \tan \alpha = 1.0$. Thus, "heighting" precision (i.e., repeatability in setting the floating mark or in x-correlation) is determined by the consistency with which Δp can be measured. This consistency may be expressed as a standard deviation, σ, computed from repeated measurements at points distributed throughout the stereomodel.

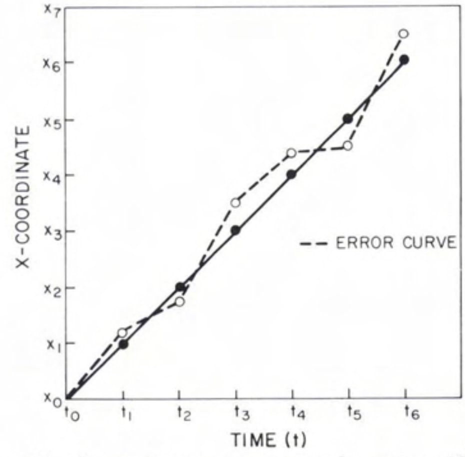


FIG. 15. Corrections to image coordinates could be determined by plotting the measured x-coordinates of timing marks against their respective time values.

In most Earth science and many cartographic applications, the difference in height, Δh, between two objects is of primary interest. Consequently, the magnitude of the height error, $\Delta h\sigma$ or $\Delta Z\sigma$, resulting from measurements at the *top* and *bottom* of the object must be estimated as follows:

$$\Delta p\sigma = \sqrt{\sigma^2 \text{ top} + \sigma^2 \text{ bottom}} \qquad (7)$$

and, therefore,

$$\Delta h\sigma = \frac{\Delta p\sigma}{2 \tan \alpha} (SF). \qquad (8)$$

Realistic $\Delta p\sigma$ values range from about ±10 to ±14 μm for sophisticated equipment such as comparators and from ±30 to ±70 μm for conventional stereoscopes/parallax bars. Values associated with automatic correlation devices are difficult to ascertain, but should compare favorably with those obtained with comparators. For the nominal image scale of 1:1,000,000 (and 15 μm pixels) these $\Delta p\sigma$ values equate to $\Delta h\sigma$ errors of ±10 to ±70 m. That is, for $\Delta h\sigma = 10$ m, it is assumed that objects must be considerably taller than 10 m before reliable determinations of height are possible. With analog images these errors can be reduced to an insignificant level by enlarging the images prior to measurement. At 1:250,000 scale, for example, the $\Delta h\sigma$ values in the above example are reduced to ±2.5 to ±17.5 m. Of course, the inherent capabilities of the image generation equipment (e.g., laser beam recorder) may influence the results.

Reliability of ground control. Ground control, in the form of identifiable points with known X, Y, Z coordinates in a defined coordinate system (e.g., UTM), is required in order to scale and level the stereo data before topographic mapping can proceed. Obviously, errors in ground control will affect map accuracy.

In practice, ground control will be obtained from available map coverage at scales of 1:20,000 to 1:50,000 in the better-mapped areas of the world. At these scales, map coordinates will generally have an RMSE of less than ±5 m. For the remote, rugged, and unmapped areas (for which Stereosat data will be of greatest value) the absence of ground control or the use of small-scale topographic maps as sources of control will prove to be a serious limitation to mapping activities. However, if data for spacecraft attitude, position, and velocity can be recovered, it should be possible to prepare reconnaissance maps of remote areas with sparse control. Analytical procedures such as those described by Case (1967) should provide an additional means of providing ground control and, perhaps, of improving the coordinate accuracies discussed below.

Earth curvature and refraction. Earth curvature will cause spot height errors of approximately ±70 m at the lateral margins of the 61.4-km swath recorded by the sensors. Errors due to Earth curvature and refraction are systematic and can be corrected during processing. The influence of variations in refraction is negligible for the narrow (5°) field-of-view.

CARTOGRAPHIC ACCURACY REQUIREMENTS

Most countries have formal map accuracy requirements; in the United States the National Map Accuracy Standards (NMAS) for planimetry and contours depicted on topographic maps may be summarized as follows:

- Planimetry—at least 90 percent of the well-defined points are plotted to within ±0.5 mm of their correct position.
- Contours—at least 90 percent of the contours are correct to within one-half the contour interval.

Although these standards are not necessarily relevant to geologic or thematic mapping tasks, they do provide a basis for formally assessing the cartographic potential of the Stereosat data. In Table 5, for example, the acceptable RMSE's in *X*, *Y*, and Z associated with NMAS (68 percent confidence level) for topographic maps at scales of 1:500,000 to 1:25,000 are listed. These values should be compared to the estimated errors in the Stereosat data.

It is difficult to conduct a sophisticated error analysis of the Stereosat system because of the unknown degree to which some of the design options discussed in this article can be implemented because of technical, political, or economic considerations. Nevertheless, in order to reach some provisional conclusions regarding the potential of line array camera system data for topographic mapping, it is appropriate to make some assumptions regarding the *minimum* errors expected under favorable circumstances.

- Sensor attitude can be recovered to within ±5 seconds of arc through one or a combination of factors, e.g., pointing and attitude control devices, ground control, GPS and timing mark data, and aerotriangulation procedures.* RMS error ≃ ±10 m in X, Y, and ±20 m in Z.
- Measurement precision will be equivalent to ½ pixel. RMS error ≃ ±8 m in X, Y, and Z.
- Miscellaneous errors, including those caused by misidentification of ground control, inaccurate map references, Earth curvature and refraction residuals, reformatting and resampling of data, processing or adjustment procedures. RMS error ≃ ± 10 m in X, Y, and Z.

If these errors are combined as shown below, an error of approximately ±20 m in X, Y and ±25 m in the Z coordinates appears to be the *best* result that can be expected.

$$\begin{aligned} \mathrm{RMSE}_{X,Y} &= \sqrt{10^2 + 8^2 + 10^2} \\ &\simeq \pm 15-20 \text{ m} \\ \mathrm{RMSE}_{Z} &= \sqrt{20^2 + 8^2 + 10^2} \\ &\simeq \pm 25 \text{ m} \end{aligned} \tag{9}$$

In order to relate the RMSE of approximately ±20 m to planimetric NMAS specifications, we must convert from the 68-percent level of confidence to the 90-percent value required by the standards. This equates to approximately ±35 m. An error of this size is acceptable for maps of 1:100,000 scale and smaller (90 percent to within ±0.5 mm). For remote areas, the anticipated RMS pointing errors of ±100 to ±200 m are compatible with the accuracy standards associated with maps of about 1:500,000 scale.

The standards for contours create a more serious problem as the closest contour interval (CI) meeting NMAS is given by

$$\begin{aligned} \mathrm{CI}_{\mathrm{NMAS}} &= 3.3 \times \mathrm{RMSE}_{Z} \\ &= 3.3 \times 25 \\ &\simeq 100 \text{ m} \end{aligned}$$

Contour intervals of this magnitude are normally found on topographic maps of rough terrain at scales of 1:250,000 and smaller (Figure 16). Thus, Stereosat does not appear to be well-suited to *formal* topographic mapping at scales larger than 1:250,000.

Conclusion

Stereosat is a proposed multipurpose mission designed to provide the Earth science and cartographic communities with stereo image data in both digital and analog formats. Stereotriplets generated in the along track direction by three line-array cameras with 15-m IFOV's and a 61.4-km swath width should permit coverage of most of the Earth's land areas during a planned three-year lifetime. The value of this coverage to cartographers, however, will be dictated by the accuracy of the digital image data, which, in turn, is largely a function of satellite control and the instrumentation incorporated in the system. Specifically, in order to limit RMSE's in *X*, *Y*, and *Z* to less than approximately ±30 m, it is necessary to (1) recover attitudes to within ±5 seconds of arc; (2) achieve attitude stability to about 10^{-5} deg/sec; and (3) incorporate timing marks in the image data.

An additional requirement which must be fulfilled if satisfactory stereo coverage is to be obtained involves the implementation of a yaw mechanism to offset the effects of Earth rotation. Systematic yaw can be introduced either to the spacecraft or to the individual cameras. Controlled spacecraft yaw offers the most direct solution, but the rate of yaw must vary systematically from about zero at the equator to 0.004 deg/sec at the poles. However, Earth rotation and the corresponding yaw mechanization introduces a rotation

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* With adequate ground control, aerial photographs obtained with metric cameras (f = 152 mm) and very precise analog or analytical instrumentation, typical RMSE's of about ±10 μm are obtained at the image scale. This is equivalent to about ±14 seconds of arc.

TABLE 5. MAXIMUM ALLOWABLE RMSEs FOR TOPOGRAPHIC MAPS MEETING NMAS

Map Scale	Planimetric RMSE $_{X,Y}$ (±0.3 mm)	Typical C.I.	Spot Height RMSE $_Z$
1:500,000	±150 m	100 m	±30 m
1:250,000	±75	50-100	±15-30
1:100,000	±30	20-50	±6-15
1:50,000	±15	20	±6
1:25,000	±7.5	10	±3

error between frames of a stereotriplet which varies from zero at the equator to a maximum of about 0.4 degrees near the poles. This is not a serious problem when using analog interpretation/measurement procedures. It does, however, reduce the possibilities for automatic mapping through the generation of terrain coordinates by the correlation of corresponding pixel displacements in the x-direction (i.e., the quasi epipolar mapping concept) (Helava and Chapelle, 1972). Other errors may be introduced by variations in satellite altitude over an oblate Earth, and the rigor to which resampling algorithms can be derived. Ideally, of course, it is desirable to avoid resampling with its attendant costs, time delays, and artifacts, by insuring the collection of error free data through adequate control of the spacecraft system.

There is considerable potential for producing thematic, digital, and image map products in the scale range from 1:50,000 to 1:250,000. Specifically, the image quality associated with a 15 m IFOV should provide adequate detail for image and thematic resource maps at scales of 1:50,000 or smaller, but is unlikely to permit the compilation of standard line map products at scales larger than 1:250,000. If geometric accuracies (RMSE's) of ±35 m (or less) can be assured for the X, Y, and Z coordinates through the utilization of attitude, velocity, and time data, it appears possible to meet formal planimetric map accuracy standards to scales of 1:100,000. Topographic mapping, however, will be restricted by the reliability of spot heights which, in turn, dictate the minimum acceptable contour interval. At present, it appears that the closest contour interval which can be reasonably attained is 100 m. As contour intervals of this magnitude are normally associated with topographic

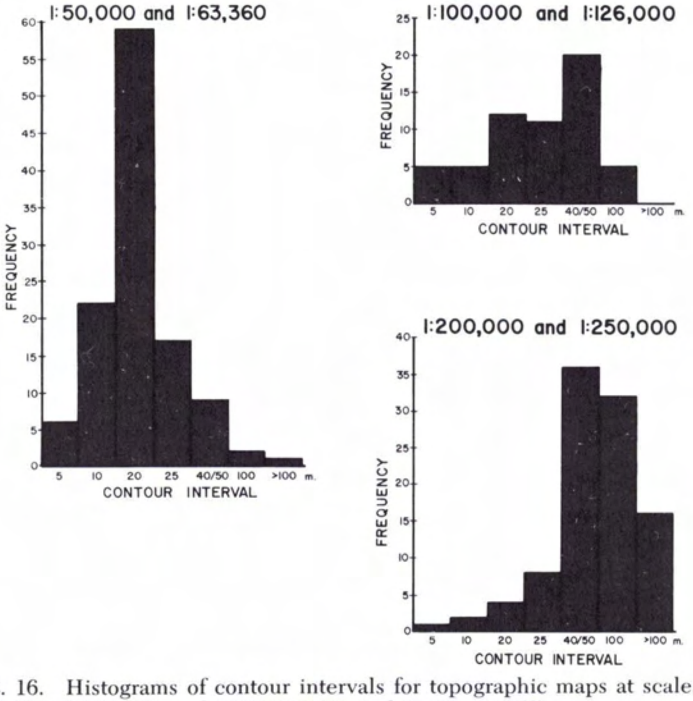

FIG. 16. Histograms of contour intervals for topographic maps at scales of 1:50,000; 1:100,000; and 1:250,000 (United Nations, 1976).

maps of 1:250,000 scale or smaller, the Stereosat data appear best suited for the formal topographic mapping of remote, rugged areas in South America, Africa, Asia, and Antarctica. Of course, it should be possible to derive the relative positions, distances, and elevations required for reconnaissance or exploration products and for image analysis tasks to within a few metres.

The real challenge of Stereosat (or a Mapsat) is in the realm of automated mapping. Even if the accuracy to which *X*, *Y*, *Z* coordinates can be recovered proves insufficient to meet formal mapping standards at scales of 1:100,000 or larger, the availability of a coordinate data base for the Earth will permit a thorough evaluation of the possibilities for constructing digital terrain models (DTM's), slope maps, and other digital map products from satellite data. It will also provide the opportunity to integrate the satellite derived coordinates with detailed geophysical and environmental surveys conducted by aircraft or field parties. The potential of Stereosat data will only be realized after cartographers and Earth scientists have had the opportunity to utilize it.

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