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Measurements from Linear Array Camera Images

Satellite control is the key to accurate measurements.

NEW SENSOR SYSTEMS based on charge transfer device (CTD) linear array technology are contemplated for use in planned or proposed satellite missions such as SPOT,[1] Stereosat,[2] Marine Observation Satellite (MOS),[3] and Mapsat,[4] but methods of extracting X, Y, Z terrain information from the image data have received relatively little attention. These missions will provide cartographers, geographers, geologists, foresters, and other scientists with high resolution data (10 to 20 m IFOV or instantaneous field-of-view) of unusual geometric characteristics in both monoscopic and stereoscopic formats. In this brief note some of the possibilities for deriving simple planimetric and height measurements from linear array camera images are considered.

ABSTRACT: *Pushbroom camera systems are contemplated for use on a number of satellite missions in the early 1980's, including* SPOT, *Stereosat, Marine Observation Satellite, and Mapsat. In order to obtain accurate planimetric and height measurements from these images, however, consideration must be given to the unique geometric characteristics of the linear array camera system. Planimetric measurements from near-orthogonal vertical images may be undertaken with the scale formula employed for vertical aerial photographs. However, height measurements from images recorded by a proposed three-camera Stereosat system require consideration of the parallel ray geometry. Differences in* x *parallax* (Δp) *are a function of elevation, time, and camera orientation angle* (α). *For an along track convergent camera configuration, height differences* (Δh) *may be closely approximated with the equation,* $\Delta h = (\Delta p/2 \tan \alpha) \cdot SF$. *Accuracy of measurements will be significantly influenced by variations in sensor attitude and velocity over the time interval required to record the pictures and by pointing errors due to tilt.*

The linear array camera operating in the "pushbroom" mode records the terrain along the orbit path as a series of successive lines or strips as a function of spacecraft velocity (v) and time (t),[5] i.e.,

$$\Delta x = v \cdot \Delta t \quad (1)$$

where

Δx = along track distance increment,
Δt = time increment, and
v = ground velocity ($\sim$6.8 km^{-1}).

Cross track coverage is limited by the number of detectors in the line array and the field-of-view (FOV) of the camera lens. Along track and cross track coverage are shown in Figure 1. No moving camera parts or scanning mechanisms are required.

Planimetric (x, y) measurements may be obtained from vertical images with the geometric relationships employed with vertical aerial photographs, i.e.,

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$$\frac{\text{focal length } (f)}{\text{spacecraft altitude } (H)} = \frac{\text{image distance}}{\text{object distance}} = \frac{1}{\text{scale factor } (SF)} \quad (1)$$

It should be realized, however, that, although the image is recorded as a near orthogonal projection in the x (along track) direction, it is comprised of a series of parallel perspective projections (one for each strip) in the y (cross-track) direction. Small displacements in the y direction due to relief and Earth curvature can be ignored unless (1) camera FOV's of more than about 5 degrees are used; (2) terrain is extremely rugged (e.g., greater than 1000 m relief); (3) images are greatly enlarged prior to analysis; and/or (4) highly analytical measurement techniques are employed. As an example, consider the proposed characteristics of the vertical Stereosat camera:

f = 705 mm
H = 705 km
FOV = 61.4 km
Scale at focal plane = 1:1,000,000

With relief (Δh) of 1000 m along a specific strip, the maximum displacement (Δy) at the lateral margin of the vertical image will be

$$\Delta y = \frac{\Delta h}{H} \cdot y = \frac{1{,}000}{705{,}000} \cdot 30.7 \text{ mm} = 0.044 \text{ mm} \quad (2)$$

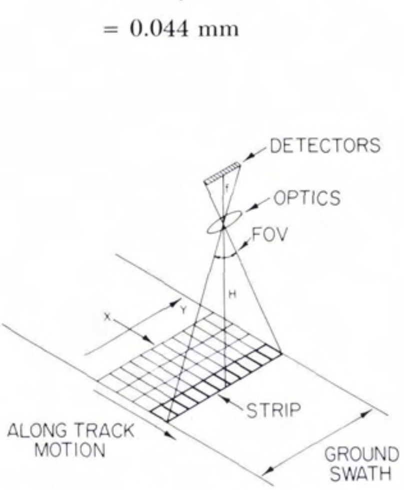

FIG. 1. Along track (x) coverage is a function of spacecraft velocity and time, whereas cross track (y) coverage depends on the camera FOV and the number of detectors.

With a 10× image enlargement, Δy is increased to 0.44 mm, which is still rather insignificant for the majority of applications. Thus, in most instances, the vertical image can be considered a map and distances scaled accordingly.

Height measurements, however, present a more serious problem. In order to obtain x parallax and the differences in x parallax required for the perception of terrain relief in the stereo mode, two approaches are proposed: (1) images recorded from adjacent orbits by cameras equipped with rotatable mirrors to control the pointing direction (SPOT); or (2) images recorded successively along the orbit path from fixed forward, vertical, and aft pointing cameras (Stereosat). By recording data from adjacent orbits the SPOT system relies on perspective geometry to develop parallaxes, whereas the three-camera system proposed for Stereosat makes use of parallel ray geometry. It is the latter system which is examined.

In the three-camera system proposed for Stereosat, forward and aft pointing cameras oriented 26.57 degrees (α) from the object vertical in the along-track direction and a vertical camera orthogonal to the terrain will be employed to obtain stereoscopic coverage. Base-to-height ratios of 0.49 (vertical and fore/aft) and 1.0 (fore and aft) are planned from the nominal altitude of 705 km (775 km slant range for forward and aft cameras).[*] With this arrangement, the x coordinates in the image planes of the forward and aft pointing cameras are a function of elevation and time (Figure 2), and height difference (Δh) measurements are closely approximated with the following equation:[†]

$$\Delta h \simeq \frac{x_1 - x_2}{2 \tan \alpha} \cdot SF \text{ or } \Delta h \simeq \frac{\Delta p}{2 \tan \alpha} \cdot SF \quad (3)$$

where

x_1, x_2 = x parallaxes measured in the image plane,
Δp = difference in x parallax,
α = camera orientation angle, and
SF = image scale factor.

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[*] The focal lengths for the vertical and oblique cameras are 705 and 775 mm, respectively. However, the altitude (705 km) may be changed, requiring a modification of the focal lengths to achieve a scale of 1:1,000,000 at the focal plane.

[†] In order to obtain more exact values for Δh, a small correction must be introduced to account for the curved trajectory of the satellite. For the referenced fore and aft stereopair, the denominator 2 tan α must be modified to 1.972 tan a.

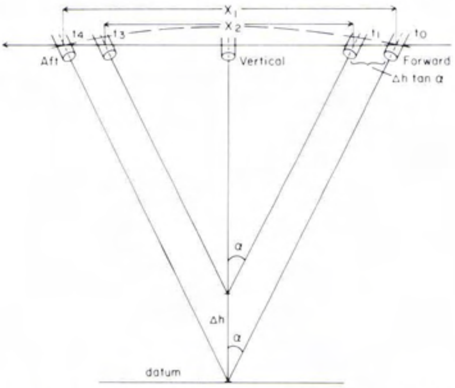

FIG. 2. For the above three-camera configuration, Δh is a function of α and of the time interval (Δt) required to record both the top and bottom of the object. In the forward/aft stereopair Δt is represented by $(x_1 - x_2) = \Delta p$. A dashed line indicates the satellite's trajectory.

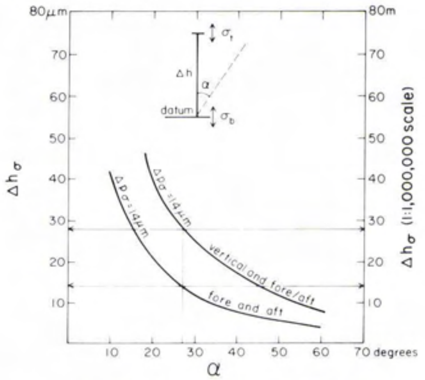

FIG. 3. The precision in setting the floating mark at the top and bottom of an imaged object results in an error, $\Delta p_\sigma = \sqrt{\sigma_t^2 + \sigma_b^2}$. A representative value of $\Delta p_\sigma = \pm 14$ μm is assumed. This error (Δp_σ) may then be converted to a height error (Δh_σ) and plotted as a function of the angle (α). A stereopair comprised of fore and aft images minimizes the influence of pointing errors, as does the enlargement of images prior to measurement.

Similar relationships were previously developed for the stereoscopic strip camera.[6] Unlike the strip camera, however, the pushbroom system is recording data along a single cross-track line at any given instant in time without film movement (or IMC) to complicate the geometry. Consequently, the quantity $(x_1 - x_2)$ as measured with either a mirror stereoscope and parallax bar or a comparator may be taken as the difference in parallax (Δp).

For heighting, the forward and aft stereopairs will give superior results since 2 tan α for a 26.57 degree angle (α) is 1.0. Thus, at the image scale, $\Delta x = \Delta p \simeq \Delta h$, which is a convenient relationship. Correspondingly, any measurement error in Δp causes an equivalent error in Δh. If the vertical image is employed with either the forward or aft image to form the stereopair, the denominator of Equation 3 becomes tanα and an error in Δp causes an error of approximately twice that magnitude in Δh. The relationship between α, Δp error, and Δh error is developed further in Figure 3.

Of course, in a pushbroom system the stereo images are generated continuously, and approximately 92 seconds are required to record a stereo-triplet in the proposed Stereosat configuration. Obviously, any variation in the attitude of the satellite over this rather long interval will produce planimetric and vertical displacements. State-of-the-art attitude correction rates range from about 10^{-4} deg/sec to 10^{-5} deg/sec, which over the above time interval could result in height errors of between approximately 125 and 10 m. Consequently, the attitude control/recovery system is an extremely important ingredient of spacecraft designed to provide data for applications requiring X, Y, Z terrain measurements.

Pointing errors or bias due to a constant tilt will introduce a systematic datum error which can be corrected with the aid of ground control, attitude information, and appropriate adjustment procedures.[7] Other errors introduced by variations in spacecraft velocity and Earth rotation can be compensated for with the aid of timing marks and appropriate spacecraft controls.

In conclusion, sophisticated processing procedures undoubtedly will be developed to extract terrain coordinates from digital data recorded by pushbroom sensors,[8] and, as with Landsat, the full potential of the data probably will not be realized until after it becomes available. Nevertheless, scientists should be able to utilize conventional measurement techniques to derive useful X, Y, Z terrain information from images generated by pushbroom sensor systems.

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