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The Relationship of Acquisition Systems to Automated Stereo Correlation*

An electro-optical space system can be designed which will optimize one-dimensional stereo correlation and lead toward the automation of topographic mapping.

Abstract: *Planning for stereo aerial photography includes consideration of the sun's elevation, which generally is set for at least 30° to insure that the scene is adequately illuminated. Planning also should exclude illumination and viewing azimuths which lead to the so-called "hot spots" (backscatter and specular reflection areas) on the image. In addition, the balancing of atmosphere effects on the two rays that create the stereo image should be accomplished in so far as possible. Today a concerted effort is being made to expedite the mapping process through automated correlation of stereo data. Stereo correlation involves the comparison of radiance (brightness) signals or patterns recorded by sensors. Conventionally, two-dimensional area correlation is utilized but this is a rather slow and cumbersome procedure. Digital correlation can be performed in only one dimension where suitable signal patterns exist, and the one-dimensional mode is much faster. Some of the factors which aid or limit the correlation process can be controlled during the data acquisition process. Space sensing systems offer unique opportunities to improve the correlation function by creating a stereo model which is very narrow in one dimension and by controlling the sun's angle to the stereo sensing system to equalize the response in the two records which make up the stereo scene. Electro-optical (EO) systems, suitable for space use, also have much greater flexibility than film systems. Thus, an EO space system can be designed which will optimize one-dimensional stereo correlation and lead toward the automation of topographic mapping.*

Introduction

Mapping of the Earth's surface by use of a stereomodel based on overlapping frame photographs is both well defined and proven effective. However, the procedures used are highly dependent on manual operations, and mapmaking from such stereomodels is both slow and expensive. Some progress toward the automation of this process has been made through automated stereo correlation but, to date, these systems have been only partially successful (Mahoney, 1981). Correlation depends on both geometry and radiometry, and film systems that create the stereo images have certain characteristics which limit automated stereo correlation. On the other hand, a space system utilizing electro-optical (EO) recording rather than film, does not have the same limitations as a film system and offers the opportunity to further automate the correlation function.

Mapping Camera Systems

Conventional aerial mapping cameras record a sizable part of the Earth's surface in a fraction of

* The term correlation as used herein refers to the generic rather than mathematical definition of the term. Thus, the matching of any two sets of data which define the same point or area, regardless of the method used, is considered correlation.

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a second. Stereo mapping cameras have fields-of-view from 40° to 120° across the flats of the format. The stereomodels created from the overlapping photographs involve angular fields of at least 40° in the cross-track (Y) direction while the angular field in the along-track (X) direction depends on the base-height ratio utilized which is reflected in the percentage of image overlap of the stereo pair. The reflected radiance from an object that is recorded by a camera depends upon the angular relationships between the sun, the object, and the camera; and the larger the field-of-view, the greater the difference in the response in the two images which make up the stereo pair. In order to obtain good stereo, the angular difference between viewing the same object from the two camera stations must be large, but this angular condition need only exist in the X direction to create the needed parallax. The sizable Y direction angular fields of view (40° to 120°) do nothing to help in the determination of elevations (x-parallax) but do create angular conditions which affect correlation and introduces sizable Y displacements which must be taken into account in the data processing. Space film mapping cameras may involve longer focal lengths such as 12 inches (305 mm) and reduced angular fields-of-view when compared to aerial cameras, but 41° is about the smallest field so far defined (Doyle, 1981).

In addition to geometry, radiometry is a key factor in any stereo system. The Earth exhibits large differences in its radiometric response and thus the camera requires a large dynamic range to record both the brightest and darkest areas. On the other hand, many Earth features exhibit only slight response differences and therefore high sensitivity is required to record the subtle differences. Mapping cameras, because of their relatively wide field-of-view, also provide unequal exposure on film unless vignetting is fully compensated. Such compensation can only be approximated by antivignetting filters. Under any given set of film-filter exposure conditions a mapping camera has limitations with respect to dynamic range and sensitivity (sensitometric properties) and one or the other (or both) of these limitations often preclude the recording of the Earth scene in desired detail (Slater, 1980; Eastman Kodak Co., 1982). The differences between many Earth surface objects and conditions can only be recorded by using several spectral bands. Most aerial film is monochromatic, but color and color-infrared (multi-emulsion) films are also available to provide a multispectral response. However, aerial film response is limited to 0.9-μm maximum wavelength, and when different wavelengths are recorded on the same film, some degradation and overlap of the spectral bands occur in the recorded images. By using two or more commonly boresighted film cameras loaded with black-and-white films filtered for different spectral responses, the multi-emulsion degradations can be overcome, but the 0.9-μm limitation still exists. Thus, film systems have only a limited multispectral capability.

Electro-Optical Space Systems

Because space is basically free of attitude disturbing forces, it is possible to design continuous digital stereo acquisition systems whereby the precise geometry required for three-dimensional mapping (X, Y, Z,) can be achieved without resorting to a frame camera with its recognized geometric fidelity. One such proposed system is known as Mapsat (Colvocoresses, 1982) and, because this system has been defined and patented*, it is used to illustrate the EO space approach. The orbit defined for Mapsat is the same as for Landsats 1, 2, and 3 with a nominal 919-km altitude and 99° inclination. The 11° field-of-view of Mapsat differs widely from that of film systems. In the X direction two of the three linear array sensors are tilted fore and aft 23° which, when coupled with the forward motion of the satellite, provides an angle of convergence of about 51°. This provides a very strong x-parallax situation with a base-height ratio of 1.0. However, in the Y direction the viewing angle is governed by the field-of-view of the optics, which is only 11°. Thus, a stereo model is generated which provides the desired x-parallax but which does not have the angular range in Y which introduces undesirable radiometric and geometric problems. Using the fore and aft arrays, the stereo model is 180-km wide across track and continuous along track. Such a model has a large advantage over one with a sizable angular extent in Y provided appropriate illumination conditions are utilized to take advantage of this elongated model shape. Figure 1 illustrates the Mapsat stereo acquisition concept.

In theory EO systems may not have any better sensitivity than a particular film which has been properly exposed and developed. However, the flexibility provided by an EO system is much higher. This flexibility is demonstrated by changes in gain setting which can be made on demand. Gain setting is roughly equivalent to gamma or contrast in a photographic system. Although the flexibility of EO systems applies to data acquisition, it is of far greater importance in image processing. The digital data generated by an EO system can be geometrically and radiometrically transformed by computer in an endless variety of ways. Film, once developed, is relatively inflexible unless digitized—a process which has many practical limitations. The effec-

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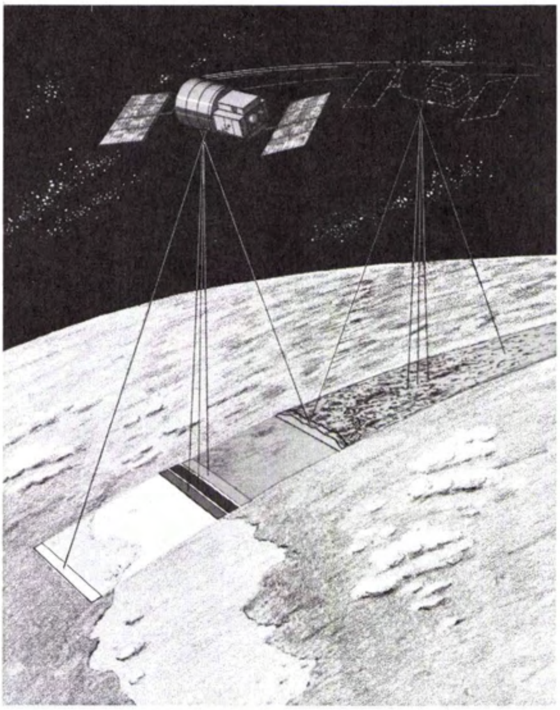

FIG. 1. The Mapset stereo acquisition concept.

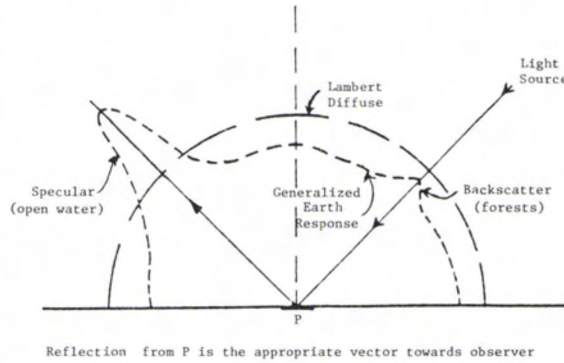

FIG. 2. Reflected radiance from two surface types (Autometric, 1966).

tiveness of electro-optical systems has recently been demonstrated by astronomers who, using EO systems rather than conventional photographic plates, have recorded the return of Halley's Comet when it was still too distant to be recorded by photography. A recent article in *Scientific American* (Kristion and Blanke, 1982) describes the advantages of charge-coupled devices (CCD), which are typical of the sensors used in EO systems. This article indicates that the dynamic range of CCDs is many times that of film. The imaging problems of astronomy and Earth sensing are in many ways closely related.

Scene Illumination and Reflectance Considerations

The reflectance characteristics of the Earth's surface are both varied and complex. Lambertian surfaces exhibit the same radiance regardless of the direction of viewing. Smooth surfaces, typified by open water, reflect like a mirror where the angle of reflectance equals the angle of incidence, and some surfaces, such as forests, reflect more light back in the direction of illumination, creating what is known as backscatter. The typical Earth's land scene is often assumed to be Lambertian, but this assumption should be modified to account for open water areas and for areas with shadows or high backscatter which create a "hot spot" in the zero-shadow area (Smith, 1968). Collectively, the Earth's surface provides some sort of semi-specular response, as illustrated by Figure 2 (Eaton and Dirmhirn, 1979). The backscatter and the specular response from a smooth water surface can both be eliminated by imaging under conditions of low to moderate solar elevation. However, the specular reflectance from a rough water surface is both higher and broader than the backscatter peak, and it frequently cannot be avoided in a stereo data acquisition system which necessarily involves two different viewing directions.

Stereo Correlation Considerations

Two separate functions are involved in stereo correlation. The first involves the search for the corresponding image data and the second involves the actual matching of the data. The trained human eye has a highly effective search capability over a sizable area whereas the computer needs a well-defined area of limited extent to make a successful search for the corresponding data. Stereo correlation normally involves the matching of a two-dimensional array of imagery or digital data, but it has been shown (Helava and Chapelle, 1972) that one-dimensional stereo correlation is both feasible and, under proper conditions, practical in the automated digital mode. Mapsat is designed to record the two sets of stereo data in the one-dimensional (epipolar) mode. Thus, the search function, which is intended to be done by computer, is simplified because the search is reduced from a two-dimensional to a basically one-dimensional pattern. In actual practice the search may involve several one-dimensional data sets but will still represent an enormous simplification compared to the usual two-dimensional search function.

Actual correlation, by either the human eye or computer, is achieved by the matching of corresponding feature records or records of groups of features. The eye identifies such features by the

TABLE 1. RANGE AND MEAN LATITUDE FOR OPTIMUM SUN CONDITIONS FOR STEREO CORRELATION BASED ON SUN ELEVATIONS OF 20° TO 70° AND SUN AZIMUTH OF 90° ± 30° TO SATELLITE HEADING. SEE NOTES 1 AND 2.

Time of Imaging at Descending Node (Equator)	Latitude Range and Mean Based on Time of Year (Equinoxes and Solstices)			
	March	June	September	December
11:00 A.M.—range	—	—	—	10°S to 35°S
mean lat.	—	—	—	22°S
10:30 A.M.—range	15°N to 10°S	—	15°N to 5°S	5°S to 35°S
mean lat.	2°N	—	5°N	20°S
10:00 A.M.—range	25°N to 15°S	40°N to 15°N	25°N to 10°S	0° to 45°S
mean lat.	5°N	27°N	7°N	22°S
9:30 A.M.—range	30°N to 15°S	45°N to 15°N	30°N to 15°S	5°N to 55°S
mean lat.	7°N	30°N	7°N	25°S
9:00 A.M.—range	40°N to 25°S	55°N to 15°N	35°N to 20°S	15°N to 75°S
mean lat.	7°N	35°N	7°N	30°S
8:30 A.M.—range	50°N to 30°S	60°N to 15°N	45°N to 30°S	20°N to 75°S
mean lat.	10°N	37°N	7°N	27°S
8:18 A.M.[3]—range	55°N to 29°S	64°N to 16°N	51°N to 33°S	26°N to 74°S
mean lat.	13°N	40°N	9°N	24°S
8:00 A.M.—range	60°N to 20°S	70°N to 15°N	55°N to 25°S	25°N to 70°S
mean lat.	20°N	42°N	15°N	22°S
7:30 A.M.—range	60°N to 0°	75°N to 20°N	65°N to 10°S	5°N to 50°S
mean lat.	30°N	47°N	27°N	22°S

[1] Same sun-synchronous orbit as Landsat 1, 2, and 3 (919-km altitude, 99° inclination).
[2] One stereo sensor (11° FOV linear array) looking 23° fore and the other looking 23° aft along the satellite heading.
[3] Time of imaging at descending mode which provides maximum latitude range of optimum sun conditions for stereo correlation. Range and mean latitude values have been carried to the nearest degree (as opposed to nearest 5 degrees) for this time (8:18) only.

size, pattern, and radiance (brightness) of their response. A computer does basically the same thing except that it matches mathematical functions based on feature size, pattern, and radiance. The degree of correlation will depend on the similarity of the feature response on the two records that create the stereo condition. Recorded feature size, spacing, and pattern differences are caused by terrain slopes and the base-height ratio, while the response differences are caused by illumination and reflectance conditions. Terrain slopes are fixed and the base-height ratio must be adequate to define the vertical accuracy required. However, the base-height ratio should be no larger than necessary in order to maintain a high degree of correlation. With Mapsat a base-height ratio of only 0.5 is used in steeper terrain where the permitted contour interval may be relatively large (lower vertical accuracy). In flatter terrain the base-height ratio of 1.0 is required and is achieved with a 51°

TABLE 2. MEAN LATITUDE AND PERCENT OF DESCENDING LIMB (DAYLIGHT, 82°N TO 82°S) THAT SUN CONDITIONS ARE OPTIMUM[3] FOR STEREO CORRELATION. SEE NOTES 1 AND 2.

Time of Imaging at Descending Node (Equator)	Annual Mean Latitude for Optimum Conditions	Percent[4] Time of Year (Equinoxes and Solstices)				Percent[4] Annual Mean
		March	June	Sept.	Dec.	
11:00 A.M.	22°S	0	0	0	15	4
10:30 A.M.	9°S	15	0	12	18	11
10:00 A.M.	4°N	24	15	21	27	22
9:30 A.M.	5°N	27	18	27	36	27
9:00 A.M.	5°N	40	24	34	55	38
8:30 A.M.	7°N	49	27	45	58	45
8:18 A.M.	10°N	51	29	51	61	48
8:00 A.M.	10°N	49	34	49	58	47
7:30 A.M.	20°N	37	34	45	34	37

[1] Same sun-synchronous orbit as Landsat 1, 2 and 3 (919-km altitude, 99° inclination).
[2] One stereo sensor (11° FOV linear array) looking 23° fore and the other looking 23° aft along the satellite heading.
[3] Sun elevation of 20° to 70° and sun azimuth of 90° ± 30° to satellite heading.
[4] Percentages given on tables 2, 3, and 4 have been computed as if the north to south velocity of the satellite were uniform. This is a simplification which is not technically correct, particularly in the polar regions. However, such a simplification is considered justified because of the special imaging conditions in the polar regions.

TABLE 3. PERCENTAGE OF THE REGION BETWEEN 65°N AND 35°S[3] THAT SUN CONDITIONS ARE OPTIMUM[4] FOR STEREO CORRELATION. SEE NOTES 1 AND 2.

Time of Imaging at Descending Node (Equator)	Percent Time of Year (Equinoxes and Solstices)				Percent Annual Mean
	March	June	Sept.	Dec.	
11:00 A.M.	0	0	0	25	6
10:30 A.M.	25	0	20	30	19
10:00 A.M.	40	25	35	35	34
9:30 A.M.	45	30	45	40	40
9:00 A.M.	65	40	55	50	52
8:30 A.M.	80	45	85	55	66
8:18 A.M.	84[5]	48[5]	84[5]	61[5]	69
8:00 A.M.	80	50	80	60	67
7:30 A.M.	60	45	75	75	59

[1] Same sun-synchronous orbit as Landsat 1, 2, and 3 (919-km altitude, 99° inclination).
[2] One stereo sensor (11° FOV linear array) looking 23° fore and the other looking 23° aft along the satellite heading.
[3] This latitude range includes over 90 percent of the world's population, economic importance, and land area (exclusive of Antarctica).
[4] Sun elevation of 20° to 70° and sun azimuth of 90° ± 30° to satellite heading.
[5] To nearest percent rather than nearest 5 percent.

convergence angle. This 51° involves two views at the same depression (vertical) angle but at a 180° difference in azimuth. Where this angular difference creates a sizable response difference, it will in turn adversely affect correlation. Such differences will be caused by specular and backscatter effects because, as previously stated, the Lambertian condition creates equal response in all directions from a particular surface. The percentage of shadow which is recorded by a sensor is also a significant factor. If one of the stereo sensors is looking toward the sun and the other away from it, the response difference is significant in areas where shadows are involved such as in a forest, city, or cornfield (Fleming, 1963). The atmosphere also creates differences in response depending on the relationship of the observer (sensor) and the sun to the scene (Slater and Jackson, 1982). In the Mapsat case, with its narrow cross-track field-of-view, significant response differences will generally occur only where one of the views is toward the sun and the other away from it. This undesirable condition can best be avoided by keeping the sun's azimuth as close as possible to 90° to the heading of the satellite. With the sun at right angles to the satellite heading, neither sensor is looking toward the sun and differences in response will be kept to a minimum. Mapsat geometry also provides for generally similar paths through the atmosphere and thus minimizes atmospheric differences (Slater and Jackson, 1982). There is no practical way by which the heading of an Earth-orbiting satellite can be kept at right angles to the direction of the sun but, through careful selection of orbit and time of day for imaging, this desirable angular condition can be optimized. To illustrate this concept, the sun-synchronous orbit of Mapsat was programmed by John Snyder of the National Mapping Division, U.S. Geological Survey for imaging at various times of day. Tables 1, 2, 3, and 4 tabulate the results. These tables illustrate the advantages of imaging with a stereo satellite at relatively low sun elevations. It would appear that crossing the descending node (equator) between 8:00 and 8:30 A.M. would be more desirable than the nominal 9:30 A.M. utilized for Landsats 1, 2, and 3. Of course, there are considerations other than stereo correlation for any general-purpose satellite; however, where stereo correlation is involved, the earlier imaging time has an obvious advantage. It should be noted that, during the last 16 months of the life of Landsat 1 (February 1977 to June 1978), its time at descending node was 8:30 A.M. rather than 9:30. During this period some of the finest

TABLE 4. TIME-OF-DAY FOR DESCENDING NODE VS OPTIMUM[3] CONDITION FOR STEREO CORRELATION. SEE NOTES 1 AND 2.

Descending Node Time	Percent of Imaging Under Optimum Conditions, Annual Mean	
	Half Orbit (82°N to 82°S)	65°N to 35°S
10:30 A.M.	10	20
9:30 A.M.	25	40
8:30 A.M.	45	65
8:18 A.M.	48[4]	69[4]
7:30 A.M.	35	60

[1] Same sun-synchronous orbit as Landsat 1, 2, and 3 (919-km altitude, 99° inclination).
[2] One stereo sensor (11° FOV linear array) looking 23° fore and the other looking 23° aft along the satellite heading.
[3] Sun elevation of 20° to 70° and sun azimuth of 90° ± 30° to satellite heading.
[4] To nearest percent rather than nearest 5 percent.

general-purpose Landsat images were obtained, several with sun elevations in the order of 20°.

Summary and Conclusions

- In order to expedite the mapping process the stereo correlation function must be automated.
- Conventional camera systems have characteristics which limit the degree to which their film products can be applied to automated stereo correlation.
- EO systems have advantages over film systems in that they have higher flexibility with respect to dynamic range, sensitivity, and processing. They also have a much broader multispectral capability than film systems.
- A space-borne EO system can generate stereo data directly in epipolar planes (one-dimensional data sets) which greatly enhances correlation by simplifying the search for corresponding data.
- By proper selection of orbit and times of imaging, the sun's direction will be basically at right angles to the along-track stereo model over sizable portions of the daylight limb of the orbit. This will optimize the similarity of response from the two imaging positions, and in turn enhance the stereo correlation function.
- As Tables 3 and 4 indicate, the sun's azimuth can be held to 90° ± 30° for 48 percent of the daylight limb, and during the imaging from 65°N to 35°S, where over 90 percent of man's activities exist, this condition will hold for 69 percent of the time. Moreover, such imaging will involve sun elevations of 20° to 70°, which are desirable limits for general-purpose Earth sensing.
- The Earth's surface is highly complex and there is no way by which the degree of automated stereo correlation can be accurately forecast for a given area. However, research can and should be continued which will indicate the relative improvement that can be expected from the proper design of a space stereo system.
- Automation of the mapping process can be enhanced through the implementation of a properly designed space stereo system.

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