September 30, 1981

AN AUTOMATED MAPPING SATELLITE SYSTEM (MAPSAT)*

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Abstract

Throughout the world, topographic maps are compiled by manually operated stereoplotters that recreate the geometry of two wide-angle overlapping stereo frame photographs. Continuous imaging systems such as strip cameras, electro-optical scanners, or linear arrays of detectors (push brooms) can also create stereo coverage from which, in theory, topography can be compiled. However, the instability of an aircraft in the atmosphere makes this approach impractical. The benign environment of space permits a satellite to orbit the Earth with very high stability as long as no local perturbing forces are involved. Solid-state linear-array sensors have no moving parts and create no perturbing force on the satellite. Digital data from highly stabilized stereo linear arrays are amenable to simplified processing to produce both planimetric imagery and elevation data. A satellite, called Mapsat, including this concept has been proposed to accomplish automated mapping in near real time. Image maps as large as 1:50,000 scale with contours as close as 20-m interval may be produced from Mapsat data.

Background

The geometry of stereo mapping photographs, whether taken from aircraft or satellite, is well known and documented. Transforming such photographs into topographic maps is a relatively slow and expensive process that for many critical steps defies automation. Compared to an aircraft, a satellite offers the unique advantages of much greater stability and uniform velocity.

Utilizing these advantages, a sensing system in space can now provide imagery of mapping quality, even though a continuous electro-optical imaging system is used instead of a mapping camera with its inherent high geometric fidelity. The next generation of space sensors will include solid-state linear arrays (fig. 1) that involve no moving parts. By continuous imaging with very high geometric fidelity they will permit, at least in part, the automated mapping of the Earth from space in three as well as two dimensions. The fundamental difference between conventional and continuous stereo methods is illustrated by figure 2.

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* Approved for publication by Director, U.S.G.S.

At least four papers have been published that relate directly to automated three-dimensional mapping. In 1952, Katz (1) showed how height measurements could be made with a stereoscopic continuous-strip camera. The geometry of such a strip camera and stereo linear arrays is basically the same. In 1962, Elms (2) elaborated on the strip camera concept and indicated its advantages over frame cameras as a possible component of an automated mapping system. In 1972, Helava and Chapelle (3) described the development of instrumentation by which a conventional stereomodel can be scanned using the epipolar-plane* principle, and thus reducing image correlation from a two-dimensional to a basically one-dimensional task.

In 1976 Scarano and Brumm (4) described the automated stereo-mapper AS-11B-X which utilizes the epipolar-scan concept and one-dimensional digital image correlation described by Helava and Chapelle. Thus the concept of reducing photogrammetric data stero correlation from two to one dimension is well established. The cited literature, however does not describe the possibility of imaging the Earth directly in stereoscopic digital form suitable for one-dimensional processing.

Beginning in 1977 a serious effort to define a stereo satellite or Stereosat (5) was undertaken by NASA. The Stereosat concept calls for linear-array sensors, looking fore, vertical and aft, but its principal objective is to provide a stereoscopic view of the Earth rather than to map it in automated mode. There are other ways of obtaining stereo imagery with linear arrays. The French SPOT (6) satellite can look left or right of the track and thus achieves stereo by combining imagery from nearby passes of the the satellite. NASA's Multispectral Linear Array (MLA) concept (7), as so far defined, calls for fore and aft looks through the same set of optics by use of a rotating mirror. However, neither the SPOT nor NASA's MLA approach are considered optimum for stereo mapping of the Earth, as neither is designed to acquire data in continuous form.

Mapsat Geometric Concept

Linear arrays represent a relatively new remote sensing concept. Five papers on this subject were presented at the ASP/ACSM annual convention during March 1978 (8,9,10,11,12). These papers concentrated on detector

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*An epipolar plane is defined by two air or space exposure (imaging) stations and one point on the ground.

technology and the application of linear array sensors in a vertical imaging mode. Welsh (13) recently described the geometry of linear arrays in stereo mode, although his error analysis for such a system is based on measurements made from images rather than computations based on the digital data.

By combining the technology of linear arrays, the concept of epipolar-plane scanning, and the experience gained from Landsat and other space sensing systems, Mapsat was defined (14), and its proposed parameters are listed in Table 1. The Mapsat concept was the work of several individuals, but perhaps the single most important contribution was that of Donald Light (verbal communication), then of the Defense Mapping Agency, who first suggested that epipolar planes, as described by Helava (3) and used in the AS-11B-X plotter, could be achieved directly from space and that topographic data might then be extracted in real time. There are several feasible configurations by which linear array sensors can continuously acquire stereo data. It was decided that the system must permit selection from the three spectral bands, provide for two base-to-height ratios of 0.5 and 1.0 and be compatible with the epipolar concept. Figure 3 illustrates the configuration selected to accomplish the stereoscopic as well as monoscopic functions.

Acquiring stereo data of the Earth in epipolar form directly from space is the fundamental geometric concept of Mapsat. The epipolar conditions shown in Figure 4 implies that five points--the observed ground point P, the two exposure stations S_1 and S_2, and the two image detectors f_i and a_i--lie in a single plane. If this epipolar condition is maintained as the satellite moves along its orbit, every point P observed by detector f_i in the forward looking array will also be observed subsequently by detector a_i in the aft looking array. Thus image correlation can be obtained by matching the data stream from detector f_i with that from a_i--a one-dimensional correlation scheme. This description applies equally to the use of the vertical with either the fore-or aft-looking array but involves a weaker (0.5) base-to-height ratio than the described use of the fore and aft arrays (base-to-height ratio of 1.0). In practice the data streams from more than one detector may be involved since there will normally be some offset in the path of a given pair of detectors. Moreover under certain conditions, correlation may be improved by a limited expansion of the correlation function to two dimensions.

Because each detector array is looking at a different portion of the Earth at any given time, Earth rotation complicates the epipolar condition. As shown in figure 5, this complication can be overcome by controlling the spacecraft attitude. This description is obviously simplified; further complications involve such factors as the ellipsoidal shape of the Earth, variations in the orbit, spacecraft stability, and even very large elevation differences. The spacecraft position and attitude must be precisely determined by such systems as the Global Positioning System (GPS or NAVSTAR) and frequent stellar referencing. Satellite attitude control involves gyros and inertial wheels, and, when a satellite is free of perturbing forces created by moving (actuated) parts, attitude can be maintained for reasonable periods to the arc-second.

Of course, the sensing system must retain precise geometric relationship to the attitude control system. Defining the correct satellite attitude and the rates in yaw, pitch, and roll to maintain the epipolar condition requires precise mathematical analysis. Two independent analyses, one by Howell of ITEK (15) and the other by Snyder (16) of U.S. Geological Survey, confirm Mapsat's geometric feasibility, and a U.S. patent has been allowed on the concept. Table 2 indicates the maximum deviations from the epipolar condition caused by the various expected error sources. This table is based on a half orbit (50 minutes) which covers the daylight portion to which imagery is basically limited. Attitude rate errors would be considerable if only corrected once every 50 minutes but, as the table indicates, 10-minute intervals based on stellar reference reduce the errors to a reasonable amount. Ten-minute stellar referencing using star sensors as described by Junkins et al., (17), is considered reasonable. Computer programs have been developed that result in the epipolar plane condition being maintained as long as adequate positional and attitude reference data are available and properly utilized. Figure 6 illustrates the simplicity of elevation determination in an epipolar plane which is the key element of Mapsat.

Obviously, the Mapsat concept can be effectively implemented only if stringent specifications regarding orbit, stability, reference, and sensor systems are met. Table 3 lists the Mapsat geometric requirements as defined to date, and each is considered to be within the state of the art.

Mapping Accuracy

By meeting the geometric requirements indicated and achieving stereo correlation, the resulting map accuracy is compatible with scales as large as 1:50,000 and contours as close as 20 m interval based on U.S. National Map Accuracy Standards. Reference 15 covers this analysis in some detail. Such accuracies result from the indicated geometric requirements and the following factors:

- Linear array detectors are positioned with sub-micron accuracy.

- Optical distortion effects, when accounted for by calibration, are negligible.

- Atmospheric refraction, because of the steep look angles, is of a very low order and is reasonably well known; air-to-water refraction is also known where underwater depth determination is involved.

- Relative timing, which is referenced to data acquisition, is accurate to within the microsecond.

- Digital stereo correlation, where uniquely achieved, provides three dimensional root-mean-square (rms) positional accuracy to within half the pixel dimension.

These considerations result in relative positional errors for defined points of only 6 to 7m (rms) both horizontally and vertically. This vertical accuracy requires the 1.0 base-to-height ratio. Such accuracy is adequate for the mapping indicated but assumes that control is available for reference to the Earth's figure. As indicated by ITEK (15) and the author (19), control points of 1,000 km spacing along on orbital path will be adequate for such a purpose. Where no control exists the absolute accuracy of the resultant maps, with respect to the Earth's figure, may be in rms error by 50 to 100 m although their internal (relative) accuracy remains at the 6 to 7 m rms level.

Stereocorrelation

The determination of elevations from stereo data requires the correlation of the spectral response from the same point or group of points as recorded from two different positions. In the aerial photography case these two positions are the camera stations, whereas with linear arrays in space the two recording positions are constantly moving with the satellite. In the photography case, correlation is achieved by orienting the two photographs to model the acquisition geometry. Once this is done, correlation can be achieved by the human operator, or the image stereomodel can be scanned and correlated by automated comparison of the signal patterns from the two photographs. A system such as the AS-11B-X (3,4) generates one-dimensional digital data in epipolar planes from the model. In theory, epipolar data should be correlated much faster than that from a system that must search in two dimensions to establish correlation. In practice, the automated correlation of digital data has been only partially successful; and, as Mahoney (18) has recently pointed out, correlation by either manual or automated systems is still a slow and costly process. To date, no one has acquired original sensor data in epipolar form. Thus, no one can really say how well such data can be automatically correlated, until a satellite such as Mapsat is flown. Simulation using digitized aerial photographs or linear-array stereo-sensing of a terrain model are relevant experiments worth conducting. However, they will provide only partial answers, since the degree of correlation will depend on the area involved. The characteristics of the Earth's surface, coupled with related conditions, such as the atmosphere and Sun angles, are highly varied; which means that the degree of correlation will also be highly varied. This problem does not imply that the Mapsat concept has not been validated. Having stereo data organized in linear digital form is of obvious advantage to create the three-dimensional model of the Earth's surface. Many areas will correlate in one-dimensional mode, others will require two-dimensional treatment, and still other areas may not correlate at all. By properly defining the satellite parameters and data processing, the correlation function can be optimized and raised well above that obtainable from wide-angle photography systems. For example, digital data can readily be modulated to enhance contrast or edges that make up the patterns on which correlation depends. Photography can also be modulated, but it is far more difficult (and less effective) than digital-data modulation, as film lacks the dynamic range and sensitivity of solid-state detectors. Mapsat will acquire data in an optimum form for automated correlation, which will expedite the precise determination of elevations and create digital elevation data that are becoming a basic tool for many disciplines.

Acquisition Modes and Products

As previously described (14), Mapsat is designed to be operated in a wide variety of modes. These include variation in resolution (10-m elements on up), spectral bands, swath width, and stereo modes. Such flexibility permits optimum data acquisition without exceeding a specified data-transmission rate that is now defined at 48 megabits per second (Mb/s).

The Earth's surface is highly varied, and data product requirements are likewise highly varied. By varying the acquisition modes and, in turn, producing a variety of products, the data management problem becomes complicated as compared to existing systems such as Landsat which produces only two basic types of data. However, solving this data management problem is a small price to pay for a system that can meet a wide variety of requirements for remotely sensed data of the Earth. Only four primary products are expected from Mapsat as follows:

(a) Raw-data digital tapes from which quick-look images can be displayed in near real time.

(b) Processed digital image tapes calibrated both radiometrically and geometrically to a defined map projection. Such data will be two-dimensional (planimetric) but describe the Earth's radiance (brightness) in multispectral form as is now accomplished by Landsat Multispectral Scanner tapes.

(c) Processed digital tapes, again calibrated both radiometrically and geometrically, but which now describe the Earth's surface in three dimensions (topographically) with an associated radiance value. Such tapes are, in effect, digital elevation data sets of the Earth's surface.

(d) Standardized images, both black-and-white and in color, which include geometric corrections and radiometric enhancements. Such corrections and enhancements will be of recognized general value and of a type that can be performed without undue delay or excessive cost. The images would also be of standardized scale.

From these four basic products, a wide variety of derivatives can be made which include the following:

(a) Black-and-white and multicolor image maps and mosaics at scales as large as 1:50,000, or even 1:25,000 (1:24,000) where map accuracy standards are not required.

(b) Thematic displays and maps involving such subjects as land cover and land use classification.

(c) Maps which depict the Earth's topography by such means as contours (as close as 20-m interval), slopes, elevation zones, shaded relief, and perspective display.

Conclusion

Mapsat will not meet all anticipated remote sensing requirements, and it will in no way replace those air-photo surveys required to meet mapping requirements for scales larger than 1:50,000 and contour intervals of less than 20 m. What it will do, is provide a precise three-dimensional multispectral model of the Earth at reasonable resolution and in digital form. Moreover, the satellite will record the changing responses of the Earth's surface as long as it is in operation.

Mapsat can be built today at what is considered to be a reasonable cost (15) as it is based on available components and technology. Moreover, it is designed for simplified operation and data processing. Assuming that an operational Earth-sensing system will be flown, surely Mapsat is a deserving candidate for such a job.

Mapsat Parameters

- Orbit—Same as Landsat 1, 2 and 3 (919 km alt).
- Sensor—Linear Arrays—Three optics looking 23° forward, vertical and 23° aft. Three spectral bands:

blue green	0.47 - 0.57 um
red	0.57 - 0.70 um
near IR	0.76 - 1.05 um

- Swath—180 km or portion thereof.
- Resolution—Variable—Down to 10 m element.
- Transmission—S (or X) band, compatible with Landsat receivers modified for data rates up to 48 Mb/s.
- Processing—One dimensional, including stereo.

TABLE 1

TABLE 2

Mapsat Epipolar Condition
Maximum Deviation (±) in Half Orbit--(50 Minutes)
(Meters on the Ground)

	Case 1. Vertical plus For or Aft--B/H = 0.5	Case 2. Fore and Aft--B/H = 1.0
o Optimum condition:	1.3 m	0.3 m
o Attitude errors (yaw and pitch) of:		
10 arc seconds	0.7	1.6
100 arc seconds	5.0	12
o Attitude rate errors of:		
10^{-6} deg./sec.	11 (2)*	22 (4)*
10^{-5} deg./sec.	110 (22)*	230 (46)*
o Elevation differences of:		
1,000 m	2.3	0.5
10,000 m	22	1.8

*( ) Values obtained by 10 minute rather than 50 minute stellar reference intervals.

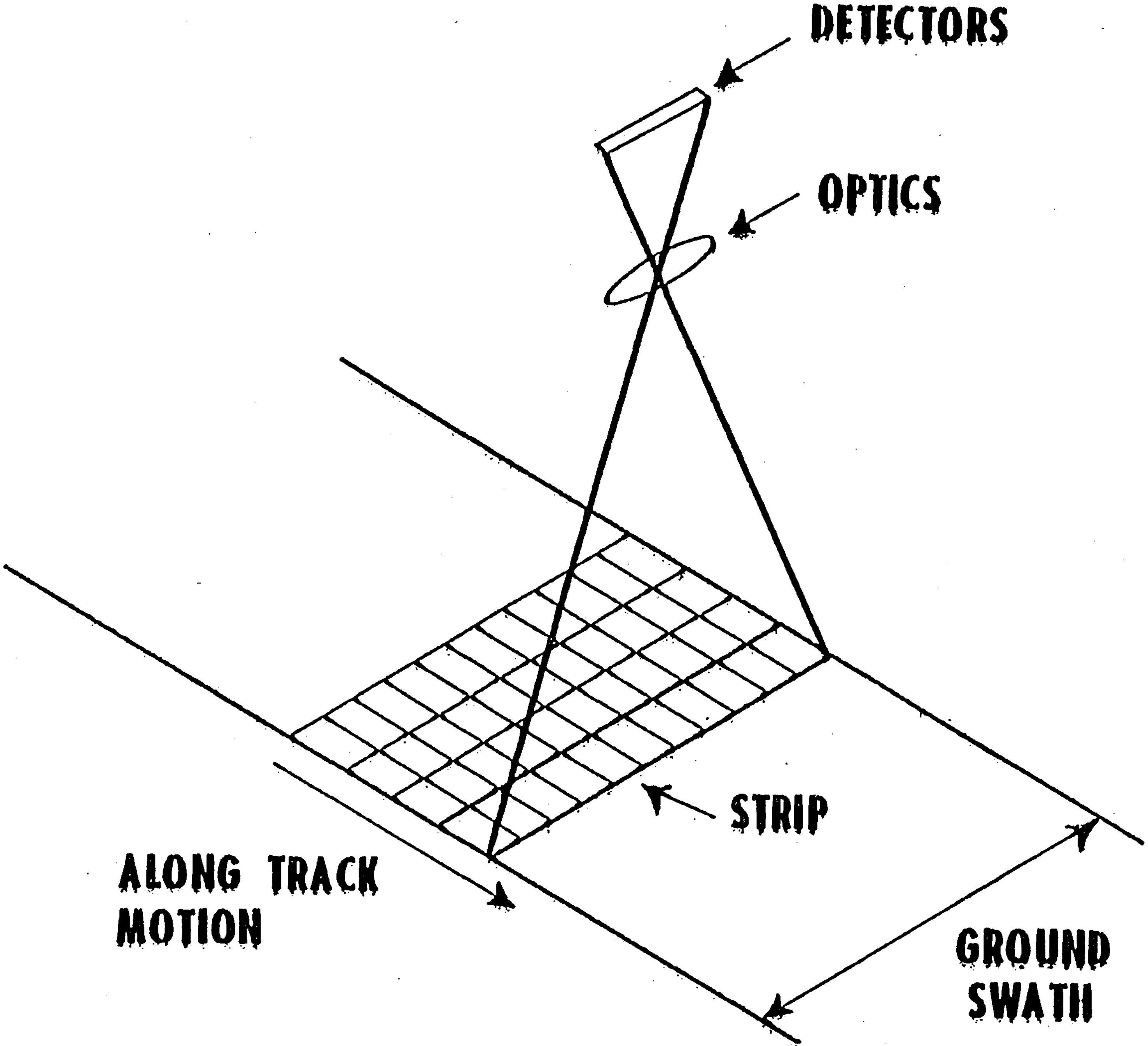
Mapsat Geometric Requirements

- Positional Determination of Satellite—10 to 20 m[1/] in all three axes.
- Pointing Accuracy—Within[2/] 0.1° of vertical.
- Pointing Determination—Within[2/] 5 to 10 arc seconds
- Stability of Satellite—Rotational rates within[2/] 10^{-6} degrees/second.

[1/] rms (1σ)

[2/] very high probability (3σ)

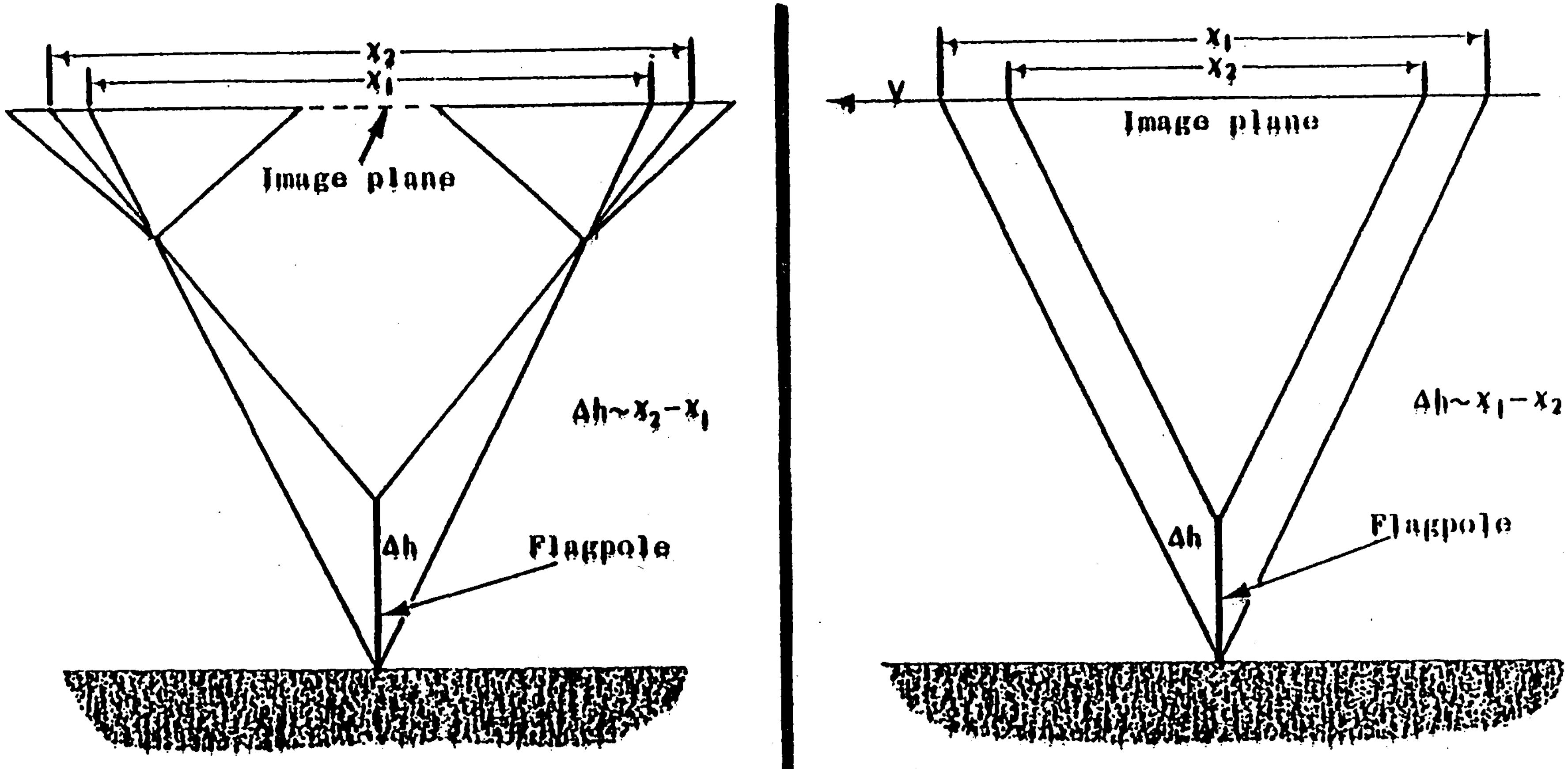
TABLE 3



LINEAR ARRAY IMAGING MODE

FIGURE 1

CONVENTIONAL VS. CONTINUOUS STEREO IMAGING MODES

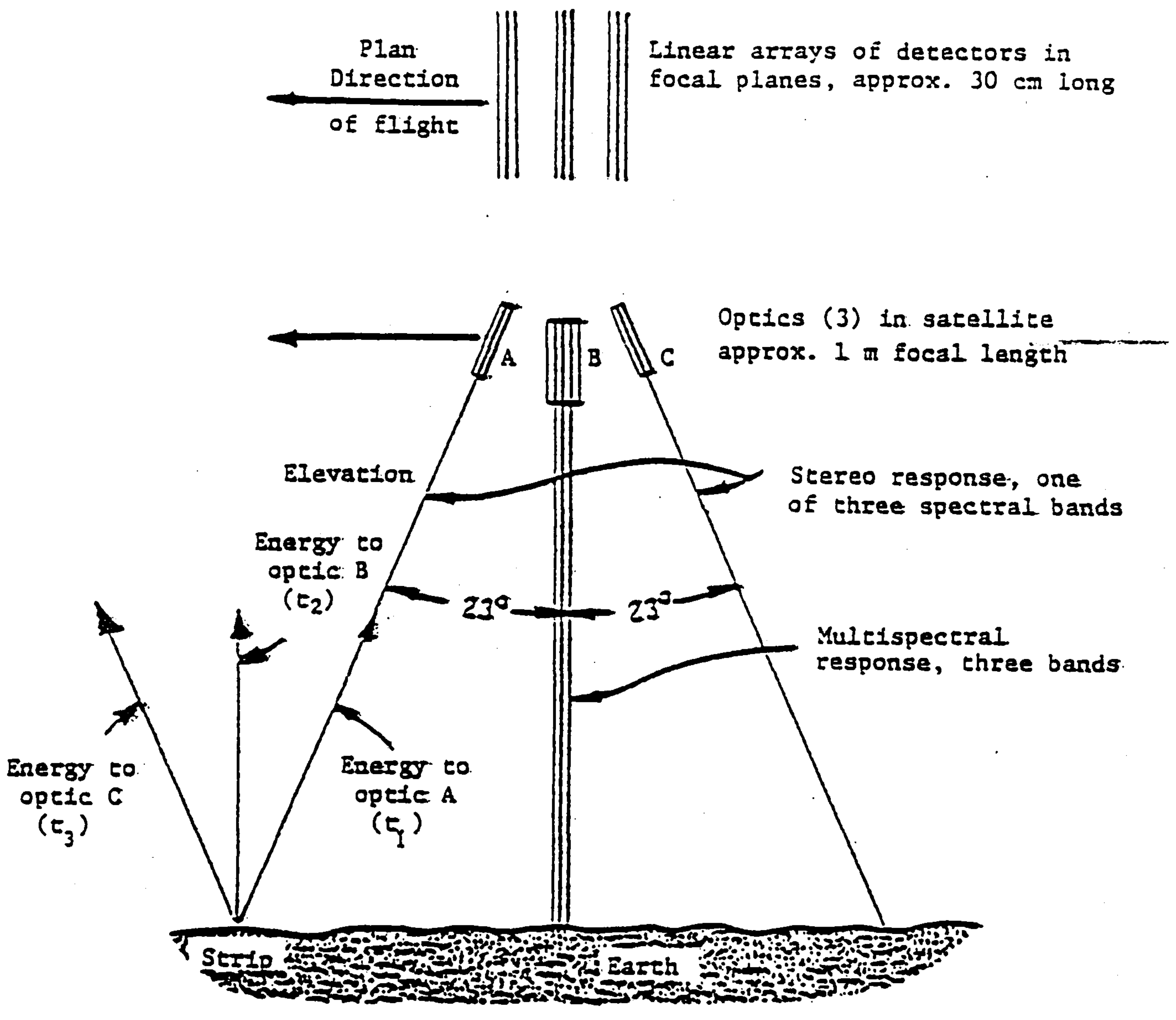


Conventional Stereo

Continuous Stereo

- Both modes resolve elevation differences
- Conventional mode involves discontinuities based on each stereo pair
- Continuous mode involves no discontinuities but requires very stable platform of known uniform velocity (V)
- Conventional mode involves 2 dimensional data processing
- Continuous mode permits 1 dimensional data processing from 2 data sets

FIGURE 2



Mapsat Sensor Configuration (not to scale).

Optics A, B, and C are a rigid part of the satellite. Optic B senses the same strip 60 seconds after A; optic C, 120 seconds after A. Any combination of A, B, and C produces stereo. Optics A and C are of about 10% longer focal length to provide resolution compatible with optic B.

FIGURE 3

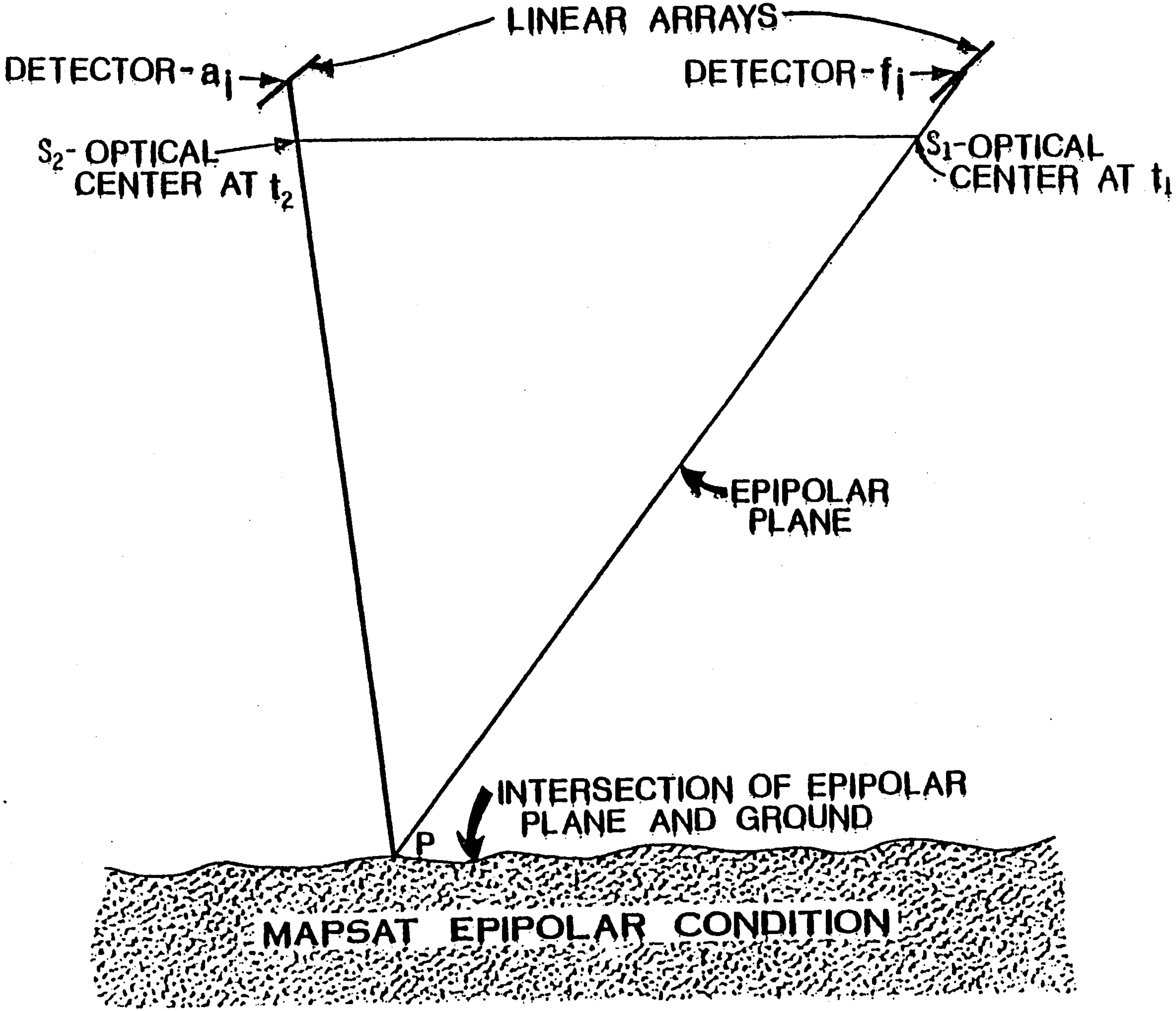
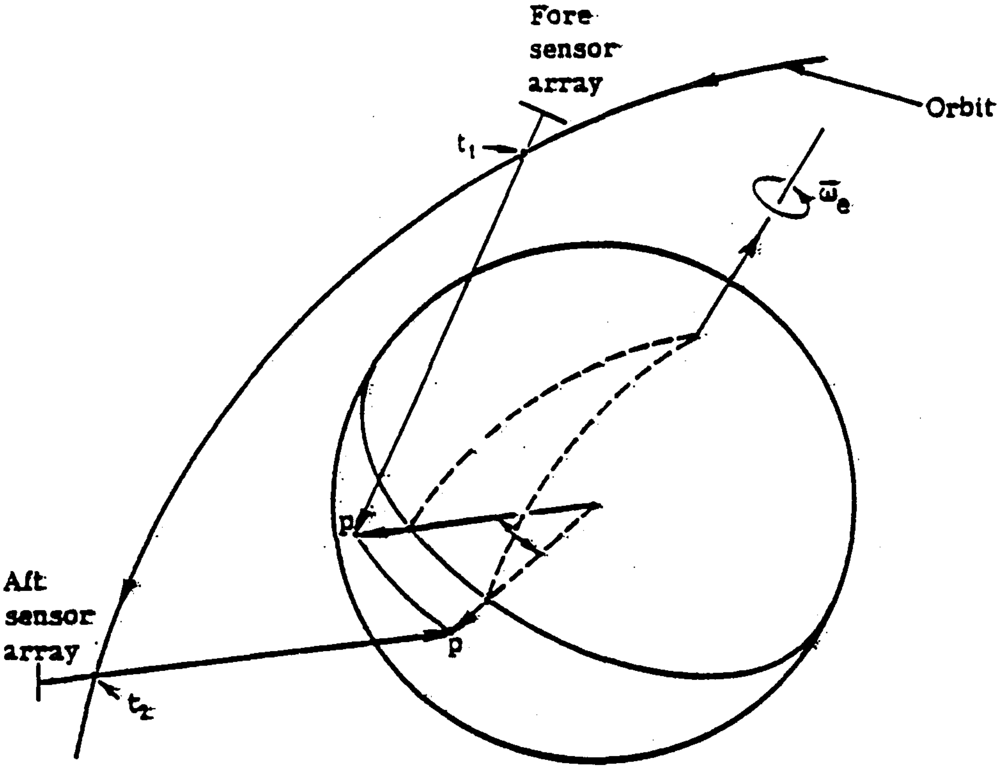

LINEAR ARRAYS
DETECTOR-a_i
DETECTOR-f_i
S_2- OPTICAL CENTER AT t_2
S_1-OPTICAL CENTER AT t_1
EPIPOLAR PLANE
INTERSECTION OF EPIPOLAR PLANE AND GROUND
P
MAPSAT EPIPOLAR CONDITION

FIGURE 4

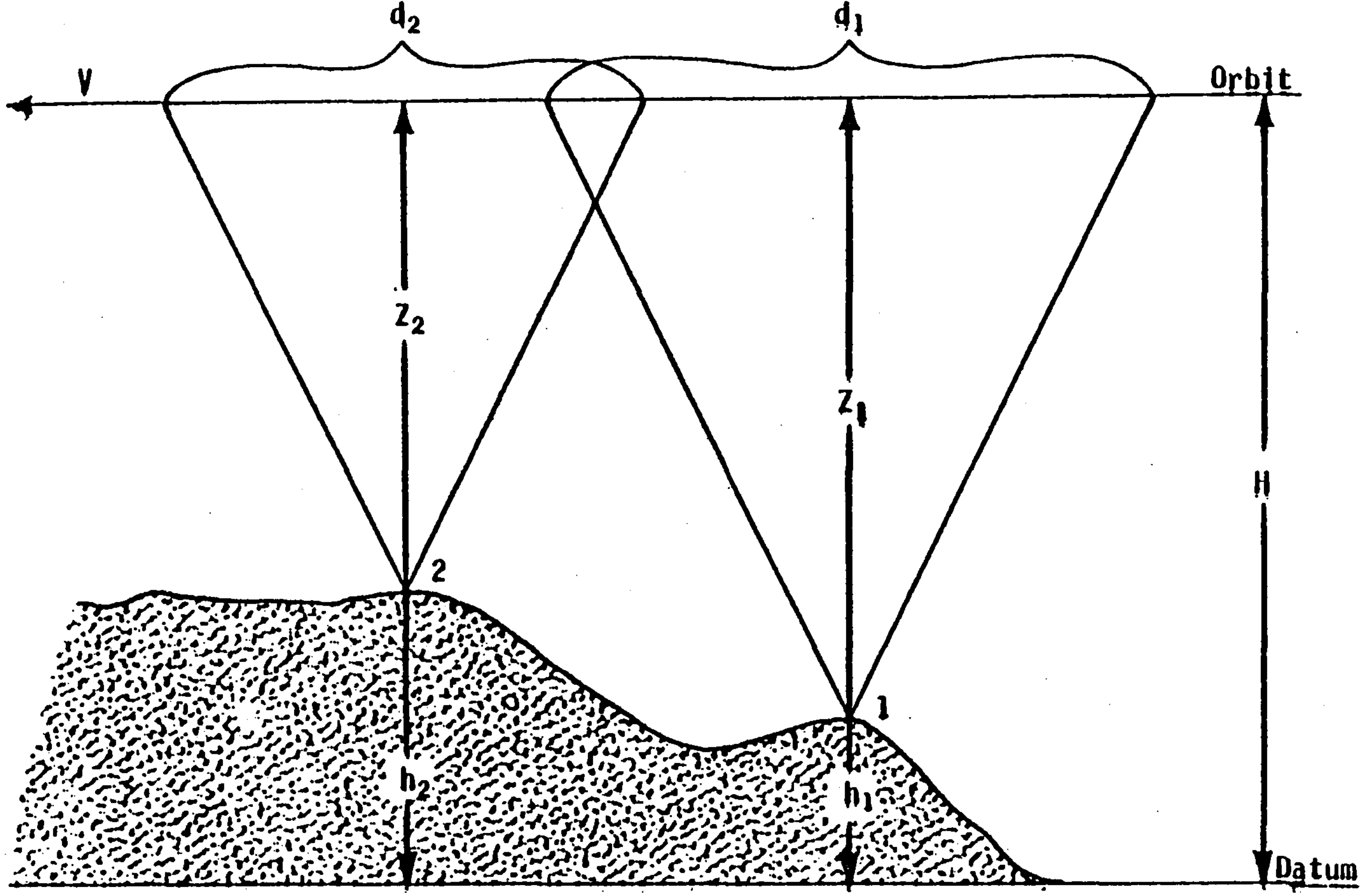


Mapsat Epipolar Acquisition Geometry

FIGURE 5

Mapsat Epipolar Plane Geometry

Elevation difference as a function of time



V = satellite velocity (constant)
t_1, t_2 = time to stereo image points 1 and 2
$d_1 = V \cdot t_1$ dist. moved to acquire stereo
$d_2 = V \cdot t_2$ data of points 1 and 2
H = satellite altitude above datum (constant)
h_1, h_2 = elevation of points 1 and 2 above datum
Z_1, Z_2 = distance from orbit to points 1 and 2

k, K = constants
$h_1 = H - Z_1 = H - k \cdot d_1 = H - k \cdot V \cdot t_1$
$h_2 = H - Z_2 = H - k \cdot d_2 = H - k \cdot V \cdot t_2$
$h_2 - h_1 = K \cdot (t_2 - t_1)$
Δh, Δt = elevation and time differences, points 1 and 2
$\underline{\Delta h = K \cdot \Delta t}$

FIGURE 6

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