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Geometric Evaluation of Skylab S-192 Conical Scanner Imagery

A geometric fidelity of ±4 pixels was obtained employing a three-dimensional mathematical model

Introduction

The geometric evaluation of imagery from the Skylab S-192 experiment, the multispectral conical scanner, was carried out in accordance with an overall implementation plan for the sensor performance evaluation (SPE) of the Skylab Earth Resources Experiment Package (EREP). The National Aeronautics and Space Administration (NASA) was responsible for monitoring and evaluating EREP hardware performance so as to provide the EREP Principal Investigators with useful data for further scientific analysis. In order to monitor the

Abstract: *Geometric evaluation of imagery obtained by the Skylab S-192 multi-spectral conical scanner was carried out by the National Aeronautics and Space Administration, L. B. Johnson Space Center, Houston, Texas, in accordance with an overall implementation plan for sensor performance evaluation of the Skylab Earth Resources Experiment Package (EREP). The three-dimensional geometric fidelity of the S-192 scanner data, the S-192 sensor pointing accuracy from the spacecraft ephemeris data for location, and the two-dimensional reproduction of the S-192 scanner data on a screening film by the use of ephemeris data were evaluated.*

A dynamic mathematical model in three-dimensional space, describing the geometry of the dynamic data acquisition system of the Skylab S-192 conical scanner, was developed in order to study the geometric fidelity of the scanner data and the S-192 sensor pointing accuracy from the spacecraft ephemeris data. An affine linear transformation in two-dimensional space was employed for evaluating the accuracy of the two-dimensional reproduction of the S-192 digital data on a screening film by means of Cyber 73/Production Film Converter and by the use of spacecraft ephemeris data.

Background information on the S-192 scanner, the mathematical models and their salient features, test results, limitations, and recommendations for the geometric evaluation of the S-192 scanner imagery are presented.

performance of the EREP instruments (e.g., S-190A Multispectral Camera, S-190B Earth Terrain Camera, S-192 Multispectral Conical Scanner, etc.) during the Skylab missions, sample data from each of the missions were evaluated immediately on receipt of the data.

Basically, two mathematical models for the geometric evaluation of the data pertaining to the S-192 imagery were developed. The first mathematical model evaluated the three-dimensional geometric fidelity of the S-192 imagery and the accuracy of the tabulations, listing the S-192 sensor pointing (latitude and longitude) with time (Greenwich Mean Time)

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as per PHO-TR524 product S052-7*. The second mathematical model evaluated the accuracy of the two-dimensional reproduction of the S-192 digital data on a screening film by utilizing the spacecraft ephemeris data on a Cyber 73/Production Film Converter (PFC) of NASA, Houston, Texas.

Background

The Skylab S-192 conical scanner is a multispectral scanner, mapping the surface of the earth by simultaneously optically scanning it in 13 spectral bands. The scan pattern on the ground consists of successive scan arcs with the center of the circle being a point on the Z-axis (local vertical) of the spacecraft (see Figure 1). Approximately 110 degrees of the 360 degrees of the circular scan provide mapping information; the remaining 250 degrees are used for data processing and calibration of the optical channels in absolute radiometric units. The scan circle subtends an angle of at least 9.0 degrees at the spacecraft. The transverse width of the ground coverage is approximately 37 nautical miles (nmi) from the nominal altitude of 235 nmi. The radiance of each small element of the scan pattern on the surface of the earth is recorded in each spectral band. The radiance of ground objects in short wavelengths regions (0.41 to 2.35 micrometer) is recorded as the varying degree of sunlight reflected from the objects. The radiance of ground objects in the 10.2 to 12.5 micrometer spectral band is mainly due to the temperature of the objects as modified by their emissivity. The external optical system collects these radiations. These radiations are spectrally dispersed and detected in the internal scanner assembly, and the resultant electrical signals are processed in an electronic assembly. The final output is digital data corresponding to the absolute radiance of the scene below. The data are stored on 22 tracks of the REP tape recorder. Upon receiving the data, it is processed and stored for use in universal format tapes generated by merging information from the high density digital video tapes and the corresponding Skylab Best Estimate Trajectory (SKYBET) tapes.

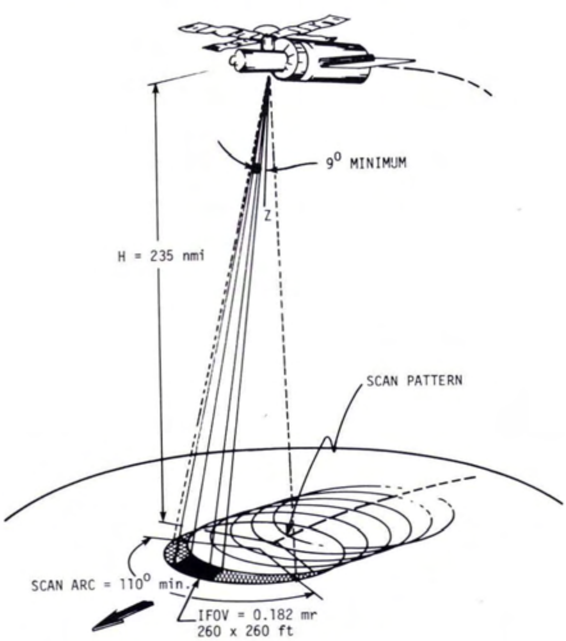


Fig. 1. Scan pattern of the S-192 multispectral scanner.

* PHO-TR524 product S052-7 is an S-192 field-of-view tabulation produced by the Philco-Ford Corporation[6]. It gives the location of the sensor field-of-view as a computed estimate from the vehicle ephemeris data.

TABLE 1. SPECTRAL PARAMETERS AND SYSTEM PERFORMANCE PARAMETERS OF S-192 MULTISPECTRAL SCANNER

Spectral channels (micrometers)	
1) 0.41 – 0.46	8) 0.98 – 1.08
2) 0.46 – 0.51	9) 1.09 – 1.19
3) 0.52 – 0.56	10) 1.20 – 1.30
4) 0.56 – 0.61	11) 1.55 – 1.75
5) 0.62 – 0.67	12) 2.10 – 2.35
6) 0.68 – 0.76	13) 10.2 – 12.5
7) 0.78 – 0.88	
Angular resolution	0.182 mr, all channels
Ground resolution	260 feet at 235 nmi altitude
Radiometric performance	$NE\Delta\rho < 10\%$ channels 1-12 $NE\Delta T < 0.4$ °K channel 13
Radius of scan circle at 235 nmi altitude	22.6 nmi
Transverse ground coverage	37 nmi (68.5 km)
Information rate per line per detector	1.10×10^3 samples/line
Total information rate 121,334	8 bit words/s or 970.67 K bits/s ± 10 bits/s
Orbital period of vehicle	93.2 min
Nominal orbital velocity	3.90 nmi/s
V/H	1.66×10^{-2} radian/s
Line rate	100 lines/s
Electrical bandwidth, Δfe	167 kHz

Figure 1 shows the scan pattern of the Skylab S-192 conical scanner and Table 1 shows the 13 spectral channels and related system performance information.

The data for all channels are recorded simultaneously. Therefore, the geometric evaluation was performed on data from only one channel, usually the one which gave a good digital display of topographic details on a CRT.

A MATHEMATICAL MODEL FOR THREE-DIMENSIONAL EVALUATION

In order to evaluate the three-dimensional geometric fidelity of the Skylab S-192 imagery, a mathematical model was developed. The mathematical model simulates the geometry of the dynamic data acquisition system of the Skylab S-192 Experiment.

The internal geometry of the S-192 conical scanner is schematically shown in Figure 2. The fundamental mathematical model of the scanner is based on a ray trace from the ground

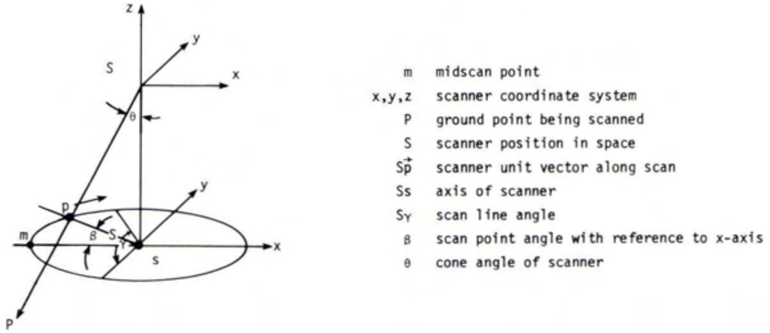


FIG. 2. Internal geometry of the sensor.

point P to the sensor S. Because the sensor S is in motion during data acquisition, an anlytical expression may be obtained which relates the instantaneous sensor position, scan direction attitude, and the ground point being scanned. In other words, the relationship establishes collinearity between the instantaneous scan direction of the scanner and the corresponding vector defined by the scanner position and the ground point being scanned.

From Figure 2, the scan direction at any instant can be expressed by a unit vector resolved in the sensor or instrument (INS) coordinate system (x, y, and z):

$$\vec{S_p} = \begin{bmatrix} -\sin\theta \cos\beta \\ \sin\theta \sin\beta \\ -\cos\theta \end{bmatrix} \tag{1}$$

where β is the angle that is subtended at the sensor axis by the scan point p and midscan point m on the circular scan line generated by the unit vector when the sensor scans an object point P. If the scan line angle, S_γ, and number of pixels (picture elements) per scan line are known, then it is possible to determine angle β for any pixel p. Thus, knowing θ and β, the vector $\mathbf{S}_p$ is defined.

Figure 3 schematically shows the dynamics of the situation. Consider an Epoch which may be the instant at the start of the first scan line in the frame of scan lines being considered. Let the Greenwich Mean Time be denoted by T_o and the subsatellite point at Epoch be $0(\lambda_o,\phi_o)$. An Inertial Local-vertical Space Rectangular (ILSR) coordinate system is then defined with its origin at O, and the Y axis pointing North in a plane perpendicular to the local vertical or the Z-axis. The X-axis forms a right-handed system with the Y- and Z-axes. The state vector of the satellite (sensor) at Epoch is known from the navigational data. In order to determine the state vector of the satellite (sensor) after time ΔT in the ILSR coordinate system, the state vector at Epoch may be utilized to give the following relationship:

$$\begin{aligned} X^s &= X_o^s + \dot{X}^s(\Delta T) + \tfrac{1}{2}\ddot{X}^s(\Delta T)^2 \\ Y^s &= Y_o^s + \dot{Y}^s(\Delta T) + \tfrac{1}{2}\ddot{Y}^s(\Delta T)^2 \\ Z^s &= Z_o^s + \dot{Z}^s(\Delta T) + \tfrac{1}{2}\ddot{Z}^s(\Delta T)^2 \end{aligned} \tag{2}$$

and,

$$\begin{aligned} \tilde{\omega} &= \tilde{\omega}_o + \dot{\tilde{\omega}}_o(\Delta T) + \tfrac{1}{2}\ddot{\tilde{\omega}}_o(\Delta T)^2 \\ \tilde{\phi} &= \tilde{\phi}_o + \dot{\tilde{\phi}}_o(\Delta T) + \tfrac{1}{2}\ddot{\tilde{\phi}}_o(\Delta T)^2 \\ \tilde{\alpha} &= \tilde{\alpha}_o + \dot{\tilde{\alpha}}_o(\Delta T) + \tfrac{1}{2}\ddot{\tilde{\alpha}}_o(\Delta T)^2 \end{aligned} \tag{3}$$

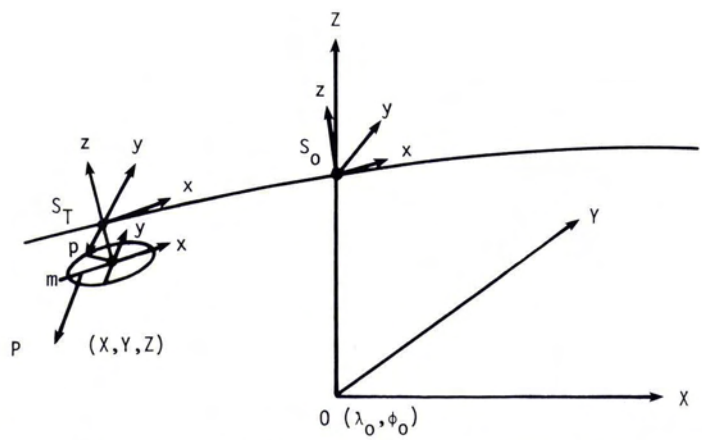
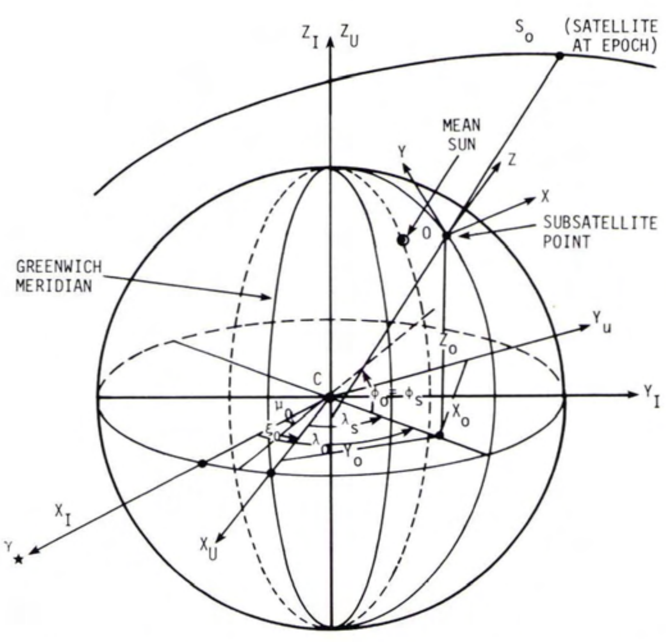


FIG. 3. Schematic of the dynamics of the Sp192 scanner data acquisition system.

where

X^s,Y^s,Z^s is the position vector of the satellite (sensor),
$\dot{X}^s,\dot{Y}^s,\dot{Z}^s$ is the velocity vector of the satellite (sensor),
$\ddot{X}^s,\ddot{Y}^s,\ddot{Z}^s$ is the acceleration vector of the satellite (sensor),
subscript "o" is the Epoch time information,
ΔT is the time-lapse from Epoch,
$\tilde{\omega},\tilde{\phi},\tilde{\alpha}$ is the attitude vector of the sensor,
$\dot{\tilde{\omega}},\dot{\tilde{\phi}},\dot{\tilde{\alpha}}$ is the rate of change of attitude vector of the sensor, and
$\ddot{\tilde{\omega}},\ddot{\tilde{\phi}},\ddot{\tilde{\alpha}}$ is the rotational acceleration vector of the sensor.

If the sensor sights a point P having geodetic coordinates (ϕ,λ,h) or geocentric coordinates (X_u,Y_u,Z_u), then these coordinates have to be converted to ILSR coordinates (X,Y,Z). The GMT information for Epoch and for the instant of scan must be known for this conversion in addition to the subsatellite position at Epoch. The geocentric coordinates are first converted to the inertial earth-centered (IEC) coordinates (X_I,Y_I,Z_I), which then are converted to the (ILSR) coordinates (X,Y,Z). Figure shows the various coordinate systems used in the conversion. Transformation matrices for converting IEC to ILSR, USR to IEC, and Local-vertical Space Rectangular (LSR) to Instrument (INS) coordinate systems are given by Malhotra[2].



X, Y, Z	ILSR-inertial local vertical space rectangular coordinate system
X_u, Y_u, Z_u	USR-universal coordinate system -universal local vertical space rectangular coordinate system or TEC-true Earth-centered
X_I, Y_I, Z_I	IEC-internal Earth-centered coordinate system
λ_s, ϕ_s. h_s	Geodetic coordinates of subsatellite point 0 at Epoch
X_o, Y_o, Z_o	Geocentric coordinates of subsatellite point 0 at Epoch
ξ_o	Angle corresponding to the GMT at Epoch since Greenwich Mean midnight
μ_o	= $(180^o$-RAMS) where RAMS = right ascension of mean sun
λ_o	= $(\lambda_s + \xi_o + \mu_o)$ = longitude in IEC system
ϕ_o	= ϕ_s = latitude in IEC system

FIG. 4. Inertial and rotating true coordinate systems of a geoid.

Thus, in the ILSR coordinate system

$$\vec{SP} = \begin{bmatrix} X - X^s \\ Y - Y^s \\ Z - Z^s \end{bmatrix} \tag{4}$$

and,

$$\vec{Sp} = \boldsymbol{M} \begin{bmatrix} -\sin\theta \cos\beta \\ \sin\theta \sin\beta \\ -\cos\theta \end{bmatrix} \tag{5}$$

where $\boldsymbol{M}$ is the rotational matrix converting sensor coordinates to the ILSR coordinates.

From the collinearity of SP and Sp we have the expression:

$$\vec{SP} = K * \vec{Sp} \tag{6}$$

where K is a scale factor or,

$$\begin{bmatrix} X - X^s \\ Y - Y^s \\ Z - Z^s \end{bmatrix} = K * \boldsymbol{M} \begin{bmatrix} -\sin\theta \cos\beta \\ \sin\theta \sin\beta \\ -\cos\theta \end{bmatrix} = K * \boldsymbol{M} \begin{bmatrix} U_X \\ U_Y \\ U_Z \end{bmatrix} \tag{7}$$

where

$$\boldsymbol{M} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \tag{8}$$

and

$$\begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} = \begin{bmatrix} -\sin\theta \cos\beta \\ \sin\theta \sin\beta \\ -\cos\theta \end{bmatrix} \tag{9}$$

Equation 7 may be written as

$$\begin{bmatrix} X - X^s \\ Y - Y^s \\ Z - Z^s \end{bmatrix} = K \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{10}$$

where

$$\begin{aligned} a &= m_{11}U_x + m_{12}U_y + m_{13}U_z \\ b &= m_{21}U_x + m_{22}U_y + m_{23}U_z \\ c &= m_{31}U_x + m_{32}U_y + m_{33}U_z \end{aligned} \tag{11}$$

Equation 10 can be written as

$$\frac{X - X^s}{a} = \frac{Y - Y^s}{b} = \frac{Z - Z^s}{c}$$

or

$$\begin{aligned} X &= X^s + (Z - Z^s)\frac{a}{c} \\ Y &= Y^s + (Z - Z^s)\frac{b}{c} \; . \end{aligned} \tag{12}$$

Each ground control point will generate two such equations, which will be used to determine misregistration ($\delta X, \delta Y$) between the computed X, Y, using the adjusted parameters of Equation 12 and the known X, Y. A least squares solution will minimize the misregistration $\delta X, \delta Y$, and also will determine the adjusted values of the parameters, which are

$$X_o^s,\ Y_o^s,\ Z_o^s,\ \dot{X}^s,\ \dot{Y}^s,\ \dot{Z}^s,\ \ddot{X}^s,\ \ddot{Y}^s,\ \ddot{Z}^s$$
$$\tilde{\omega}_o,\ \tilde{\phi}_o,\ \tilde{\alpha}_o,\ \dot{\tilde{\omega}},\ \dot{\tilde{\phi}},\ \dot{\tilde{\alpha}},\ \ddot{\tilde{\omega}},\ \ddot{\tilde{\phi}},\ \ddot{\tilde{\alpha}}$$

Equation 12 will be used to determine X, Y values for any ground point imaged as a known pixel in the Skylab S-192 scanner imagery. The Z-information for the ground point corresponding to any pixel may be taken as a constant for flat areas and interpolated from some sort of a digital terrain model in cases where topography has significant relief. It may be pointed out that the above mathematical treatment considers terrain relief in the sense that it minimized misregistration $\delta X, \delta Y$ at the Z-level of the point. Of course, a data base carrying Z-information will be needed.

From the practical point of view in space applications, the acceleration $\ddot{X}^s$, $\ddot{Y}^s$, $\ddot{Z}^s$ and $\ddot{\tilde{\omega}}, \ddot{\tilde{\phi}}, \ddot{\tilde{\alpha}}$, may be considered insignificant for a short span of time. A frame of about 2,000 scan lines taken at the rate of about 100 scan lines per second, a span of about 20 seconds, may be considered short.

The details of the least squares solution are given in Malhotra[2].

The Salient Features of the Mathematical Model and the Data Reduction Technique

The salient features of the mathematical model and the data reduction techniques are—

- The earth is considered an ellipsoid of revolution (Fisher's: major axis = 6,378,166.00 m, minor axis = 6,356,784.28 m).
- The rotation of the earth is accounted for.
- The solution for the parameters of the mathematical model is based on rigorous least squares method.
- The SKYBET information is utilized to approximate the initial values of the parameters in the solution, and in the formation of additional observational equations from the *a priori* knowledge of the parameters. However, the solution is not entirely dependent on the SKYBET information.
- The mathematical model considers the elevation of the points. This provides a means to consider the terrain topography in the determination of location X, Y corresponding to any pixel in the imagery.
- Assuming no abrupt discontinuity (due to engine thrust) in the Skylab (or sensor) motion defined by the parameters, the limitation of this mathematical model, which is not based on rigorous orbital mechanics considerations, is the length of time slice for which the S-192 imagery can be registered image to ground (called absolute registration). To date, tests on S-192 data up to 60 seconds of time slice has been successfully registered and evaluated. However, modifications can be made in the mathematical model for considering greater length of "data-take."

In brief, the data reduction technique for the three dimensional geometric evaluation of the S-192 imagery is— A set of well-distributed topographic detail points over the entire frame of scan lines is selected both on the topographic map sheets (1:250,000 or larger scale) and on the digital display of the scene under consideration. The map provides the object space coordinates (geographic, geocentric, geodetic, or local vertical) of these points, whereas the digital display provides the line-sample count of the same points (pixels). The line-sample count is converted to elapsed time relative to a pre-defined epoch, and also used to obtain the direction cosines of the scan direction in the scanner (instrument) coordinate system (x, y, and z). For each of the topographic detail points thus selected, two equations, one each for X- and Y-coordinates, are then established in accordance with the mathematical model (Equation 12). Additional observational equations are written for each of the parameters being solved for by utilizing the *a priori* knowledge of these parameters from the SKYBET data. A weighted least squares solution results in the best fit between the set of points in the imagery and on the ground, resulting in residuals or misregistration ($\delta X, \delta Y$) in the X- and Y-coordinates of the points used in the solution. Residuals were also computed for several check points picked over the entire scene.

The following products were needed in the preparation of input data to the computer run for the solution of the parameters of the mathematical model for the registration of S-192 imagery:

- A computer compatible digital tape for display of a selected band (usually #7 or #8) which gives the best topographic details in a scene.
- A hardcopy of the scene from the Data Analysis Station (DAS) of NASA, Houston, Texas, with a grid overlay (100 lines × 100 samples) over the entire scene. This product is used to obtain a line-sample count of a topographic detail in the scene.
- Topographic map sheets (1:250,000 or larger scale) for the scene. Geographic coordinates of the selected topographic detail points are obtained.
- Relevant SKYBET information needed in the solution. Some of the relevant information supplied for each scan line is
  - The Greenwich Mean Time at start of a scan line,
  - The scan line number,
  - The latitude and longitude (degrees, minutes, and seconds) of the spacecraft nadir,
  - The roll (right wing up), the pitch (nose up), and yaw (nose towards right wing) in degrees, minutes, and seconds,
  - Altitude of spacecraft,
  - Ground velocity (kilometres-per-second), and
  - Orbital inclination angle.

Results of the Three-Dimensional Evaluation

Based on the above-described dynamic mathematical model for the image to ground absolute registration of the S-192 data, the following two evaluations were made for the SL-2, SL-3, SL-4 Skylab missions:

- Evaluations of three-dimensional geometric fidelity of the S-192 imagery, and
- Evaluation of the S-192 sensor pointing tabulations as per PHO-TR524 Product S052-7.

Three-Dimensional Geometric Fidelity Evaluation

This geometric evaluation of the Skylab S-192 conical scanner was performed on three "data takes" for each of the Skylab missions, SL-2, SL-3, and SL-4. The "data takes" were one of 60 seconds and two of 20 seconds time slices, each from a different Skylab pass.

In all of the cases considered, the residual errors after registration of the "data-take" for 20 second and 60 second time slices were found to be random in nature. The accuracy of determination of the ground coordinates from the data line-sample values of an unknown point was compatible to the accuracy of the input data, such as the accuracy of the coordinates of the ground control points obtained from a topographic map. A typical result of absolute registration from an SL-2 "data-take" is shown in Figure 5. Similar results were obtained for missions SL-3 and SL-4. These results are tabulated in Tables 2 and 3.

The following are some of the important conclusions drawn from the above analysis:

- The S-192 scanner performs in a very systematic manner so as to lend itself to geometric modeling which simulates the data acquisition system.
- The residual errors at the control and check points selected in a scene are random to within ± 4 pixels (one sigma level), which is approximately ± 300 metres at a resolution of about 80 metres (pixel size is about 80 m × 80 m).
- Both the 20 seconds and 60 seconds of "data-take" are registered equally well by the mathematical model.
- There is a high degree of correlation between the instantaneous location (X^s,Y^s), and roll and pitch (ω,ϕ) of the scanner. Unless the location is known with a high degree of accuracy, it is not possible to determine the scanner attitude to a high degree of accuracy. A study of this aspect with simulated data is recommended.
- Due to the uncertainty in the SKYBET information and due to the high degree of correlation between scanner location and its attitude, precise determination of interlock angle between S-192 scanner and S-190A photographic cameras by this mathematical model was not possible.

As a point of interest to the investigators, the parameters of the mathematical model for absolute spatial registration of the S-192 imagery can be used to create a registered tape for the entire scene so as to generate an undistorted display of the scene. It is also possible to overlay data from other sensors and missions by a similar technique, and create multi-sensor and temporal-data registered tapes which may be used for classification and interpretation of earth resources and for other tasks. The registered data may be displayed at any desired scale to obtain an undistorted hardcopy for certain applications. An overall accuracy of about ± 4 pixels over the entire scene is expected with the present technique.

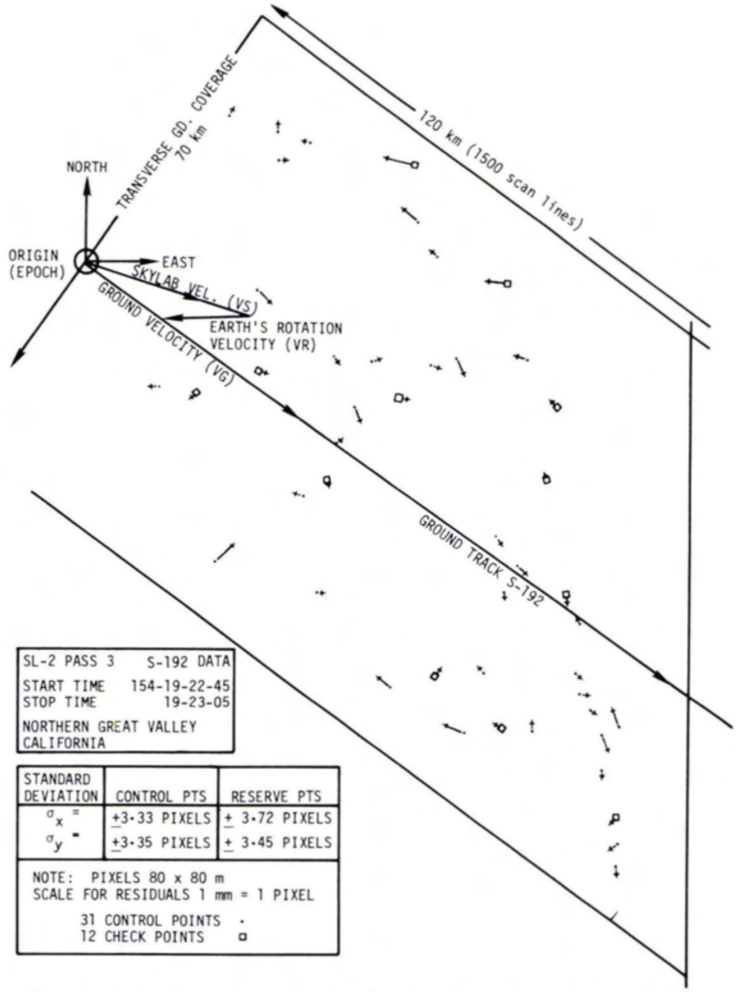


FIG. 5. Absolute registration of S-192 data (northern Great Valley, California).

TABLE 2. SL-3: RESULTS OF ABSOLUTE REGISTRATION OF S-192 DATA

SR#	SITE/PASS	GMT START DAY-HR-MIN-SEC	STOP MIN-SEC	RESIDUAL ERRORS (PIXEL*) CONTROL POINTS X	Y	CHECK POINTS X	Y
1	MISSISSIPPI DELTA, NEW ORLEANS PASS #52A	264-13-46-00	46-20	± 3.8	± 3.2	± 4.0	± 4.3
2	WISCONSIN PASS #14A	217-15-00-15	01-15	± 3.3	± 3.2	± 4.0	± 3.7
3	WASHINGTON, D.C. PASS #14A	217-15-03-45	04-10	± 4.0	± 3.8	± 3.7	± 3.8

* PIXEL = 80 × 80 m (approximately)

POINTING ACCURACY EVALUATION

The PHO-TR524 product S052-7 is an S-192 field of view (FOV) tabulation. It gives the location of the sensor field of view as a computed estimate from the vehicle ephemeris data.

TABLE 3. SL-4: RESULTS OF ABSOLUTE REGISTRATION OF S-192 DATA

SR#	SITE/PASS	GMT START DAY-HR-MIN-SEC	STOP MIN-SEC	RESIDUAL ERRORS (PIXEL*) CONTROL POINTS X	Y	CHECK POINTS X	Y
1	MOBILE, MISSISSIPPI PASS #87	21-20-09-20	10-40	± 3.7	± 3.0	± 3.9	± 4.2
2	WISCONSIN PASS #90	25-17-15-00	15-40	± 4.3	± 3.6	± 3.5	± 3.3
3	NEVADA/ARIZONA PASS #93	27-18-59-50	00-30	± 3.3	± 3.7	± 4.3	± 42

* PIXEL = 80 × 80 Meters (approximately).

Greenwich mean time (GMT), latitude/longitude of left-most, central, and right-most pixels for every 100th scan line of S-192 sensor are tabulated.

Evaluation of the product was made by comparing the S052-7 location of the center pixel for a given scan line with its precise location (within ± 4 pixels or ± 12 seconds of arc) given by the registered location values obtained by the mathematical model for the absolute spatial registration of the S-192 imagery, described above. Some of the results from the analysis of the PHO-TR524 product S052-7 are given in Tables 4, 5, and 6 for the Skylab S-192 data taken during missions SL-2, SL-3, and SL-4, respectively. These tables show that the tabulated latitude and longitude values differ from the more accurate values, which are computed from the mathematical model, by a much lesser degree (by about 2 minutes of arc) during missions SL-2 and SL-3 than during mission SL-4, when the differences are over 4 minutes of arc. This was anticipated because of the appreciable drift experienced during the SL-4 mission from the onboard attitude gyros, which generate larger pointing errors. Also, gradual changes in the difference values both in latitude and longitude are noticeable in all the missions, which may be looked upon as a drift in the ephemeris data caused by onboard instrumental drift causing drift in the tabulated data as well. From the analysis of a few cases, two from SL-2, three from SL-3, and two from SL-4, it can be said that the utility of the product S052-7, which is meant for picking the right data for a certain area of interest, is not marred by the existing pointing errors, which are either small or are determinable.

A Mathematical Model for the Two-Dimensional Evaluation of the Screening Film of the S-192 Data

Screening films were generated by the Cyber 73/PFC (Production Film Convertor) of NASA, Houston, from the Skylab S-192 scanner data, either on the universal format compu-

TABLE 4. MISSION: SL-2
LOCATION OF DATA: GREAT NORTHERN VALLEY PASS #3 (LAT: 40° 20′ N/LONG: −220° 40′ W)

SCAN LINE # (IN A FRAME)	TIME (GMT) hr	min	sec	CENTER PIXEL LAT. ′	DIFF.* ″	LONG ′	DIFF.* ″
400	19	22	45.465	0	38.3	0	07.2
500			46.519		36.4		06.6
600			47.574		33.6		09.7
700			48.629		32.6		11.3
800			49.684		32.9		11.8
900			50.738		34.1		12.1
1000			51.793		35.5		12.8
1100			52.848		38.6		12.8
1200			53.903		43.6		11.4
1300			54.958		49.8		9.1
1400			56.013		57.1		6.2
1500			57.068	1	05.7		2.6

* DIFFERENCE = (S052-7 Product Value) − (Registered Value).

TABLE 5. MISSION: SL-3
LOCATION OF DATA: WASHINGTON, D.C. PASS #14 (LAT. 38° 45′ (N)/LONG= −76° 10′ (W)

SCAN LINE # (IN A FRAME)	TIME (GMT) hr	min	sec	CENTER PIXEL LAT. ′	DIFF.* ″	LONG ′	DIFF.* ″
100	15	03	46.356	0	39.6	−0	21.1
200			47.415		37.3		19.6
300			48.475		35.9		19.1
400			49.534		35.1		19.7
500			50.593		34.3		20.5
600			51.653		32.7		20.6
700			52.712		29.9		19.7
800			53.771		25.2		17.0
900			54.831		22.4		15.8
1000			55.890		19.8		14.5
1100			56.949		16.9		12.6
1200			58.008		14.0		10.5
1300			59.068		10.7		08.1
1400	15	04	0.127		07.7		06.3
1500			1.186		04.8		05.1
1600			2.246		02.4		02.4
1700			3.305		00.0		00.1
1800			4.364	−0	02.6	+0	02.3

* DIFFERENCE = (S052-7 Product Value) − (Registered Value).

ter compatible tapes or on the high density digital magnetic tapes. The ancillary record on the tapes contained such information as the Greenwich Mean Time (GMT) of start of each scan line; scan line number; latitude and longitude of the subsatellite point; roll, pitch, and yaw of the spacecraft; and other housekeeping information. For the production of 5 inch and 70 millimetre screening films, the software of the PFC utilized the ancillary information so

TABLE 6. MISSION: SL-4
LOCATION OF S-192 DATA: MOBILE, MISSISSIPPI PASS #87 (LAT. 32° 30′ (N)/LONG. 89° 30′ (W)

SCAN LINE # (IN A FRAME)	TIME (GMT) hr	min	sec	CENTER PIXEL LAT. ′	DIFF.* ″	LONG. ′	DIFF.* ″
100	20	09	20.317	3′	47.45	5	57.53
200			21.373		47.50		55.94
300			22.429		46.90		54.70
400			23.485		47.46		53.85
500			24.541		48.06		53.26
600			25.597		48.44		53.00
700			26.653		48.51		52.51
800			27.709		48.52		51.91
900			28.765		48.36		50.76
1000			29.820		48.15		49.42
1100			30.876		47.53		48.18
1200			31.932		47.80		47.84
1300			32.988		48.64		48.08
1400			34.044		49.69		48.80
1500			35.100		50.57		49.69
1600			36.156		50.88		50.35
1700			37.212		50.30		50.97
1800			38.268		49.20		51.39
1900			39.324		49.12		52.56

* DIFFERENCE = (S052-7 Product Value) − (Registered Value).

as to place each of the scan line pixels along an arc that conforms to the ground trace of the scan. At every 100th scan line there is a minor tick mark beside the scan line and on the along-tract edge of the scene. At every 1500th scan line there is a major tick mark along with the Greenwich Mean Time, latitude, and longitude information which are asynchronous to the scan line counters. Curved white lines appear every 1500 scan lines apart. Other curved white lines randomly distributed throughout the imagery may be due to non-repeatable malfunctions in reading the video data of the original data tapes.

The screening films thus generated were evaluated for along- and cross-track scales, and non-orthogonality or skewness of the scene, by means of a least squares fit of a set of image points defined by along- and cross-track coordinates (x,y) on a screening film to the corresponding points defined by the X,Y coordinates on a map. This task is performed by an affine transformation in two dimensional space. The following is the mathematical expression for the transformation:

$$X = \left[(x - a)(1 + c) + (y - b)(1 + d)e\right] \cos f + \left[(y - b)(1 + d)\right] \sin f$$
$$Y = \left[(x - a)(1 + c) + (y - b)(1 + d)e\right] (-\sin f) + \left[(y - b)(1 + d)\right] \cos f$$

The transformation consists of six parameters:

- two translations (a,b) between the two sets of coordinate systems (x,y) and (X,Y);
- two scale factors (c,d), along- and cross-track of the screening film;
- skewness or non-orthogonality (e) between x and y axes of the screening film; and
- common rotations (f) between the two sets of coordinate systems.

Figure 6 shows the two coordinate systems and the parameters.

Results of Two-Dimensional Evaluation

Evaluation of the initial products from the Cyber 73/PFC system showed that the scales along x and y differed by as much as 12 percent, and the skewness in the scene was as high as 0.05 radians (about 3 degrees). Based on the results of the above evaluation, the PFC algorithm was modified and a second batch of screening films generated, which was found to have scale differences of less than 1 percent and skewness of about 0.05 radians as before. During these investigations the ephemeris drift angle was found to be biased by 3.15 degrees. A third batch of screening films was generated with ephemeris drift angle increased by 3.15 degrees. Evaluation of this product showed the scale differences were less than 1 percent and the non-orthogonality or skewness in the scene was less than 0.005 radians (about 20 minutes of arc). This product was then accepted as being adequate to serve the intended purpose of pre-viewing sensor data for an area of interest by correlating it to the Greenwich Mean Time of acquisition or the latitude-longitude ancillary information.

Tables 7 and 8 show the results of the two-dimensional geometric evaluation of the screening films.

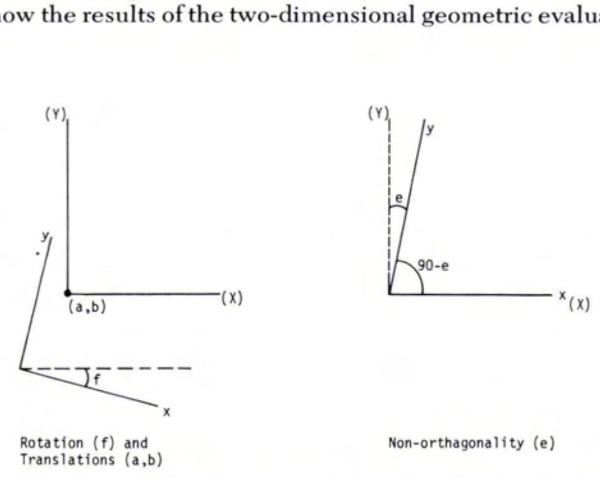


FIG. 6. Coordinate systems: Screening film (x, y) and map (X, Y).

TABLE 7. CYBER 73/PFD: GEOMETRIC EVALUATION OF SCREENING FILM (CONICALLY SCANNED AND GENERATED WITH EPHEMERIS DRIFT ANGLE)

Test Site (1)	Arc Angle (deg.) (2)	Drift Angle (deg.) (3)	Scale S_x (4)	Scale S_y (5)	Ratio $R = S_x/S_y$ (6)	% Scale Diff. (7)	σ_x or σ_y (8)	Non-Orth. (e) (9)	# of Pts. in Transf. (10)
1. New Orleans Ascending Pass #52 GMT 264:13:46:10	116.25	Ephemeris value (δ) + 2.289	740,789 ± 800	748,917 ± 800	0.9891 ± 0.001	1.1	± 150 m	0.056 ± 0.007	15
2. Saskatchewan Descending Pass #50 GMT 262:20:06:50	116.25	Ephemeris value (δ) −0.449	Rel. to S-190A 0.2821 ± .001	Rel. to S-190A 0.2857 ± .001	0.9875 ± 0.004	1.2	± 0.08 m.m.	0.057 ± 0.005	10
3. New Foundland Ascending Pass #40 GMT 257:17:24:10	116.25	Ephemeris value (δ) + 0.569	Rel. to S-190A 0.28242 ± .001	Rel. to S-190A 0.28266 ± .001	0.9991 ± .004	0.1	+ 0.07 m.m.	0.041 ±0.005	10
4. Texas Descending Pass #55 GMT 335:17:30:00	116.25	Ephemeris value (δ) − 2.281	795970 ± 1200	806788 ± 1200	0.9870 ± .003	1.3	+ 250 m	0.052 ± 0.004	17

RECOMMENDATIONS

The parameters of the mathematical model for absolute spatial registration can be used to generate a registered data tape. This algorithm can be developed with least effort whenever a need for it arises. Also, the mathematical model can be further modified to handle longer "data-takes" than 60 second time slices by considering additional orbital parameters in the model. Tabulations such as the PH0-TR524 product S052-7, relating the Greenwich Mean

TABLE 8. CYBER 73/PFD: GEOMETRIC EVALUATION OF SCREENING FILM (CONICALLY SCANNED AND GENERATED WITH MODIFIED EPHEMERIS DRIFT ANGLE)

Test Site (1)	Arc Angle (deg.) (2)	Drift Angle (deg.) (3)	Scale S_x (4)	Scale S_y (5)	Ratio $R = S_x/S_y$ (6)	% Scale Diff. (7)	σ_x or σ_y (8)	Non-Orth. (e) (9)	# of Pts. in Transf. (10)
1. New Orleans Ascending Pass #52 GMT 264:13:46:10	116.25	δ + 3.15	740,755 ± 800	746857 ± 800	0.992 ± .001	0.8	± 105 m	− 0.001 ± 0.001	15
2. Saskatchewan Descending Pass #50 GMT 262:20:06:50	116.25	δ + 3.15	Rel. to S-190A 0.26185 ± 0.0003	Rel. to S-190A 0.26361 ± 0.0003	0.993 ± 0.001	0.7	± .05 m.m.	0.003 ± 0.002	10
3. New Foundland Ascending Pass #40 GMT 257:17:24:10	116.25	δ + 3.15	Rel. to S-190A 0.26210 ± 0.0003	Rel. to S-190A 0.26396 ± 0.0003	0.993 ± 0.001	0.7	± .02 m.m.	− 0.005 ± 0.001	10
4. Texas Descending Pass #55 GMT 335:17:30:00	116.25	δ + 3.15	795,854 ± 800	799,793 ± 800	0.995 ± 0.001	0.5	± 160 m	− 0.002 ± 0.002	17

Time (GMT) of scan with the field of view (FOV) of the S-192 scanner, can be obtained with an accuracy of ± 12 seconds of arc.

It is expected that the registration accuracy by the technique developed can be improved by obtaining higher accuracy ground control points for the solution. To date, the analysis on various "data-takes" was done by considering the ground coordinates accurate to ± 250 metres (obtained from 1:250,000 map sheets), which is about ± 3 pixels. Registration of data is therefore limited to ± 3 pixels at best. However, control good to ± 2 pixels may provide better accuracy of registration.

Sample tests of the S-192 screening films and other products must be carried out from time to time for quality control. The facilities for such tests must be provided when needed.

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Articles for Next Month