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DEPARTMENT OF COMMERCE
WEATHER BUREAU

METEOROLOGICAL SATELLITE LABORATORY
REPORT NO. 11

Perspective Locator Grids for Tiros Pictures

WASHINGTON, D. C.
OCTOBER 1962

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METEOROLOGICAL SATELLITE LABORATORY

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PERSPECTIVE LOCATOR GRIDS FOR TIROS PICTURES

by Morris Frankel and Charles L. Bristor

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National Oceanic and Atmospheric Administration
TIROS Satellites and Satellite Meteorology

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Corrections to text and figures follow. The corrected figures replace those now in the report.

Page IV, figure 4a-4b Image-object plane ....

Page 12, line 25: .... of the object-plane circle ($\alpha + \Delta\alpha$ (max)), where $\Delta\alpha$ (max) is ...

Page 38, line 9: delete: follower after (704 tape 3).

Page 25. Fig. 8

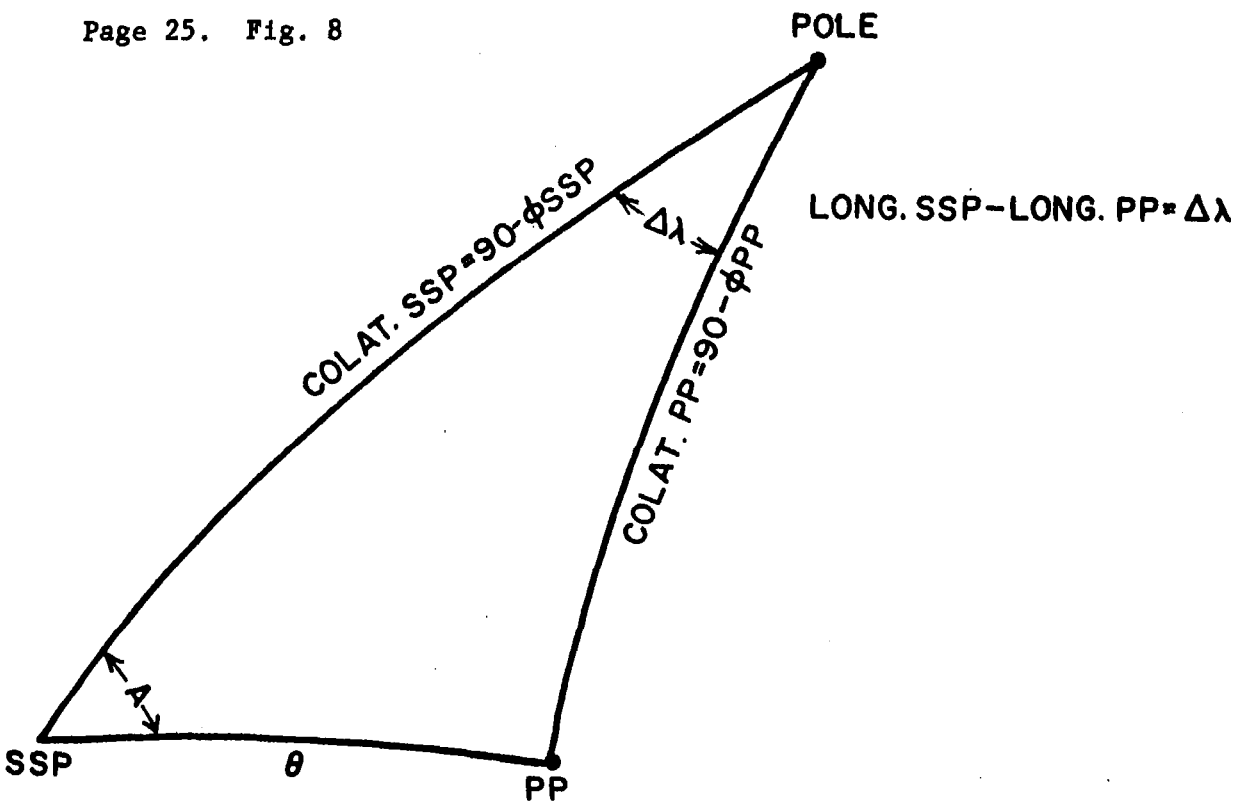

Fig. 8. Geographic spherical triangle.

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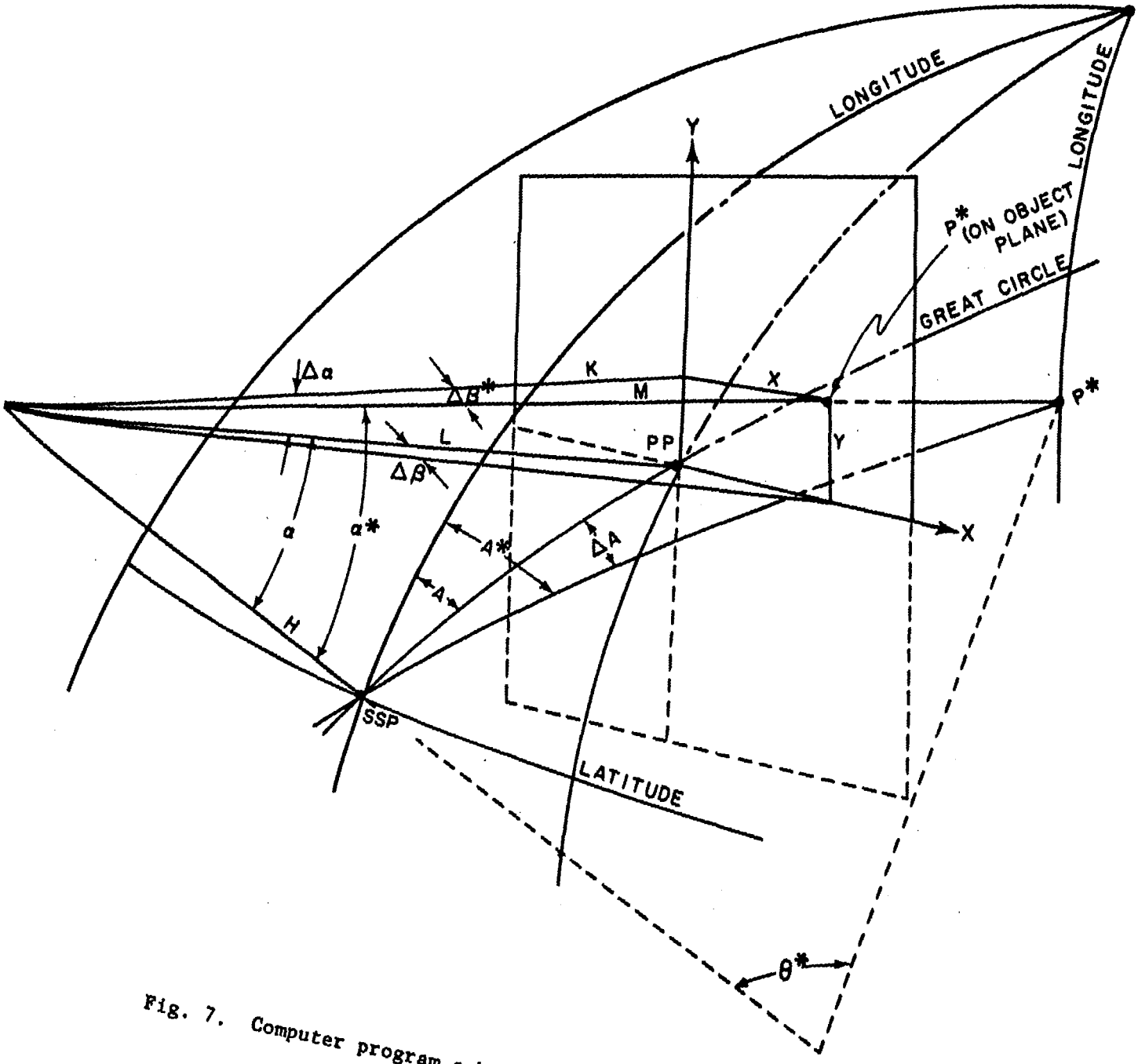

Fig. 7. Computer program spherical trigonometry

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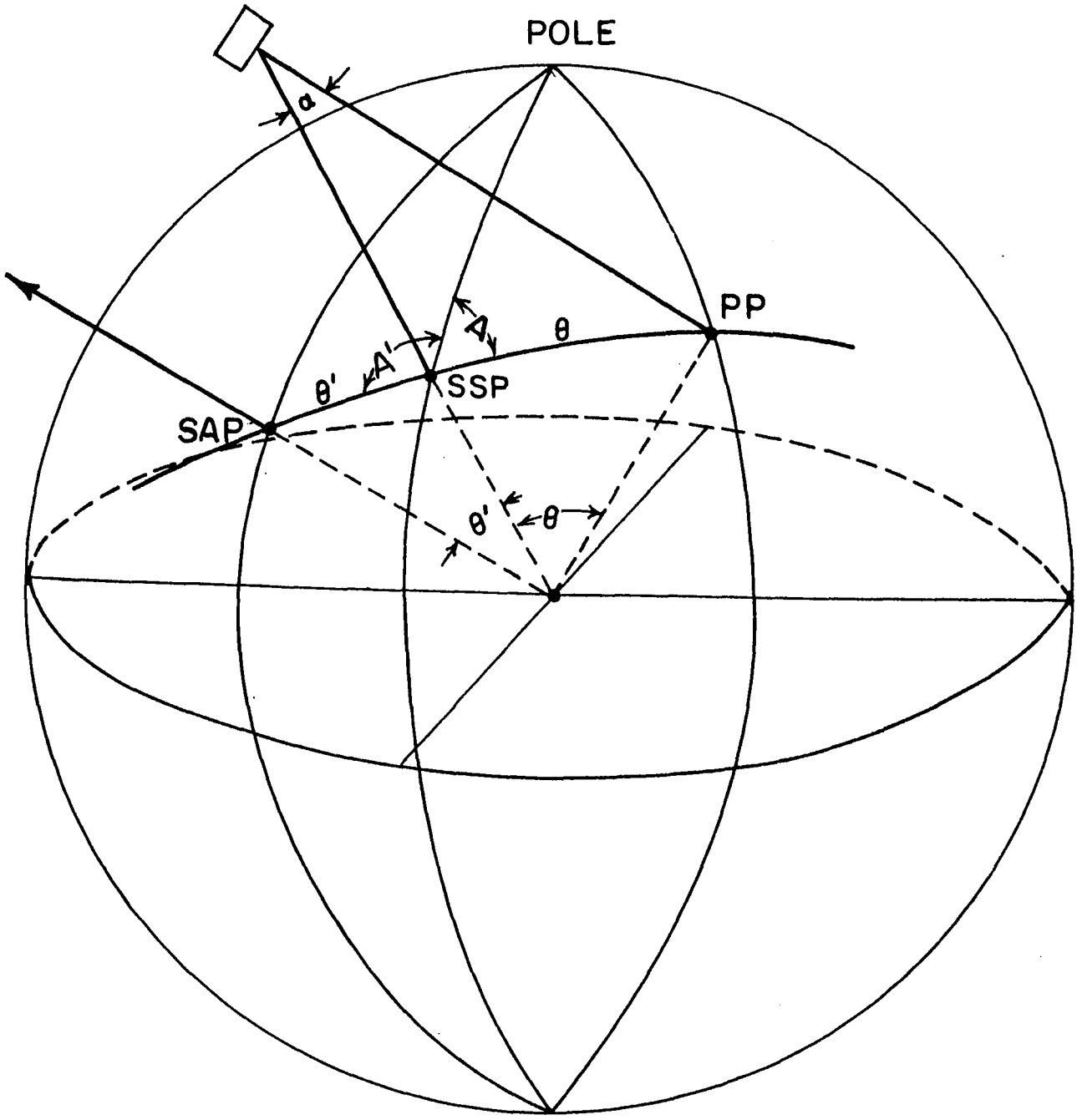

Fig. 10. Definition of spin-axis point (SAP)

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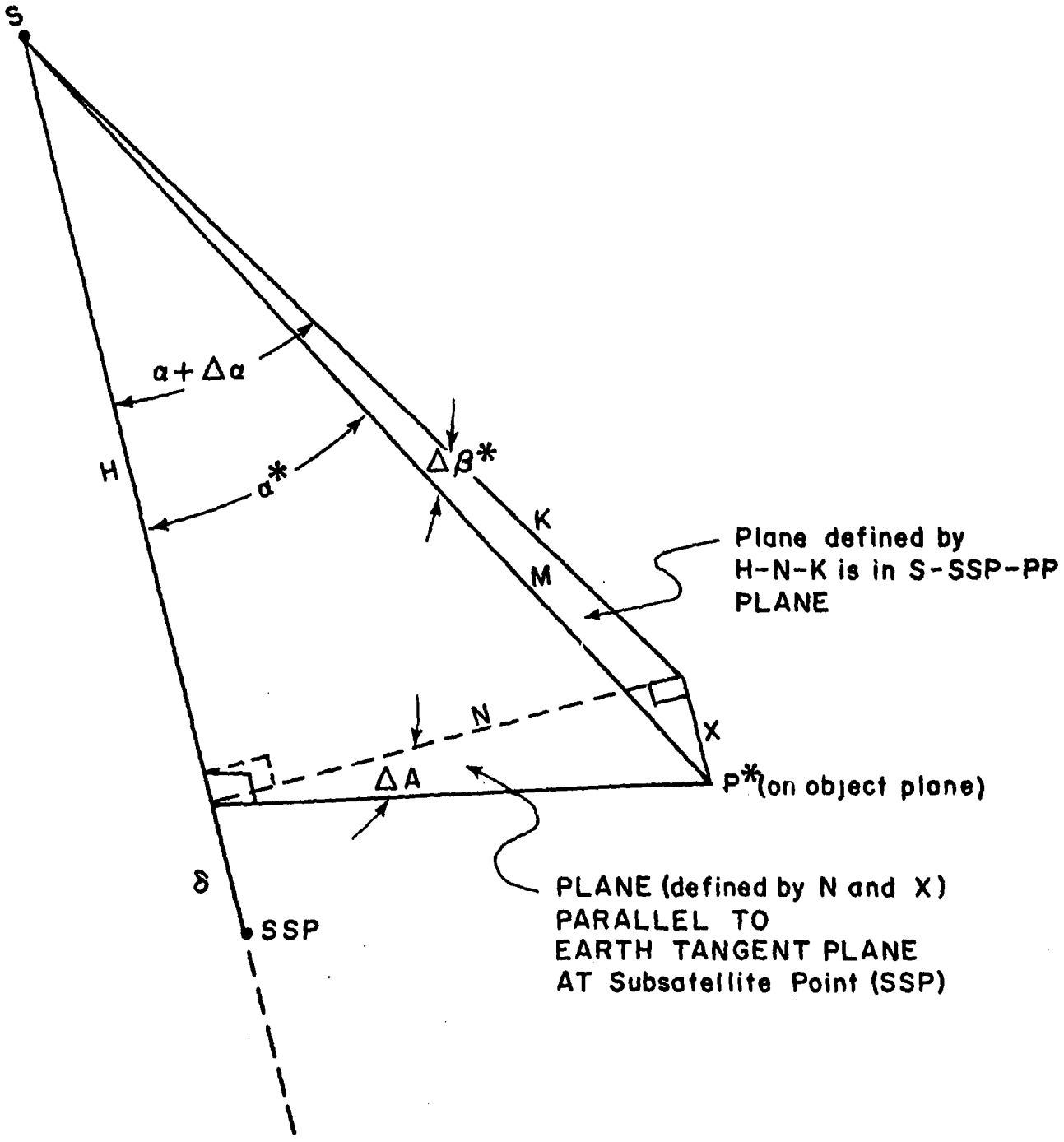

Fig. 11. Computer program plane trigonometry

PERSPECTIVE LOCATOR GRIDS FOR TIROS PICTURES

I. INTRODUCTION

Computer activities in satellite meteorology within the Weather Bureau began during the latter part of 1958 at which time the task of geographically locating features of interest in photos obtained by rockets and satellites was undertaken. The present purpose is to document these efforts - first discussing early digital rectification studies on the IBM 704 and then describing, in some detail, the current perspective geographical locator grid programs produced by the Meteorological Satellite Laboratory for TIROS.

A greatly abbreviated description of the gridding process has been presented by Bristor [1]. The gridding programs described below were originally designed primarily to provide locator information for archived pictures. Many versions of these programs have since been adapted to a variety of purposes including the location of measurements from the TIROS radiometer sensor package. Somewhat parallel efforts have been directed toward the operational processing of cloud photos through contracts with Allied Research Associates Inc. as described in reports by Glaser [2] and Dean [3].

Problems involving uncertainties in input parameters to such programs are discussed in separate papers by Doolittle, Miller, and Ruff [4] and by Hubert [5].

Detailed instructions and input data formats for the described gridding programs are included in an appendix.

II. EARLY DIGITAL STUDIES

By December 1958 it appeared obvious to the two members of the computation unit of the Weather Bureau's early Meteorological Satellite Section that much tedious hand work could be eliminated if picture location information could be produced by computer. The great number of individual pieces of information (one vidicon picture raster of 500 elements X 500 lines contains 250,000 "spots" of information) seemed to preclude complete digital machine processing on the IBM 704. Nevertheless some studies were carried out in an attempt to obtain concrete timing figures for the rectification (the reprojection of the photo onto a standard map base) of such a photo by digital methods.

For this test a White Sands Proving Ground rocket photo taken from a report by Negley [6] was "scanned" by eye and gray tone on a scale of 0-9 was recorded as picture intensity information over a coarse 10 X 10 raster of grid points. Using a simplified version of the locator

mathematics and using approximate height, sub-point location, and attitude information, rough latitude-longitude locations were obtained for the picture elements. By repeating this process for many raster sets, a stable computation timing figure of approximately twenty picture element locations per second was obtained.

Even allowing for improvements in the efficiency of the program, it appeared that this task, for a single picture, might take hours on the 704 if each individual scan spot were located by using the complete set of mathematical relationships.[1] Experience gained with this program did suggest ways of improving computation efficiency and, with the possibility of faster computers, some additional work was done.

Through the cooperation of the Bell Telephone Laboratory, a more realistic data sample was obtained. Dr. R. E. Graham, Engineer in charge of Visual Research, very kindly offered the services of his laboratory to prepare a video digital magnetic tape record of a cloud photo. A section of a "Hugo" rocket photo was thus scanned and digitized to simulate information to be obtained from the scan rasters of satellite vidicon cameras (see figure 1). Picture resolution was reduced in order to limit the volume of digital data so that the tape used for this experiment contains 99 lines, each with 105 samples of picture information.

The previous program was modified to accept this input but the computations were basically the same. Locations were computed for every second spot and written on tape for image transfer to a map projection. The locations and all data (reduced to a gray scale of 16) were also printed. A sample prepared in August 1959 is presented in figure 2.

Plans were under way to make program speedup modifications and to produce rectified image output when the impending launch of TIROS I intervened. At this point, digital studies in mass processing of pictures were set aside in favor of producing perspective geographic locator grids which could be placed upon the unrectified photographs to permit further hand processing of the picture information. The tentative conclusion was that a much faster computer of large capacity would be needed before mass processing of digitized pictures could be carried out as a real-time operation.

---

[1] A current study under AFCRC auspices and carried out by IBM yields similar figures with 29,000 element locations requiring approximately 12 minutes on the 704 (see Mach and Gardner [7]).

Two basic gridding programs are described below - one which generates latitude and longitude for an X, Y point specified on the image plane and the other which works the problem in reverse, finding the image X, Y point for a specified latitude/longitude intersection on earth. Obviously, in either case, any distortions introduced by the camera system must be recognized and accounted for in relating light rays in object space to their counterparts in image space. Both gridding programs are thus dependent upon the vidicon system program described next.

Vidicon System Program with Symmetric Lens Distortion

Computations that refer to the manner in which the video signals are treated by the vidicon system do not involve the geographic computations directly and can therefore be applied to all pictures obtained from a given camera configuration (on the assumption that all components remain stable).

These computations relate grid points on the picture image to angles required in object space, considering only the radially symmetric component of the lens distortion in passing from object space to the picture image.

Input information to this program consists of the aperture angle of the lens and selected X, Y, pairs from an empirically derived lens distortion curve which relates image and object angles (see figures 3a and 3b). The output consists of tables of trigonometric functions of the angles required in the geographic computations, and is punched on a set of cards which are combined with the program cards of the geographic locator programs discussed in the next section.

An "image" plane is assumed on the video side of the lens and a parallel "object" plane on the earth side, both perpendicular to the optic axis (figures 4a and 4b). A circle is drawn on each plane centered at the optic axis, with radius on the object plane equal to 1/2 the tangent of the aperture angle of the lens, and with the corresponding image plane radius obtained by interpolation from the distortion table. The image plane diameter is divided into 47 units centered at the optic axis, and a rectangular coordinate system is established within the image plane circle with those units. The resulting grid consists of 1653 points within the circle symmetrically arranged about the axes.

If the image plane is considered to be at the focal distance of the lens, the circle on the image plane circumscribes the square picture image, and geographic locations computed for points of the grid locate

corresponding points of the picture on the earth. The intermediate step of transferring the image plane grid to the object plane is accomplished by the video system computations.

In figure 4a an arbitrary point (P') on the image can be specified in terms of X', Y' measurements on the image plane. Since L (the focal distance of the given lens) is known from the camera characteristics, Y' and X' can be related to component angles in image space: $Y' = L' \tan \Delta\alpha'$, $X' = L' \tan \Delta\beta'$. Such orthogonal component angles may also be combined to express a resultant angle μ' in image space and a radial angle γ on the image plane.

$$\mu' = \tan^{-1} \sqrt{\tan^2 \Delta\alpha' + \tan^2 \Delta\beta'} \tag{1}$$

$$\gamma = \tan^{-1} (\tan \Delta\alpha' / \tan \Delta\beta') \tag{2}$$

In this form the radial distance (I') on the image plane can be related to equivalent radial distances (I) and to corresponding points (P*) in object space. Angle γ, the plane radial angle, is the same on the image and object planes by the definition of radial distortion, and angle μ on the object plane is obtainable from μ', the resultant angle of $\Delta\alpha'$ and $\Delta\beta'$, by interpolation in the distortion table. Angles $\Delta\alpha$ and $\Delta\beta$ in space, (see fig. 4b), can then be computed by solving equations (1) and (2) for the object plane equivalents, that is

$$\Delta\beta = \tan^{-1} \sqrt{\tan^2 \mu / (1 + \tan^2 \gamma)} \tag{3}$$

$$\Delta\alpha = \tan^{-1} \sqrt{\tan^2 \mu - \tan^2 \beta} \tag{4}$$

Angle $\Delta\beta^*$ to the general point P* on the object plane, is a function of $\Delta\alpha$ and $\Delta\beta$:

$$\tan \Delta\beta^* = \frac{X}{K} = \frac{X}{L} \cdot \frac{L}{K}$$

$$\Delta\beta^* = \tan^{-1} (\tan \Delta\beta \cos \Delta\alpha) \tag{5}$$

Only $\Delta\alpha$ and trigonometric functions of $\Delta\beta^*$ are required in the geographic computations, and tables of these are the output of the

vidicon system program. Because of the symmetry of the grid points the above computations are performed only for the 437 points of the first quadrant. Figure 3a shows the image-object space symmetric distortion for the TIROS wide-angle lenses.

In this manner the grid points on the image plane, which have direct correspondence with points on the processed satellite picture, are transferred to the object plane, from which they are projected to the surface of the earth by the geographic computations.

Vidicon System Program with Generalized Distortion

The vidicon system program described above accounts only for the symmetrical lens components of the total distortions that are present in the pictures received at the read-out stations. The vidicon system itself, the tape recording system, the transmission and receiving electronics, all add distortions to the object field of view of the lens. Stable components of these additional distortions are accounted for in the current gridding program. Standard "target-shot" photographs are taken through the complete satellite system prior to launch. A statistical analysis of these pictures is made at the Naval Photographic Interpretation Center by comparing known distances and angles of the target object field with corresponding measurements made on the photographs. The symmetrical components of all distortion sources are mathemetrically separated from the total distortions, in a computer program prepared by NPIC and MSL personnel. The symmetrical factors are prepared for use in the current version of the gridding computations in a form similar to that represented by figure 3a. The effects of symmetrical distortions are shown in figure 5.

The additional "asymmetric" components of the distortions are prepared in separate tables consisting of multiplication factors to be applied to the symmetrically distorted distances of points on the image plane from the principal point, and angular displacement of the radial angles to the points. These are prepared for a set of approximately 500 points on concentric circles on the image plane. A comparison of symmetric and complete distortion information is indicated in figure 6.

A third table is prepared by the same program, of the X, Y coordinates of the fiducial marks that are superimposed on the satellite pictures.

These three sets of tables are read into the computer as part of the data that are required to compute individual grids. The symmetrical distortion can be applied to all grids, and is always performed. The asymmetric distortion corrections vary at individual points of the picture. Before they can be applied to corresponding points on the computed image plane grids the rotation angle must be known between the grid coordinate system (principal line and the line normal to it through the principal point) and the picture coordinate system (the line normal to the scan lines through the principal point, and the line parallel to the scan lines through the principal point). Similarly, the fiducial marks may be added to the grids in the proper locations only if the rotation angle is known.

Separate computer programs and manual techniques are available to determine these roll angles under appropriate conditions. Such conditions rarely have prevailed prior to TIROS IV. However, the major part of the variations due to distortions is removed by the symmetrical distortion corrections. Studies made in MSL concerning the additional improvements performed by the asymmetric distortion corrections have yielded inclusive answers to the question as to whether the additional preparation and computation time is justified.[2]

Geographic Program with Preselected X, Y Image Points.

In this program the origin of the object plane grid discussed above is assumed to be at the earth intersection of the optic axis (PP in fig. 7, the "principal point"), and the Y-axis is assumed to be in the plane of the optic axis and the radius vector from the center of the earth to the vehicle. This radius vector intersects the surface of the earth at the "sub satellite point" (SSP in fig. 7). Two angles, the nadir angle α at the satellite and the azimuth angle A on the earth, which define the size and orientation of the great circle arc between SSP and PP, are considered primary orbital-attitude information in these computations and the earth locations of the grid points are obtained by adding computed angular increments to this "principal line."

The height of the satellite above the earth (H in fig. 7) and the latitude and longitude of the sub-satellite point are necessary input information for the computation of α and A; they are available in the published NASA "Attitude World Maps" for TIROS satellites. Original plans for these computations assumed that optic axis attitude information could be computed from horizon-sensor equipment installed

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[2]Doolittle [8] indicates that there is little to be gained in applying asymmetric distortions to the TIROS III photographs read out at Wallops Island.

in the TIROS satellites, and would also be available in the Attitude World Maps. This equipment has not functioned properly, and a number of manual and machine computing methods have been devised from photogrammetric techniques to compute the nadir and azimuth angles directly, or the location of the principal point, or the location of a "spin axis point" defined as the earth intersection of the radius vector parallel to the optic axis (SAP in fig. 10). Although the geographic computation program can accept any one of those three possibilities as input, the most frequent source of attitude input data has been a photogrammetric "resection" computing machine procedure which was programmed to compute spin axis location from the X, Y picture coordinates of recognizable landmarks and points along the horizon [4]. The geographic program will accept either binary-card output of this photogrammetric program, or manually-punched Hollerith cards from information prepared by that program or from other sources.

Given the location of the principal point and the sub-satellite point, the length of the principal line (θ in fig. 8) and the azimuth angle (A) can be computed by solution of the spherical triangle Pole-SSP-PP of figure 8 (assuming a spherical earth). Using the haversine form of the spherical triangle equations,

$$\begin{aligned} \mathrm{hav}\,\theta &= \mathrm{hav}\left[(90-\phi PP)-(90-\phi SSP)\right] \\ &\quad + \sin(90-\phi PP)\sin(90-\phi SSP)\,\mathrm{hav}\,\Delta\lambda \\ \theta &= \cos^{-1}(1-2\,\mathrm{hav}\,\theta) \end{aligned} \tag{6}$$

$$\begin{aligned} \mathrm{hav}\,A &= \frac{\mathrm{hav}(90-\phi PP)-\mathrm{hav}\left[(90-\phi SSP)-\theta\right]}{\sin(90-\phi SSP)\sin\theta} \\ A &= \cos^{-1}(1-2\,\mathrm{hav}\,A) \end{aligned} \tag{7}$$

The nadir angle α is then computed from Θ and the height of the vehicle (see fig. 9). Assuming a spherical earth, the great circle arc Θ is also the angle at the center of the earth between the radius vectors to the sub satellite and principal points. The line N is the perpendicular distance between PP and the satellite radius vector. Then, since

$$N = RE \sin \Theta$$

$$\delta = RE - R = RE(1 - \cos \Theta)$$

$$\alpha = \tan^{-1} \frac{RE \sin \Theta}{H + RE(1 - \cos \Theta)} \tag{8}$$

Alternatively, given the location of the spin axis point, equations (6) and (7) may be applied in identical fashion to the spherical triangle, Pole - SSP-SAP, (fig. 10) to compute Θ and A'. But $\alpha = \Theta$ since the spin axis radius vector is parallel to the optic axis, and A = A' - 180, since the spin axis point (SAP) and optic axis point (PP) are on opposite sides of the sub satellite point on the great circle arc passing through the three points.

Angles α and A from the above computations and angles $\Delta\alpha$ and $\Delta\beta^*$ from the video system computations (fig. 4b, and equation 5) are used to locate each grid point on the earth. For this purpose, a plane is assumed tangent to the earth at the sub satellite point, and therefore perpendicular to the radius vector to the satellite. This plane is then moved along the radius vector (remaining perpendicular to it) so as to pass through the point being computed. Angles α, $\Delta\alpha$ and $\Delta\beta^*$ are then used to compute ΔA (fig. 11) the azimuth increment on the above plane (parallel to the earth-tangent plane), which is equivalent to the azimuth increment on the surface of the earth in turning from the principal point to the computed point, P* (see figs. 7 and 11)

$$\tan \Delta A = \frac{X}{N} = \frac{X}{K} \cdot \frac{K}{N}$$

$$\Delta A = \tan^{-1} \frac{\tan \Delta\beta^*}{\sin(\alpha + \Delta\alpha)} \tag{9}$$

The total azimuth angle from the meridian of the sub satellite point to the great circle arc through the computed point is then

$$A^* = A + \Delta A \qquad \text{(see fig. 7).}$$

Angles α , $\Delta\alpha$ and $\Delta\beta^*$ are also used to compute α^* , the nadir angle to the point being computed:

$$\cos\alpha^* = \frac{H}{M} = \frac{H}{K} \cdot \frac{K}{M}$$

$$\alpha^* = \cos^{-1}\left[\cos(\alpha + \Delta\alpha)\cos\Delta\beta^*\right] \tag{10}$$

Equation (8) can be generalized for any point being computed, and can be solved for θ^* (fig. 7) if α^* is known:

$$\tan\alpha^* = \frac{RE \sin\theta^*}{H + RE(1 - \cos\theta^*)}$$

$$\tan\alpha^* \cos\theta^* + \sin\theta^* = \frac{(H + RE)\tan\alpha^*}{RE}$$

Multiplying both sides of the equation by $\frac{\sin\alpha^*}{\tan\alpha^*} \equiv \cos\alpha^*$

$$\sin\alpha^* \cos\theta^* + \cos\alpha^* \sin\theta^* = \frac{H + RE}{RE} \sin\alpha^*$$

$$\sin(\alpha^* + \theta^*) = \frac{H + RE}{RE} \sin\alpha^*$$

$$\theta^* = \sin^{-1}\left[\left(\frac{H + RE}{RE}\right)\sin\alpha^*\right] - \alpha^* \tag{11}$$

Given Θ^* and A^*, spherical triangle equations equivalent to those in (6) and (7) can be set up to solve for the colatitude of the given point and for $\Delta\lambda$ to the meridian of the given point (fig. 8):

$$\mathrm{hav}(90-\phi P^*) = \mathrm{hav}\left[\Theta^* - (90-\phi SSP)\right] + \sin\Theta^* \sin(90-\phi SSP)\,\mathrm{hav}A^* \quad (12$$

$$\phi P^* = 90 - \cos^{-1}\left[1 - 2\,\mathrm{hav}(90-\phi P^*)\right]$$

$$\mathrm{hav}\,\Delta\lambda P^* = \frac{\mathrm{hav}\,\Theta^* - \mathrm{hav}\left[(90-\phi SSP) - (90-\phi P^*)\right]}{\sin(90-\phi SSP)\,\sin(90-\phi P^*)} \quad (13)$$

$$\lambda P^* = \lambda SSP - \cos^{-1}(1 - 2\,\mathrm{hav}\,\Delta\lambda P^*)$$

The above computations are performed only for grid points that are below the horizon, i. e., that are on the earth. At the horizon the ray to the grid point is tangent to the earth. There is therefore a critical α such that

$$\alpha(CR) = \sin^{-1}\left(\frac{RE}{H+RE}\right) \geq \alpha^* \quad (14)$$

and locations are computed only when the computed α^* is less than or equal to that $\alpha(CR)$. The X, Y coordinates of the horizon line on the image plane are also computed in this program. The method that is used selects the $\Delta\beta^*$ of the grid points on the object plane which are immediately above the horizon and computes $\Delta\alpha$ and $\Delta\beta$ for points on the horizon which have exactly the same $\Delta\beta^*$. Given $\Delta\beta^*$ and $\alpha^* = \alpha(CR)$, equation 10 is solved for $\Delta\alpha(CR)$:

$$\Delta\alpha(CR) = \cos^{-1}\left(\cos\alpha(CR)/\cos\Delta\beta^*\right) \quad (15)$$

and equation (5) is then solved for $\Delta\beta(CR)$:

$$\Delta\beta(CR) = \tan^{-1}\left[\tan\Delta\beta^*/\cos\Delta\alpha(CR)\right] \quad (16)$$

These angles on the object plane are converted to X, Y coordinates on the image plane in a procedure analogous to that described in equations (1)-(4) for passing through the lens distortion in the opposite direction.

The procedures and equations described above have been programmed (in the Fortran Coding System) for analysis of TIROS I pictures on the IBM 704 machine, but the program operates also on the IBM 7090 (at an average of approximately 10 seconds per picture), through the 704/709 Input-Output Compatibility Program, IB IOC2.

This basic program has been adapted to several problems. One version, which produces only a limited selection of locations around the perimeter of the field of view along with the location of the principal point, has been used extensively to prepare documentation catalogues to denote, generally, the area viewed by "swaths" of pictures on individual orbits. Another version has been reduced to subroutine form and yields location information only for rays entering at an angle of 45° to the principal axis. This version serves as a portion of the TIROS IR data processing programs which combines raw sensor data with orbital, attitude, and calibration information. The most general version which has been used to a considerable extent within MSL and also by the Australian Meteorological Service, produces printed output as presented in figures 12 and 13.

III. GEOGRAPHIC PROGRAM WITH PRESELECTED LATITUDE/LONGITUDE POINTS

The most efficient program for perspective gridding determines X, Y image locations only for the wanted integer latitude, longitude intersections. The program just described requires interpolation to obtain such image X, Y intersection locations. Since the earlier program was an outgrowth of digital rectification studies and was oriented to that purpose, it was decided that the major rewriting of the gridding program for the 7090 should be optimized to compute only the integer latitude, longitude intersections. The basic equations described previously were accordingly solved in the reverse context to produce the present most commonly used gridding program.

In this version a central latitude/longitude intersection is selected near the middle of the area of the earth that is within the field of view. The longitude is then successively increased along the selected latitude by integral units (the spacing is a parameter of the program) until the intersection is beyond the edge of the field of view or above the horizon; the latitude is then traced in the opposite direction in a similar fashion. The same process is repeated

along successively higher latitudes, then along successively lower latitudes, until the lattice of selected intersection points covers the entire field of view.

To avoid excessive packing of the points as the horizon is approached, a "program" horizon is assumed at a location equal to 95% of the actual critical angle defined by equation (14). The true horizon curve is, however, computed and is included in the output of the program. As the field of view approaches the poles the number of longitude intersection points along latitude circles may also increase beyond the storage capacity set aside in the program (25 locations for either half of the latitude arc). In such cases the longitude spacing (but not the latitude spacing) is increased until the number of points is decreased sufficiently to fit within the alloted storage space.

As each geographic grid point is selected it is projected to the object plane and then passed through the symmetrical distortions and, if desired, through the asymmetric distortions, to determine an X, Y point on the image plane in a manner analogous to the preceding discussion, using inverse forms of the original equations in a procedure operating in the opposite direction.

The principal point is the midpoint of the grid only if there is no horizon in the grid; in the latter case a midpoint is computed along the principal line which is midway between the nadir angle to the horizon ($\alpha + \alpha(CR)$ of eq. 14) and the nadir angle to the bottom of the object-plane circle ($\alpha + \Delta\alpha$ (max)), where $\Delta\alpha$ (max) is the half-angle aperture of the lens. A weighted mean of the two angles is used in the program, to minimize the packing of grid lines in the upper half of the area. Equations (11) (12) and (13) are used to compute the latitude and longitude of the midpoint, with A* = A = azimuth angle of the principal line and $\alpha^* = \alpha + \Delta\alpha(MID)$. This location is rounded to integral units of the spacing parameter, and the rounded location is used as the center point of the grid-line computations. All other points are then obtained by incrementing and decrementing the central latitude and longitude as described above. The procedure to convert these locations to corresponding image X, Y coordinates is as follows:

Equations (13), (12) and (11) are used to compute ΔA and α^* from latitude and longitude. Equations (10) (9) and (5) are then used to compute $\Delta\alpha$ and $\Delta\beta$ on the object plane, and equations (4), (3), (2), and (1) (in that order) to compute the corresponding symmetrically distorted $\Delta\alpha'$ and $\Delta\beta'$ on the image plane. Asymmetric distortions may be applied optionally in the program when the film rotation angle is

known, by selecting the appropriate multiplication and additive factors from the distortion tables and applying them to μ and γ respectively, before computing $\Delta\alpha'$ and $\Delta\beta'$. The final X, Y coordinates that are used in the output subroutines are the tangents of $\Delta\beta'$ and $\Delta\alpha'$, respectively.

Tables of the locations of significant points along the major coastlines are included in the program. The tables are examined for points within the area of the grid, and sections of any coastlines that are within the area are included in the output. These coastline locations are computed by identical methods used to convert grid latitude-longitude intersections to X, Y points on the image plane.

The current version of the gridding program computes grids in an average of 12-15 seconds for the mechanical data plotter (line drawn) output and approximately 8-10 seconds[3] for the cathode ray tube photo process described below. The grid-print version took approximately 15 seconds for off-line printed output, which did not, however, include any horizon or coastline information. An interim program was used briefly between the two versions to produce interpolated grid and coastline information for the data plotter from an optional binary tape output of the grid-print program.

Several different versions of this program are now in use. One of these generates an output tape which directs an Electronic Associates Data Plotter, model 3410. A sample of this output is presented in figure 14. Such grids are drawn nine to a 30" X 30" paper or transparent plastic sheet. Drawing time ranges between twenty and thirty minutes per sheet. A standard 2400' tape reel will contain about 18 such grid output files. This version has been used to generate approximately 2000 grids for TIROS I photographs, both for archiving and for case studies. It has also produced some 8000 grids for TIROS III archives.

Another version of this program generates output to feed the General Dynamics SC 4020 High Speed Microfilm Recorder. Each grid is traced on the cathode ray tube and simultaneously recorded on 35 mm microfilm. Output grids such as that shown in figure 15 are

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[3]This time is expected to be reduced to approximately 5 seconds when the output is completely buffered.

produced in less than one second on the microfilm. A tape reel generated by the 7090 will contain twelve times as many grids as that produced for the Data Plotter. This high speed version will produce archival grids for TIROS IV.

Other specialized versions of this program are being used to simulate Nimbus grids.

IV. FUTURE PLANS

This report essentially documents the MSL gridding efforts in support of TIROS. Many versions of both basic programs have been produced for a variety of uses and, except for minor modification requests, no further work on these basic program packages is anticipated. As mentioned above Nimbus photogrids have been simulated and it is anticipated that that program version will serve as an emergency back-up tool in the real-time Nimbus operation.

Two major new programs are planned:

1. A photo melded grid program will produce image X intersections for a preselected open lattice of vidicon raster lines (Y intersections) for a segment of the latitude or longitude line which lies in the image area. Such information, when synchronously combined with the actual photo raster as "over-ride" signals, will produce a dotted line grid directly on an image obtained when a tape with such melded information is played through a kinescope monitor, photo facsimile, or other output device.

2. A new program to yield latitudes and longitudes for a preselected lattice of X, Y image points will also be produced - in this case selecting the image points as a logically square array in terms of scan spot and line number on the vidicon raster. Complete distortion characteristics can thus be assigned to this set of points (under the assumption that attitude and orbit are known). The set of locations thus produced will become the basic input to new rectification programs which will interpolate needed latitude/longitude data for other raster spots.

ACKNOWLEDGMENTS

We wish to thank Mr. N. W. Springer for special photo lab assistance and Mr. P. E. Lehr whose editorial assistance contributed substantially to the paper.

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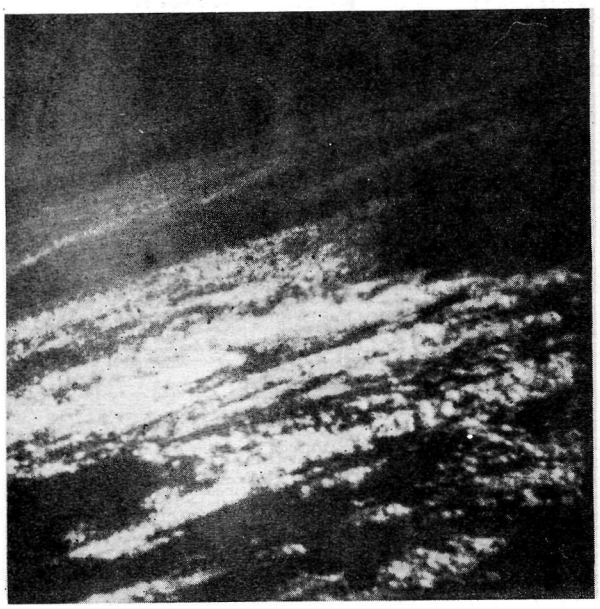

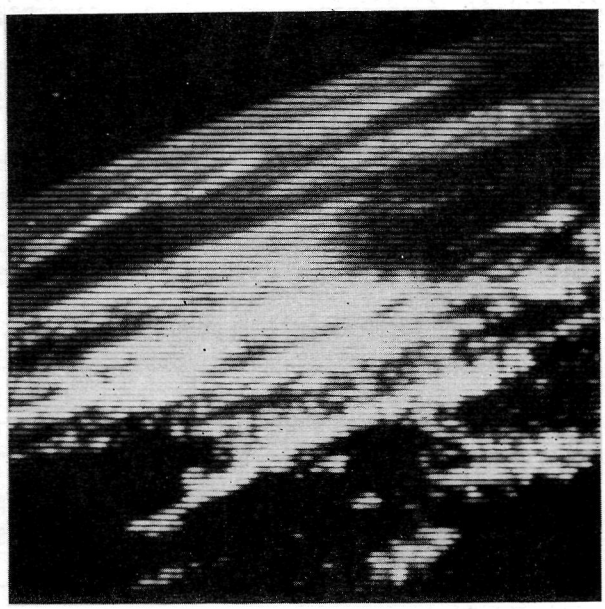

Fig. 1. "Hugo" rocket photo looking east-southeast from Wallops Island, Virginia at an altitude of 83 miles, December 1959 (left); and kinescope photo of image produced by play back of digital tape (right).

35.45	68.31	5	5	35.44	68.32	6	6	35.42	68.32	6	5	35.41	68.32	4	4	35.39	68.33	5	4
35.38	68.33	5	5	35.36	68.33	5	4	35.35	68.34	3	4	35.33	68.34	4	3	35.32	68.34	2	2
35.30	68.35	3	4	35.29	68.35	3	3	35.27	68.35	3	0								
ROW 44																			
36.12	68.43	6	5	36.10	68.44	5	5	36.09	68.44	6	6	36.07	68.45	6	6	36.06	68.45	6	6
36.04	68.46	6	6	36.03	68.46	6	6	36.02	68.47	6	6	36.00	68.47	6	6	35.99	68.48	6	6
35.97	68.48	5	5	35.96	68.48	5	5	35.94	68.49	5	4	35.93	68.49	4	4	35.91	68.50	4	3
35.90	68.50	3	4	35.89	68.51	4	3	35.87	68.51	3	3	35.86	68.51	3	3	35.84	68.52	3	3
35.83	68.52	3	4	35.81	68.53	3	3	35.80	68.53	2	2	35.78	68.53	2	2	35.77	68.54	1	1
35.75	68.54	2	2	35.74	68.55	3	3	35.73	68.55	3	4	35.71	68.55	4	4	35.70	68.56	4	4
35.68	68.56	5	5	35.67	68.56	4	4	35.65	68.57	4	4	35.64	68.57	5	5	35.62	68.58	5	4
35.61	68.58	4	5	35.59	68.58	5	5	35.58	68.59	5	6	35.56	68.59	6	6	35.55	68.59	5	5
35.54	68.60	6	6	35.52	68.60	5	5	35.51	68.60	5	4	35.49	68.61	4	3	35.48	68.61	4	5
35.46	68.61	4	3	35.45	68.62	2	1	35.43	68.62	1	2	35.42	68.62	2	1	35.40	68.63	2	2
35.39	68.63	2	2	35.37	68.63	2	4	35.36	68.64	4	0								
ROW 45																			
36.18	68.69	6	5	36.16	68.69	6	6	36.15	68.70	6	6	36.13	68.70	6	6	36.12	68.71	6	5
36.11	68.71	5	6	36.09	68.72	6	6	36.08	68.72	6	6	36.06	68.72	6	5	36.05	68.73	5	5
36.04	68.73	5	4	36.02	68.74	4	4	36.01	68.74	4	4	35.99	68.75	3	3	35.98	68.75	3	3
35.96	68.75	4	5	35.95	68.76	4	4	35.94	68.76	4	4	35.92	68.77	4	4	35.91	68.77	4	4
35.89	68.77	3	2	35.88	68.78	2	2	35.86	68.78	2	2	35.85	68.79	3	2	35.84	68.79	2	2
35.82	68.79	2	3	35.81	68.80	4	3	35.79	68.80	4	4	35.78	68.81	4	4	35.76	68.81	4	3
35.75	68.81	3	3	35.74	68.82	2	2	35.72	68.82	2	4	35.71	68.82	5	5	35.69	68.83	4	3
35.68	68.83	2	4	35.66	68.83	4	4	35.65	68.84	5	5	35.63	68.84	5	5	35.62	68.85	5	5
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35.53	68.87	3	2	35.52	68.87	2	2	35.50	68.87	3	3	35.49	68.87	3	2	35.48	68.88	2	2
35.46	68.88	3	3	35.45	68.88	3	5	35.43	68.89	5	0								
ROW 46																			
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35.53	69.11	3	5	35.51	69.11	5	5	35.50	69.11	4	0								
ROW 47																			
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35.94	69.23	2	3	35.92	69.23	3	2	35.91	69.23	1	1	35.89	69.24	1	2	35.88	69.24	3	2
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ROW 48																			
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36.19	69.36	3	3	36.18	69.36	3	4	36.16	69.37	4	4	36.15	69.37	3	3	36.14	69.37	3	2
36.12	69.38	3	3	36.11	69.38	3	4	36.10	69.38	4	5	36.08	69.39	4	4	36.07	69.39	4	3
36.05	69.40	3	3	36.04	69.40	3	3	36.03	69.40	4	4	36.01	69.41	2	2	36.00	69.41	2	2
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35.92	69.43	0	0	35.90	69.44	0	0	35.89	69.44	0	1	35.88	69.44	1	1	35.86	69.45	2	3
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35.78	69.47	3	4	35.77	69.47	5	4	35.75	69.47	5	4	35.74	69.48	4	4	35.72	69.48	5	5
35.71	69.48	4	4	35.70	69.49	3	3	35.68	69.49	3	3	35.67	69.49	3	3	35.66	69.50	4	4
35.64	69.50	3	4	35.63	69.50	5	6	35.61	69.51	5	0								
ROW 49																			
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36.30	69.51	5	4	36.29	69.52	3	3	36.27	69.52	3	3	36.26	69.52	3	3	36.25	69.53	3	4
36.23	69.53	4	4	36.22	69.54	4	3	36.21	69.54	3	3	36.19	69.54	3	4	36.18	69.55	4	3
36.17	69.55	3	4	36.15	69.55	5	5	36.14	69.56	4	4	36.13	69.56	5	4	36.11	69.57	4	3
36.10	69.57	3	4	36.09	69.57	4	4	36.07	69.58	3	2	36.06	69.58	1	1	36.05	69.58	0	0
36.03	69.59	0	0	36.02	69.59	0	1	36.01	69.60	1	0	35.99	69.60	0	0	35.98	69.60	0	0
35.96	69.61	0	0	35.95	69.61	0	0	35.94	69.61	0	0	35.92	69.62	1	3	35.91	69.62	4	5
35.90	69.62	4	3	35.88	69.63	1	1	35.87	69.63	0	1	35.86	69.63	2	3	35.84	69.64	5	4
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ROW 50																			
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36.07	69.75	0	0	36.06	69.75	0	0	36.05	69.76	0	0	36.03	69.76	0	0	36.02	69.76	0	0
36.01	69.77	0	0	35.99	69.77	0	1	35.98	69.77	2	3	35.97	69.78	4	5	35.95	69.78	4	2
35.94	69.78	1	1	35.93	69.79	0	1	35.91	69.79	1	1	35.90	69.79	1	3	35.89	69.80	5	5
35.87	69.80	6	6	35.86	69.80	6	6	35.85	69.81	5	3	35.83	69.81	3	2	35.82	69.81	3	5
35.81	69.82	5	6	35.79	69.82	6	6	35.78	69.82	6	6	35.77	69.83	6	6	35.75	69.83	6	6
35.74	69.83	6	6	35.73	69.84	5	5	35.71	69.84	5	0								
ROW 51																			

Fig. 2. Sample output of computer rectification of digitized "Hugo" rocket photo, prepared Aug. 1959 on IBM 704 computer.

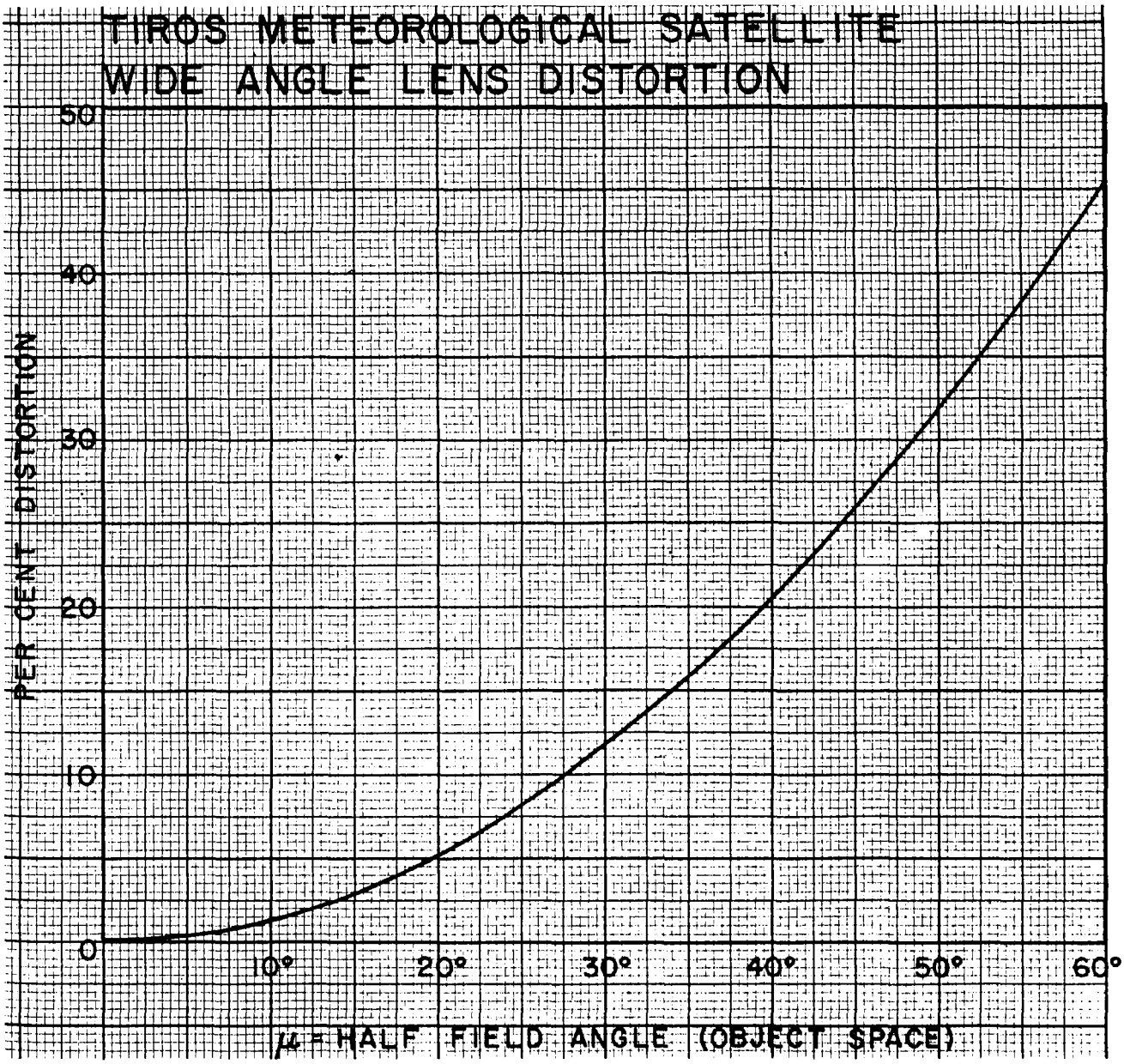

TIROS METEOROLOGICAL SATELLITE
WIDE ANGLE LENS DISTORTION
PER CENT DISTORTION
50
40
30
20
10
0
10°
20°
30°
40°
50°
60°
μ = HALF FIELD ANGLE (OBJECT SPACE)

Fig. 3a

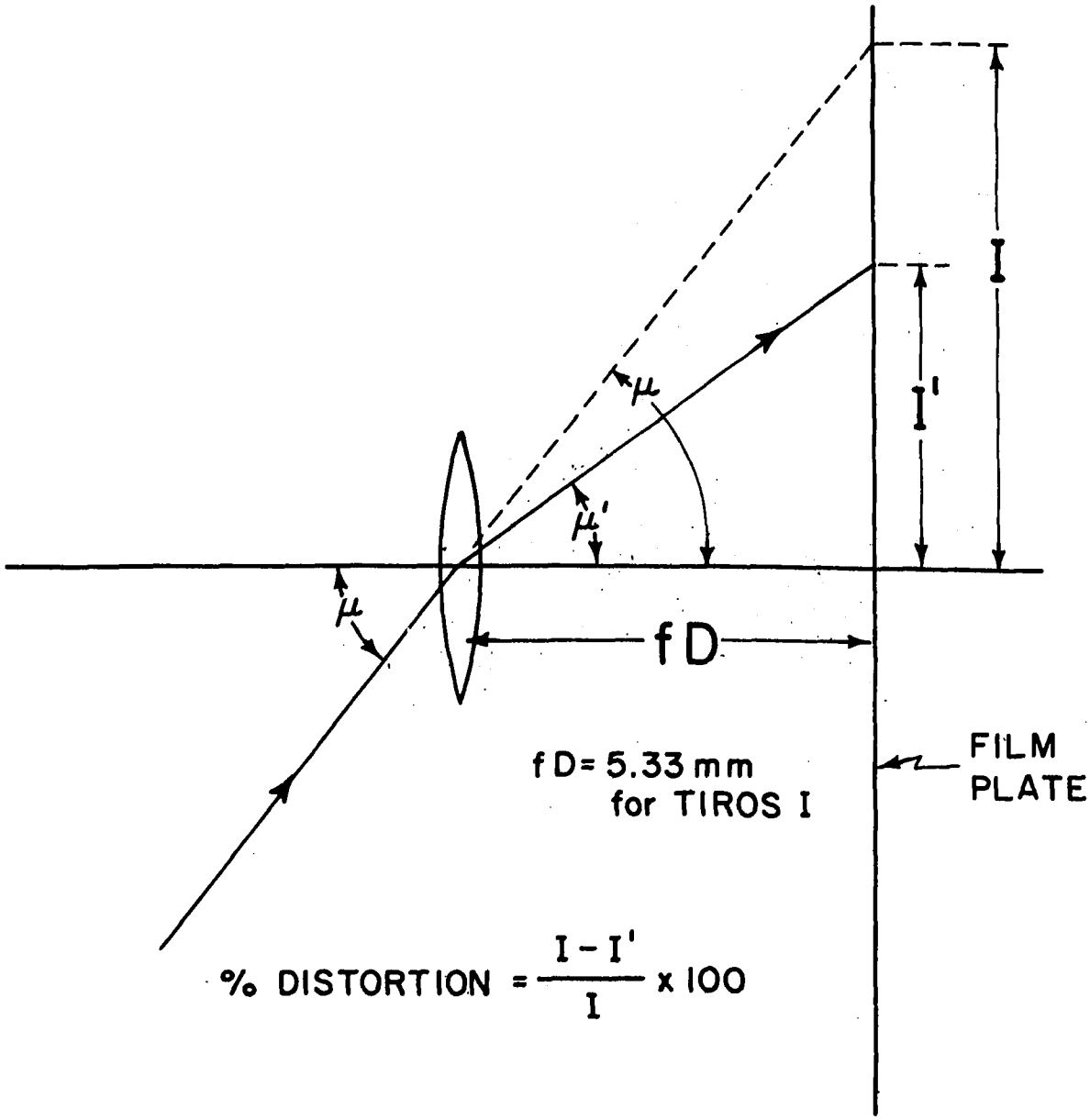
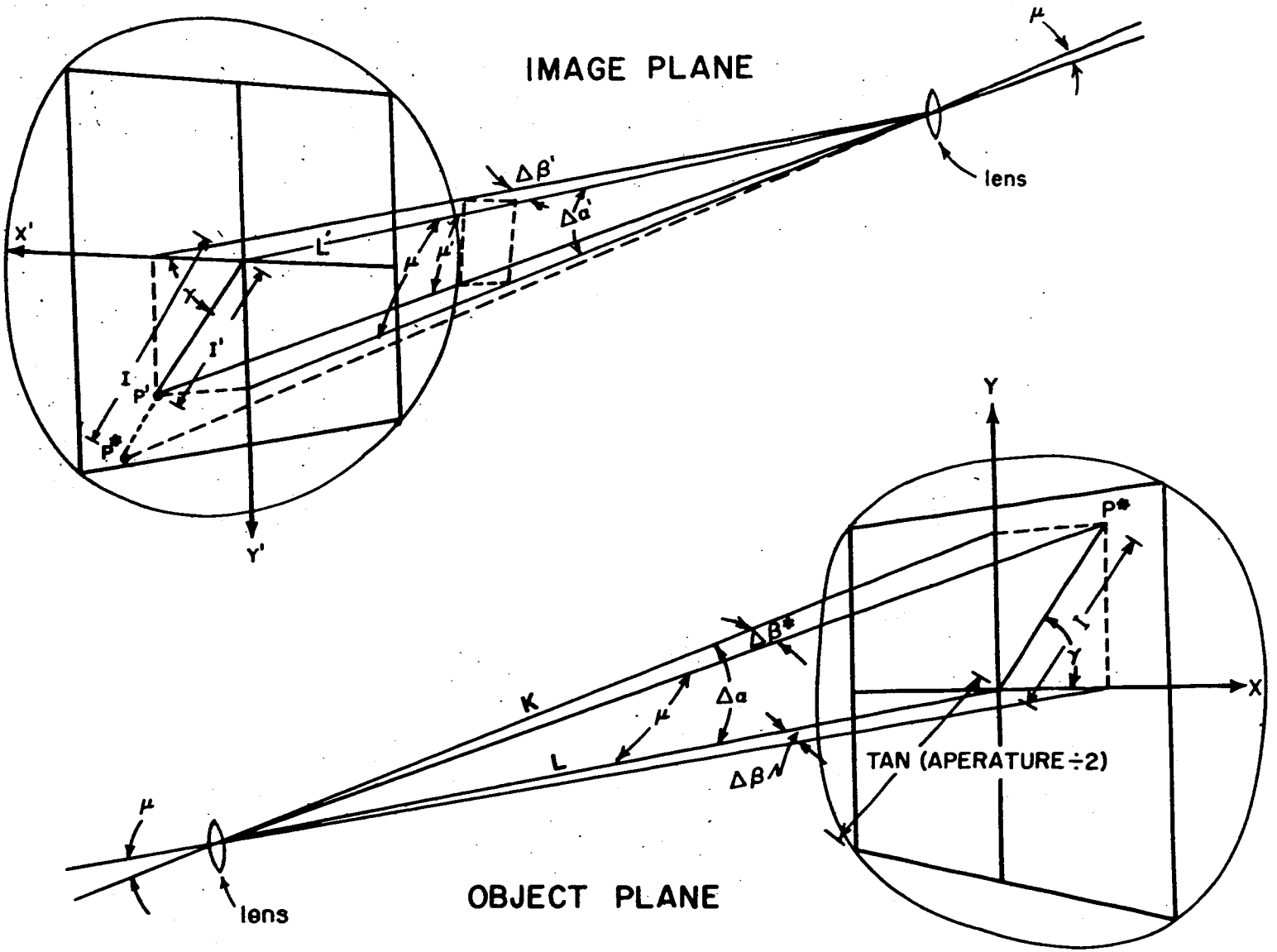


Fig. 3b. Lens distortion definitions.



Figs. 4a - 4b. Image-object plane relationships.

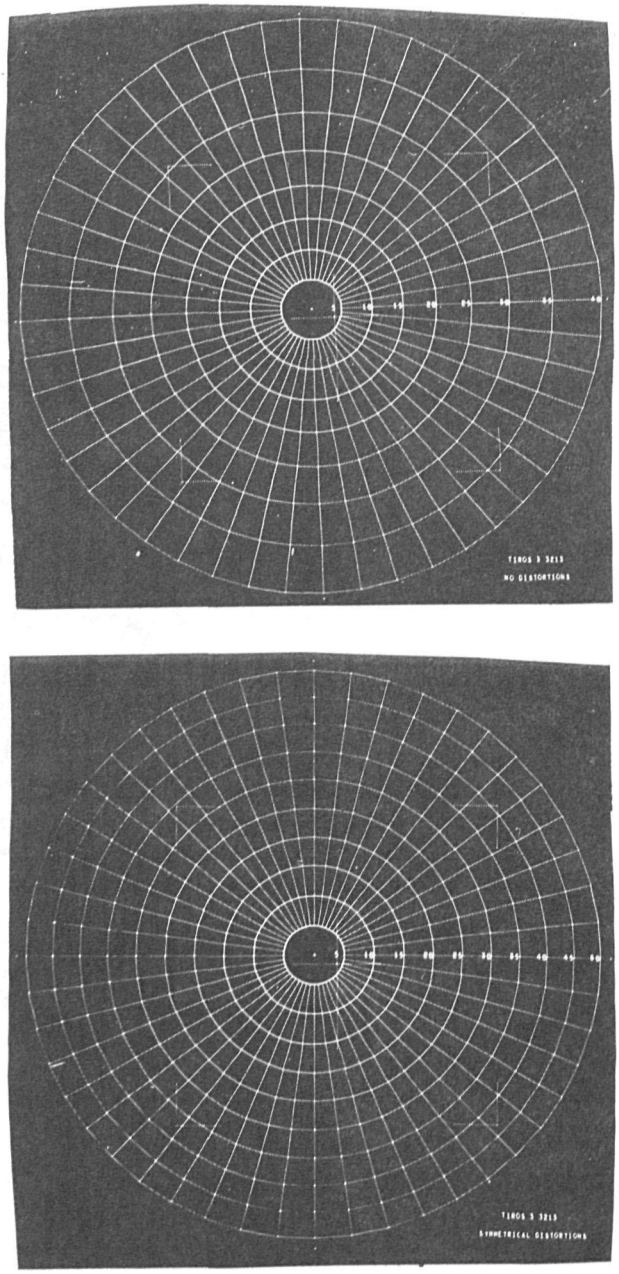


Fig. 5. Image-object angle relationships without distortion (upper) and the equivalent relationships with symmetric distortion (lower) for TIROS III, Circles are at 5° increments of object-plane angles.

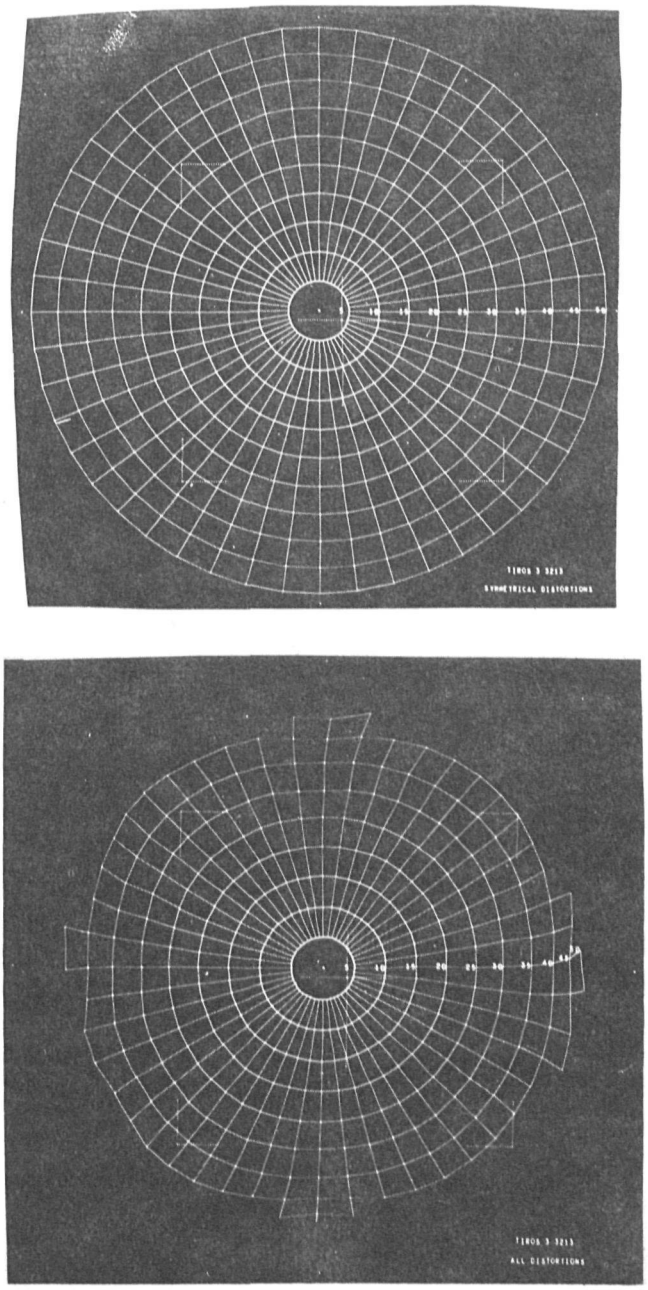


Fig. 6. Image-object angle relationships for symmetric distortion only (upper) and for all distortions (lower) for TIROS III camera 2 tape, at Monmouth, N.J.

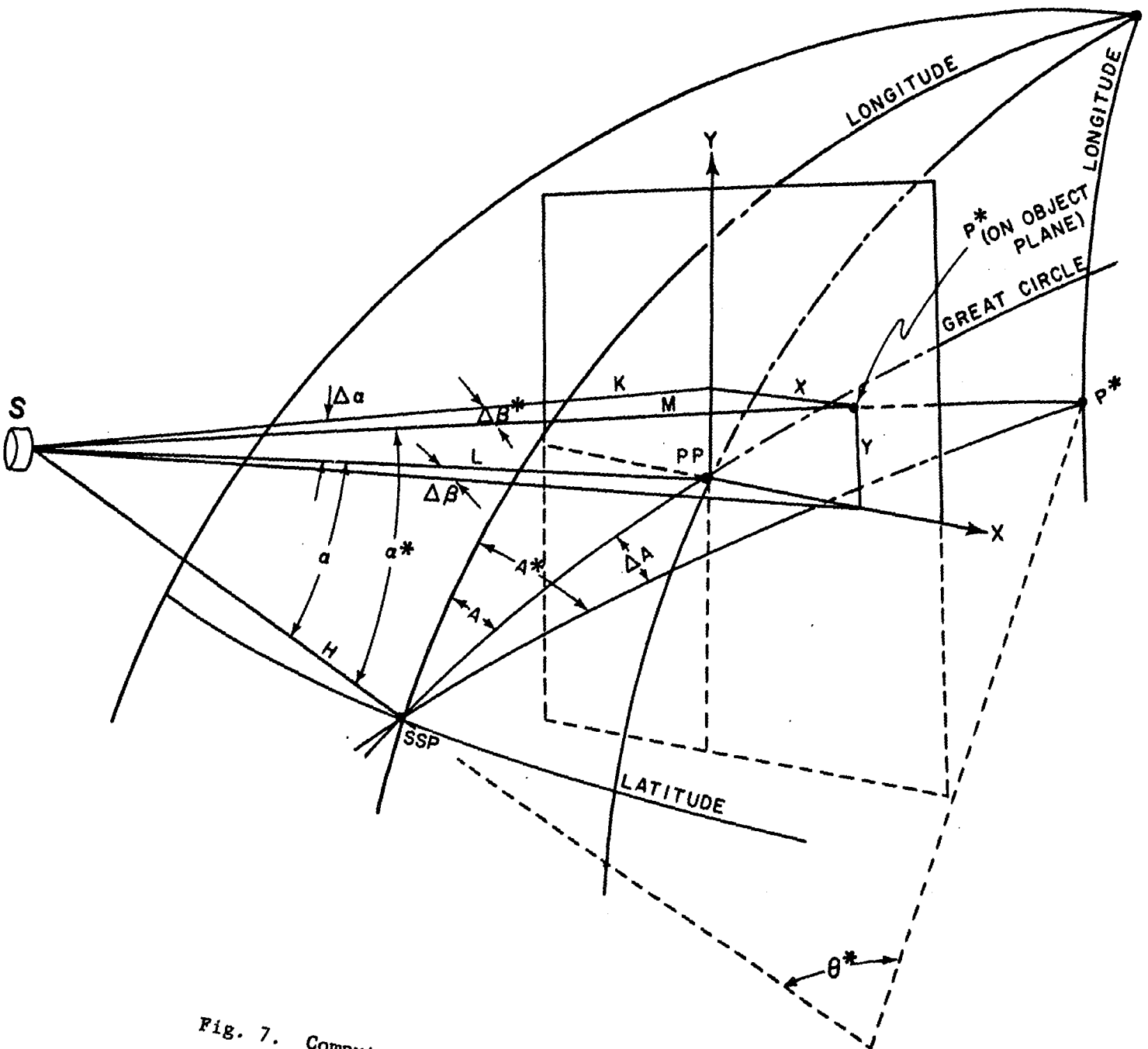


Fig. 7. Computer program spherical trigonometry

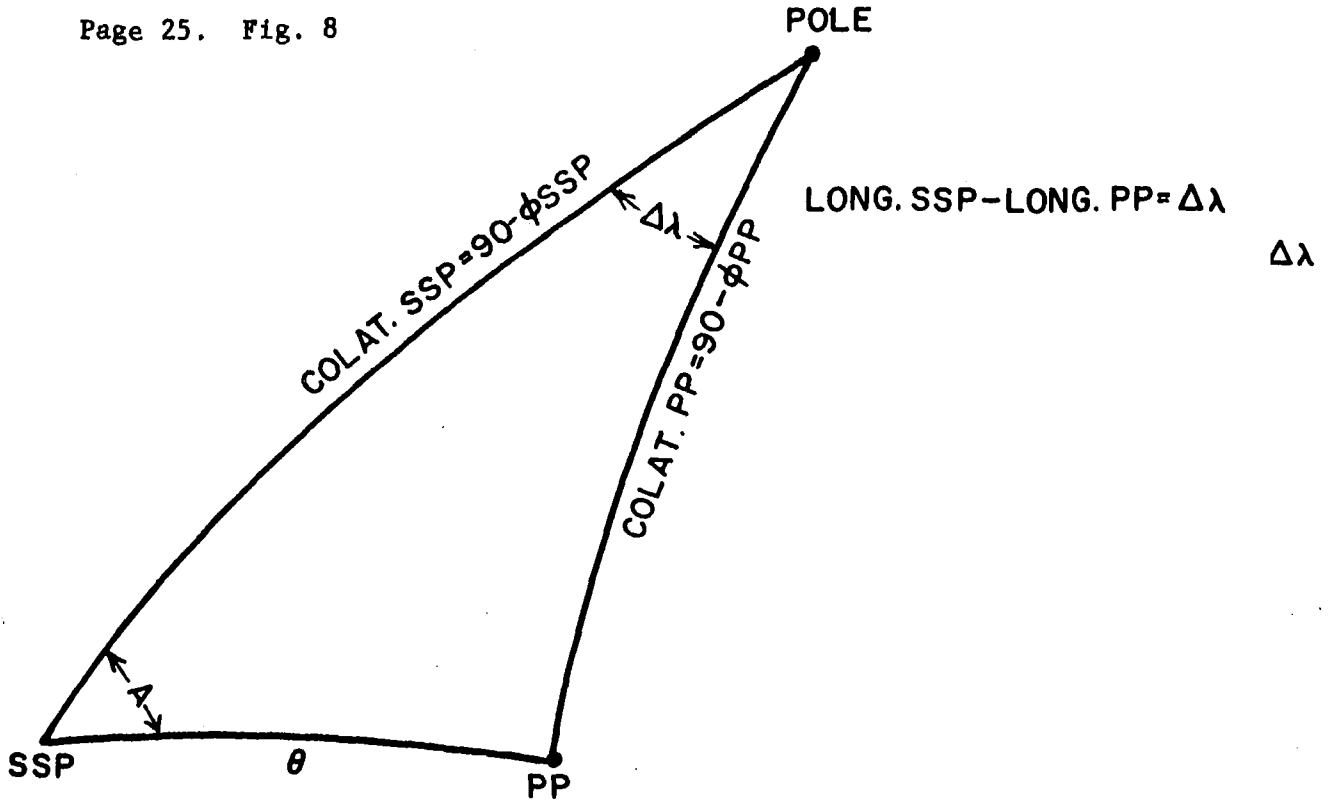


Fig. 8. Geographic spherical triangle.

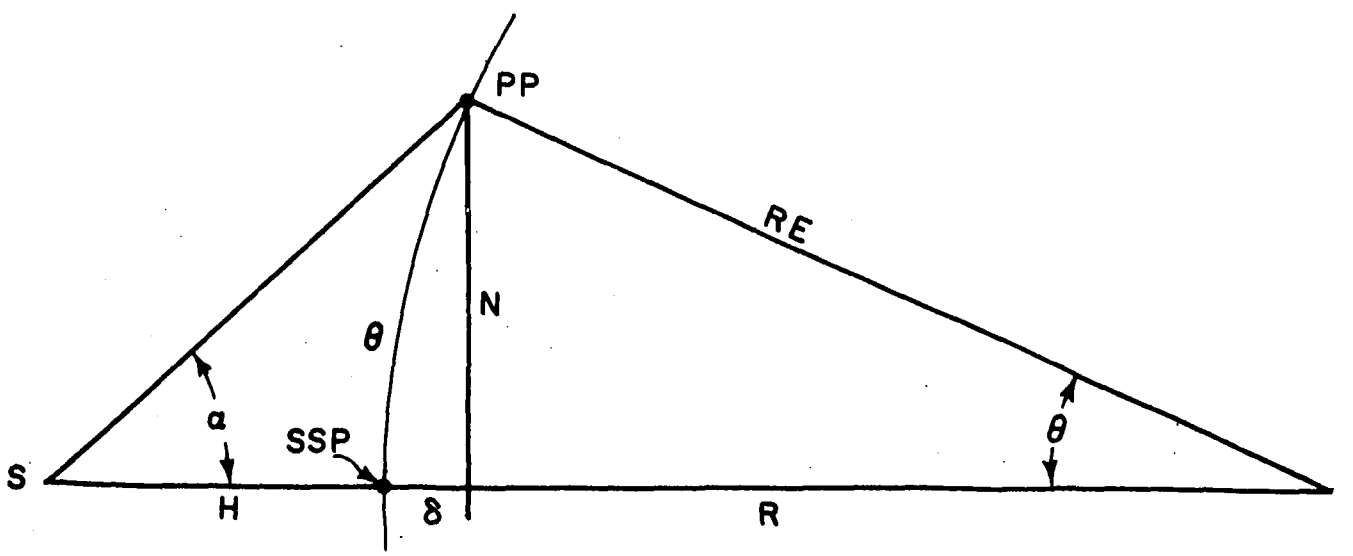


Fig. 9. Relationship between nadir angle (α) and great circle distance (θ) between sub-satellite and principal points.

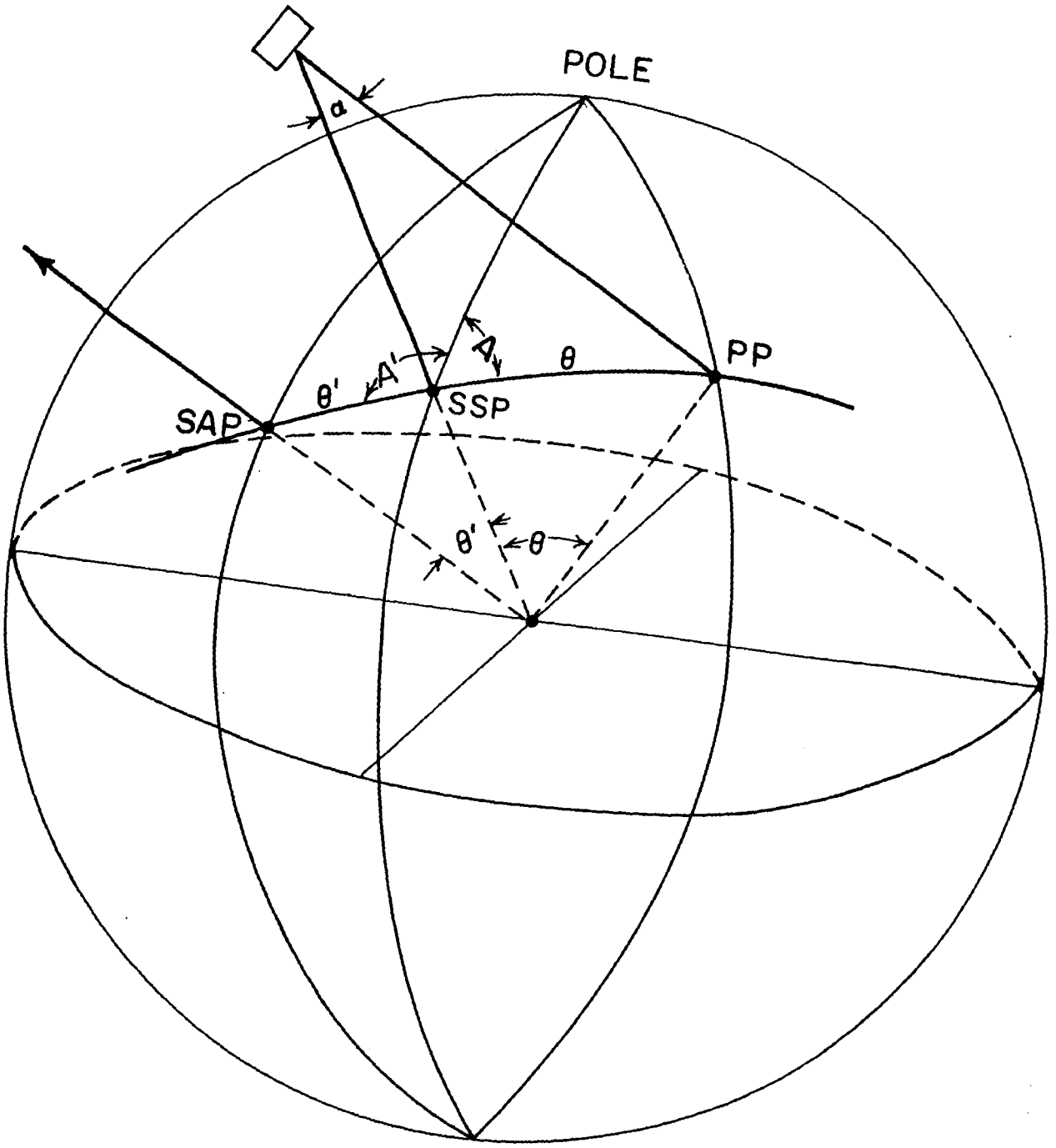


Fig. 10. Definition of spin-axis point (SAP)

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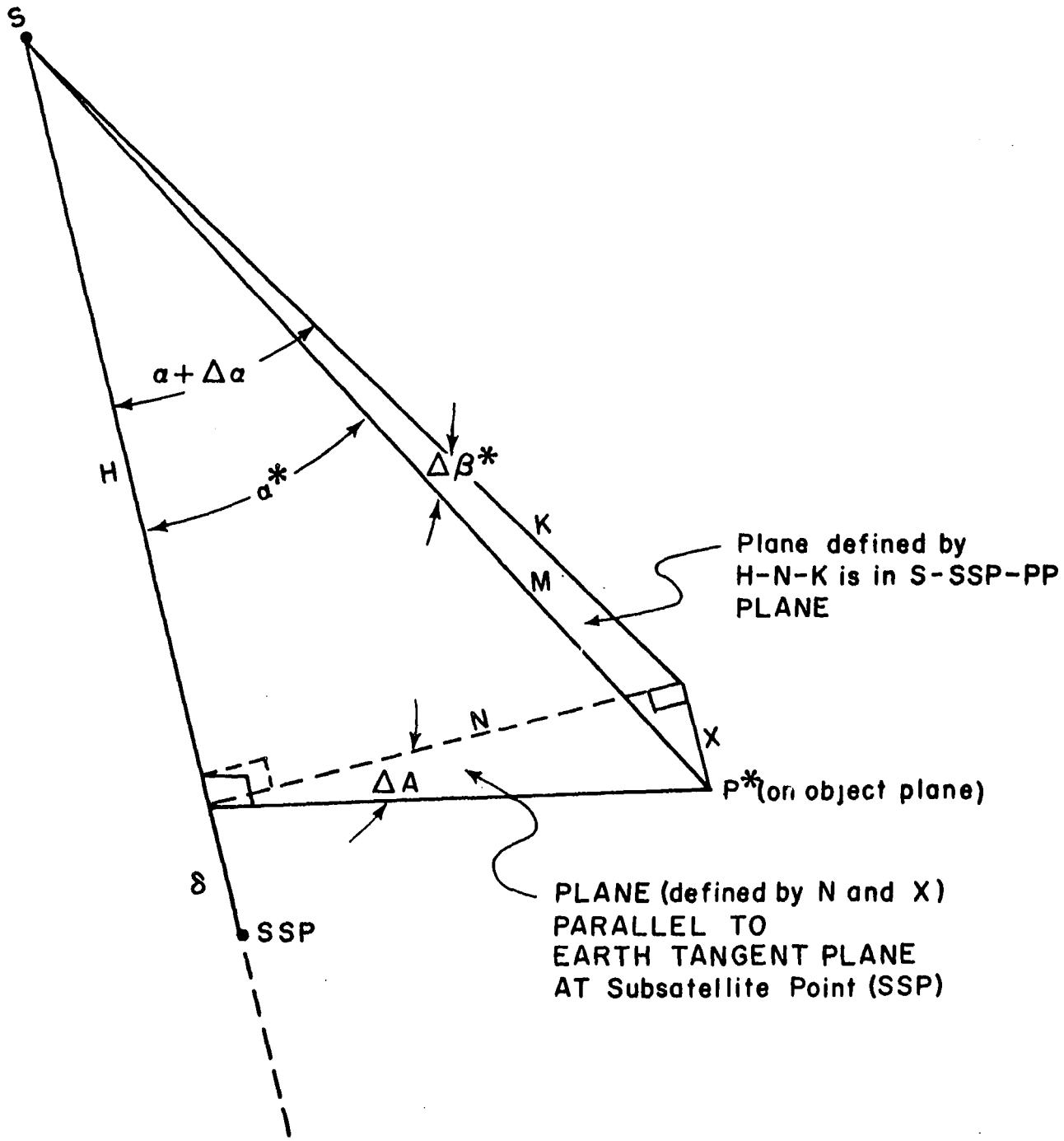

Fig. 11. Computer program plane trigonometry

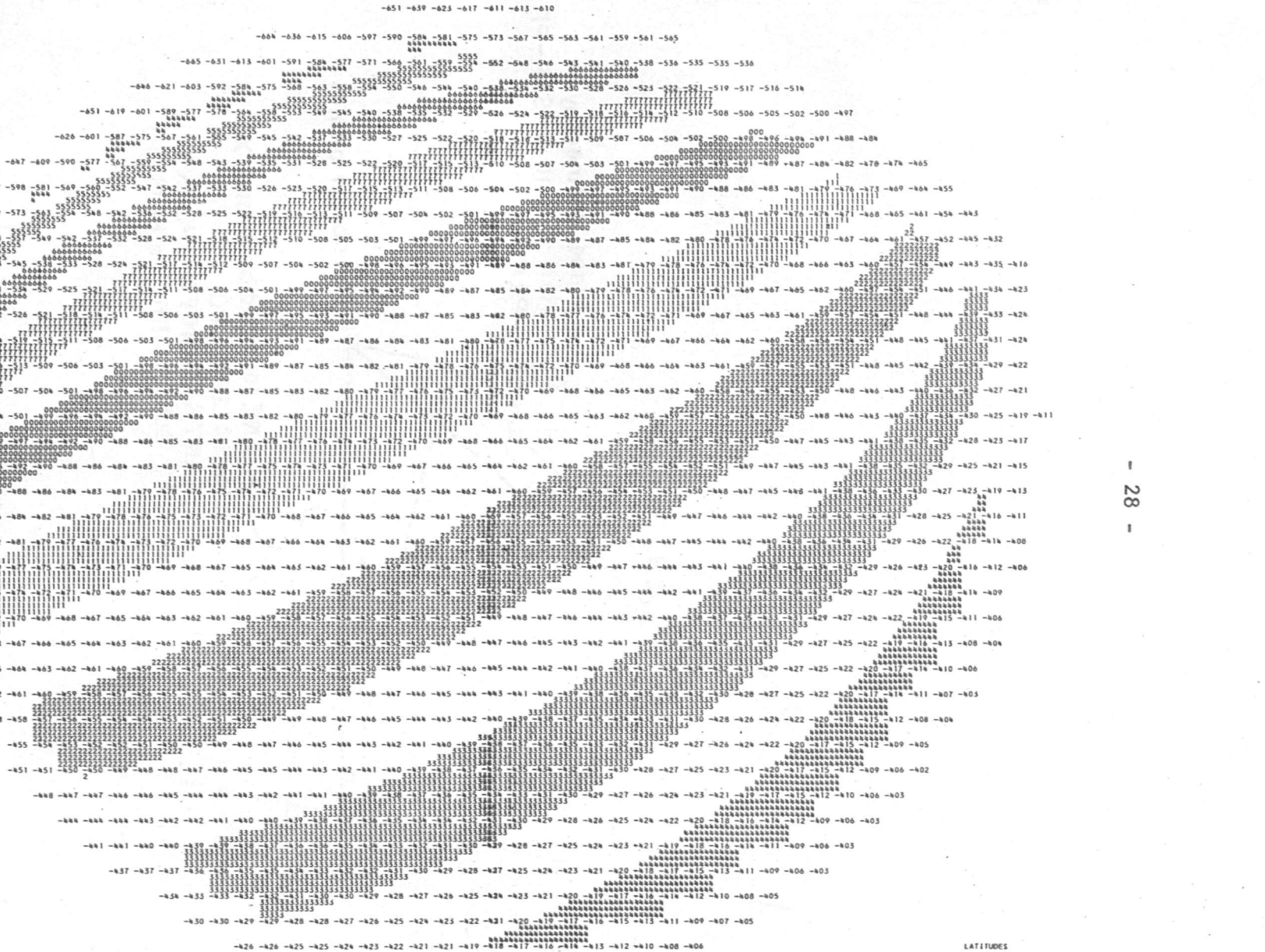

Figure 12. Latitude grids.

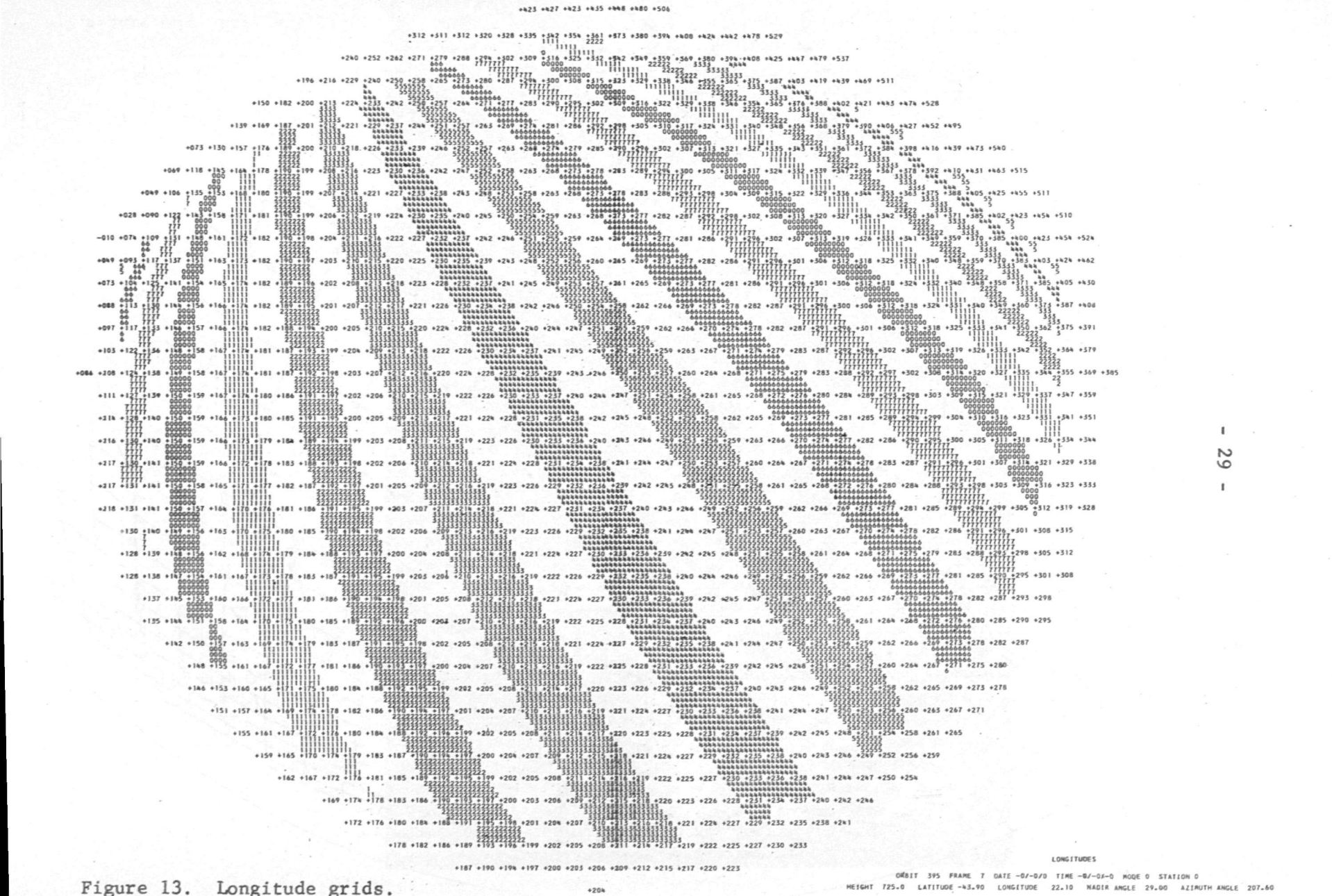

Figure 13. Longitude grids.

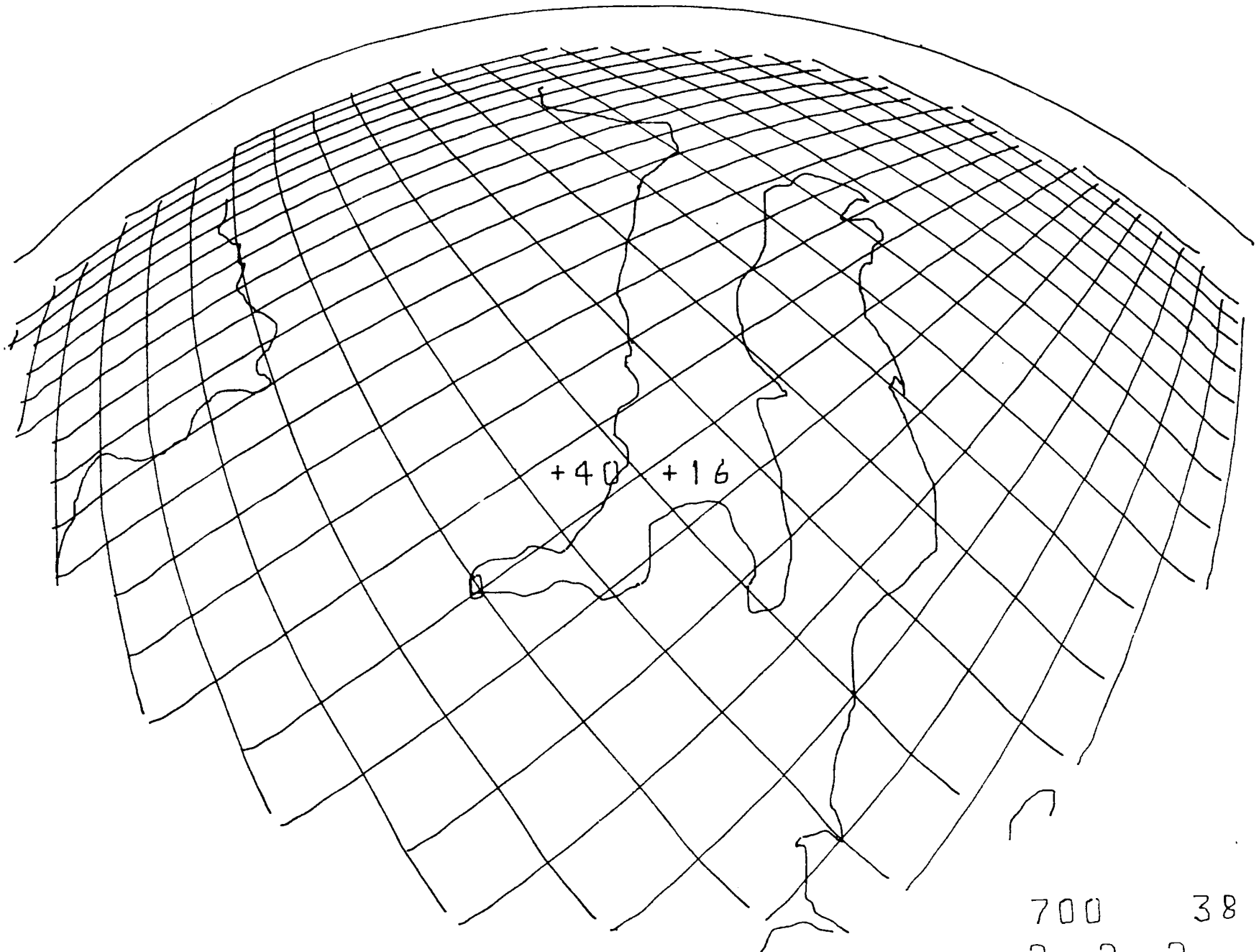

Fig. 14. Grid produced by E.A. Data Plotter.

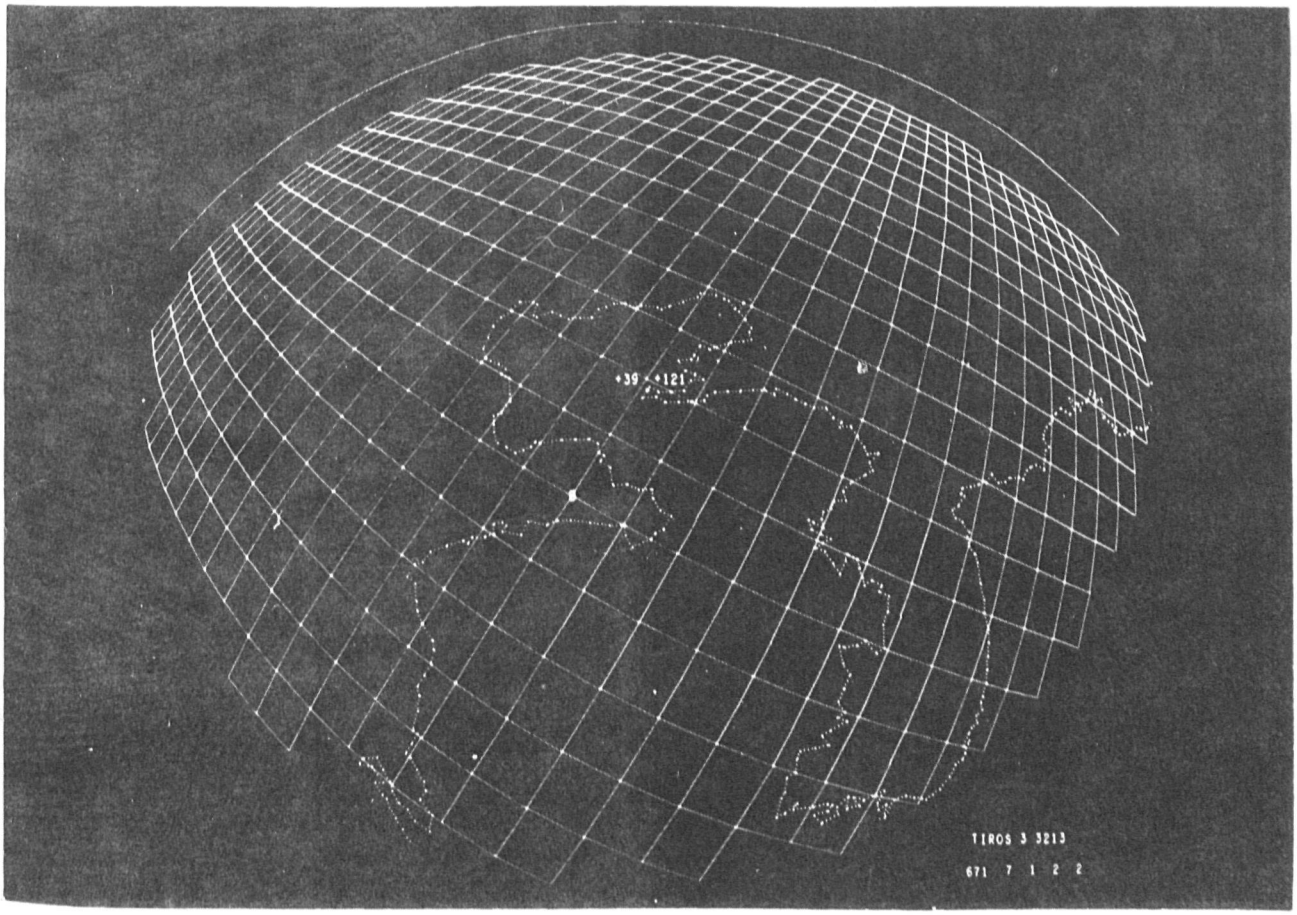

Fig. 15. Grid produced by SC 4020.

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APPENDIX

The following information is of value to a prospective user of the various programs described herein. In each case the format of the input data card is described in detail giving card column number and specifying units and scaling of the various items to be supplied. Where appropriate, supplemental operator instructions are provided to permit various output options.

Operating versions of the programs have been removed from Fortran Monitor control. A subroutine has been written which prepares the complete program, including associated subroutines, in a form which permits punching the program on a set of absolute binary cards. The current program was punched in column-binary form off-line. These cards, preceded by an appropriate loader and followed by an absolute transfer card, were then written on tape off-line and the resulting tape is the operational job tape. The grid print operational program is on absolute row-binary cards and operates through the on-line card reader, preceded by the 704/709 input-output compatability program IB IOC2 for operation on the 7090.

Data Card Format, Line-Follower Gridding Program

Cols.	
1-4	Height, in km and tenths. 712.4 = 7124
5-8	Lat. of S.S.P., in Deg and tenths, with sign. N is +, S -. 2.5°N = +025, 60.3°S = -603.
9-13	Long. of S.S. P., in Deg. and tenths, measured positively to the East, optionally 0 → + 359.9, or 0 → ± 180.0. 5.3°E = + 0053. 73.6°W = - 0736 or +2864.
14-17 / 18-22	Lat. and Long. or Nadir and Azimuth — As defined by code in col. 23, below
23	Defines type of data in cols. 14-22:

0: Lat. and Long. of principal point
1: Nadir and azimuth angles of principal pt.
2: Lat. and Long. of spin-axis point

Lat. and long. are defined as in cols. 5-13 above. Nadir angle is the positive angle at the satellite to the sub-satellite and principal points. Azimuth angle is the angle on the earth between the meridian of the S.S.P. and the principal line, measured counter-clockwise from the principal line.

24-27	Pass No.
28-29	Frame No.
30	Station No. : 1 = Pt. Mugu, 2 = Wallops Is.
31	Mode : 1 = Direct; 2 = taped
32	Camera No.

Operator Instructions, Line-Follower Gridding Program

Ready the program tape on A1, a BCD output tape on A3, a grid ouput tape on B1, and the data cards, followed by 4 blank cards, on the card reader.

Functions of the sense switches (down position):

2. Eliminate coastline output.

3. Apply asymmetric distortions.

4. Add the fiducial marks to the output

Clear, and press "load tape." Final stop is at location 1. Print the A3 output off-line with format control and draw the B1 output on the line-follower.

Data Card Format, 1653 Pt. Grid-Print Program

Cols.	
1-6	Ht in hundreds of km with leading zero e. g. 712 km = 071200
7-12 13-18	Lat. Long. } ± (+ is west) degrees, tenths, and hundredths e. g. -34.1 = -03410
19-24 25-30	Lat. Long. } or Nadir Azimuth } (see 31 below) -131.2° = 13120
31	0 Lat. long. in cols. 19-30 } of prin. 1 Nadir, azimuth in " " } point 2. Lat. long. of spin axis point in 19-30
32	Camera
33-36	Pass No.
37-38	Frame No.
39-40	Month
41-42	Day
43	Year (last digit)
44-45	Hr.
46-47	Min.
48-49	Sec.
50	0 ---Taped, 1----direct
51	Station 0----NJ, 1----Hawaii
52	Ersatz principal point indicator

All information beyond Col. 31 is optional.

Set-Up-Card Format, Grid-Print Overlay Program

Cols.	
1-2	No. of grid data cards that follow
3	Type of data: Blank or 0 for BCD card input; any significant punch for binary-card input.
4	Binary output control: blank or 0 to test sense switch 3; any significant punch to eliminate binary tape output for line-follower.
5	BCD output control: blank or 0 to test sense switch 6; any significant punch to eliminate BCD output for off-line grid print.

Operator Instructions, Grid-Print Overlay Program

A computational set consists of one set-up card followed by the number of data cards specified on that card. Any number of sets may be processed at a time.

Add the computational sets at the end of the program deck, and follow the last set by 4 blank cards.

Ready the deck on the card reader, a BCD output tape (if required) on A3 (704 tape 10) and a line follower program binary tape (if required) on B3 (704 tape 3) ~~follower~~.

Functions of the sense switches (down position):

3. Binary output, unless superseded by a punch in column 4 of the set-up card.

6. BCD output, unless superseded by a punch in column 5 of the set-up card.

Final stop at location 0. Print the A3 output, if any, off-line with format control and the special carriage tape. Hold the B3 output, if any, for input to the line-follower program.