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National Oceanic and Atmospheric Administration
National Environmental Satellite Service

# Operational Procedures for Estimating Wind Vectors From Geostationary Satellite Data

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AND LEE M. MACE

WASHINGTON, D.C.
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# OPERATIONAL PROCEDURES FOR ESTIMATING WIND VECTORS FROM GEOSTATIONARY SATELLITE DATA

Michael T. Young, Russell C. Doolittle,
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Data Processing and Analysis Division

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CONTENTS

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ABSTRACT. The derivation of estimated wind speed and direction vectors from cloud motions observed by Applications Technology Satellites (ATS 1 and ATS 3) is discussed. Techniques used in converting digital satellite data into time-lapse film loops are described and illustrated. The analysis of cloud motion fields in the film loops by meteorologists of the National Environmental Satellite Service and the preparation of these data as input for machine analysis into high and low level wind vectors are described. Software procedures for computer rectification of errors arising from angular distortions in the viewed cloud field are presented.

## INTRODUCTION

Applications Technology Satellites ATS 1 and ATS 3 are situated at an altitude of 22,300 statute miles above the equator. At this altitude their orbital period corresponds to the rotation of the earth and they are therefore geosynchronous. Every 25 minutes upon command during daylight hours cameras aboard each satellite take pictures of the sunlit side of the earth (fig. 1 ). The pictures are transmitted to Wallops Island, Va. and are relayed to the National Environmental Satellite Service (NESS) at Suitland, Maryland. At Suitland, a series of pictures, normally seven covering a 2 1/2-hour time period, is processed into a film loop that displays cloud motions over the viewed earth disk. Cloud displacements are derived from the film loop for both high-level (cirrus) and low-level (cumulus, stratus) clouds. These displacements, recorded in image coordinates, are used as data input into a computer program that translates them into cloud velocity vectors. The validity of cloud motion vectors as wind estimates is discussed elsewhere (Hubert and Whitney 1971). The objective here is to describe the current operational method by which an analyst derives useful upper and lower level wind estimates over oceans and other data-sparse areas.

## PICTURE PROCESSING TECHNIQUES

With the cooperation of NASA, the cameras aboard ATS 1 and ATS 3 are activated daily from the NESS Data Acquisition Station at Wallops Island, Va. During the picture-taking phase, ATS cameras scan the earth from north to south and complete one picture in approximately 22 minutes. As the cameras scan the earth, the picture data are transmitted automatically to the Wallops Island Data Acquisition Station. Here the picture signal is processed and relayed via microwave transmission to the NESS Data Processing and Analysis Division (DAPAD) at Suitland, Maryland. Detail of the picture data flow is provided elsewhere (Bristor 1970). At DAPAD, 10-by 10-in film negatives are produced and processed into prints and 16-mm movie loops. The photofacsimile recording device on which the pictures are received at Suitland is shown in figure 2.

Earth locator grids, such as the one shown in figure 3, are melded with the picture sequence. Each picture in the sequence must be alined with its neighbors. An alinement device is used in this pin register process (fig. 4). Once the registry template is taped to each picture, the multiple exposure camera operation is conducted using a similar registry device (fig. 5). This facility provides the option to produce film loops of the full earth disk or enlargements of selected areas.

Seven sequential pictures encompassing a 2 1/2-hour time period comprise a closed film loop. The loop, when run continuously through a projector, repeatedly displays cloud motions and allows for a systematic analysis of the cloud motion field. To define the cloud motions more accurately, the first and last frames in the film sequence are repeated 20 times. The result is a film loop that presents the initial cloud field, holds it motionless for a few seconds, displays the cloud motions during the next six frames, and holds the final cloud field motionless. The entire sequence is repeated as the loop returns to the first frame and displays the initial cloud field. By "holding" the first and last views in the sequence, cloud motion vectors can be identified and measured more easily.

## EXTRACTION OF CLOUD MOTION VECTORS

Pictures taken by ATS satellites show almost an entire earth hemisphere. An accurate presentation of cloud cover is possible over a circular area banded by 40°N and 40°S latitude and 40° of longitude east and west of the satellite subpoint (the point on the earth directly beneath the satellite). The satellite subpoint for ATS 3 is near 0°N and 70°W. Pictures from ATS 3 are used to analyze the area 40°N to 40°S and 30°W to 110°W. ATS 1 is located directly above a point near 0°N and 150°W and is used to analyze the area 40°N to 40°S and 110°W to 170°E.

At NESS, film loops are normally prepared for wind vector analysis for the North and South Atlantic Oceans (including South America) and the North and South Pacific Oceans. These areas are chosen for analysis because they are generally devoid of other operational meteorological observations. Loops covering enlarged smaller areas, such as those around tropical storms, are prepared as required.

The film loop is projected onto a paper worksheet placed on a plotting board. An overhead, closed-loop movie projector is used to display the film on the worksheet. The analyst measures cloud motions by making a pencil mark at the initial position of the cloud element and a second pencil mark at the final cloud position. He then indicates the direction of motion with an arrow joining the two points. High-and low-level wind vectors may be marked with different-colored pencils. An experienced analyst can identify up to 200 vectors per hour.

## SELECTING CLOUD MOTION VECTORS

The analyst's major problem is distinguishing between low, middle, and high clouds. Recognition of the major synoptic features is essential for identification and evaluation of associated cloud patterns. Such features as cyclonic vorticies, cold fronts, tropical disturbances, jet streams, and subtropical high pressure systems are readily identified.

Since only low-level and high-level cloud motions are extracted for analysis, careful judgments must be made to distinguish each from middle-level, non-representative cloud motions. Clouds of suppressed vertical development, such as cumulus and stratocumulus occurring under the influence of a well developed subtropical high pressure system, make excellent low-level tracers. Sharply defined cumulus elements occurring behind cold fronts also are useful as low-level wind indicators. Cirrus clouds, readily identifiable by their filmy appearance and rapid motion, can easily be recognized and used as indicators of high level winds.

Conversely, cloud elements near frontal systems are often associated with middle-level flow. It is best to avoid using clouds that appear to change in size, shape, or brightness during the film sequence, since they are often advected by winds at varying levels.

## DIGITIZER OPERATION

The translation of cloud image coordinates to cloud motion vectors is accomplished most efficiently by computer analysis. To be acceptable as computer input, cloud displacements must be formatted numerically. This is done by the use of the Bendix "Datagrid" Digitizer (fig. 6). The digitizer is a two-dimensional coordinate measuring system that translates the end-points marked on the work sheet into an X-Y coordinate field. Coupled with an output device, in this case an IBM 029 Card Punch, it can supply the properly formatted numerical data for computation.

The "Datagrid" Digitizer consists of two parts, a plotting board and cursor, and an electronic counter. The plotting board is a formica-covered table with a 30- by 36-in. working area. A rectangular array of electronic conductors is imbedded in the table. The cursor is a clear plexiglass disk containing cross hairs and a small circle for centering the point to be digitized. A coil is mounted in the body of the cursor. As the cursor is moved, X-Y coordinate signals are generated in the imbedded grid through inductive coupling. These signals are interpreted digitally with accuracy to 0.001 in.

The digitizer and card punch are used to transcribe image coordinates and geographical reference coordinates onto data cards as follows: The work sheet marked with the start and end points of the motion vectors is placed on the plotting board. As the cursor is placed over the start and end points of each vector, a button is pushed to record the X-Y coordinates of each point on punch cards. The digitized data thus generated are acceptable for computer analysis.

Since the loop movie image scene is projected onto the work sheet with considerable enlargement, the X-Y coordinates obtained from it do not limit the precision of the computation. For example, the angular increment at the satellite, represented by 0.001 inch on the digitizer board, corresponds to approximately one-fifteenth of the stepping angle between successive scan lines of the satellite camera. (There are 2,000 scan lines per frame on ATS 1 pictures and 2,400 per frame on ATS 3).

## RECTIFICATION

Some inherent problems are encountered in the translation of cloud image motions into cloud speeds and directions relative to the earth. One of the major difficulties is the angular distortion resulting from the flat plane camera view of the spherical earth. Apparent cloud motions are true directly beneath the camera but become distorted toward the horizon. This distortion must be rectified by translating the cloud motions to a spherical-earth projection from the plane rectangular coordinate system of the film loop image.

A second problem is the effect of the motion of the satellite with respect to the earth. Given a truly geostationary satellite, and spin-axis orientation constant with respect to axes fixed in the earth, the first and last pictures of the loop would have identical fields of view. These conditions were essentially met in the early days when the orbit was nearly equatorial and the spin-axis nearly parallel to the earth's axis of rotation. Manual rectification of the image cloud motion vectors was carried out using tables and graphs adapted by L. F. Whitney, Jr. of NESS from the work of T. T. Fujita of the University of Chicago. This procedure takes advantage of the common perspective view. However, with the increased orbital inclinations, and with satellite spin-axes displaced several degrees from alinement with the polar axis, the assumption of a constant perspective is no longer sufficiently valid. Each satellite moves in a figure-8 pattern above its subpoint. ATS 1 moves 4° north and south of the equator during a 24-hour period, and as much as 2° toward the north or south during the picture-taking sequence. ATS 3 moves about 282° north and south of the equator during 24 hours. Also, the spin-axis goes through a cyclic roll-yaw interchange around the orbit when not alined with the orbit normal. This introduces variations in azimuth and tilt between pictures, and even within pictures; consequently, the camera perspective is constantly changing. The motions of both the satellite and the spin axis are predictable and can be taken into account for computing accurate wind speed and direction vectors.

Cloud motion is now derived from the cloud-image displacements by a computer program. For ease in treating the satellite and spin-axis motions, image vectors are not rectified as entities. Instead, each end point is located on the earth independently and wind speeds and azimuth are computed from these two points. A description of the computer program is included in the appendix.

## CONCLUDING REMARKS

The use of automated methods to obtain wind estimates from ATS film loops has improved the output both qualitatively and quantitatively. The computer analysis corrects for satellite motions and visual distortions inherent in the photographic process. It also relieves the analyst of the time-consuming labor involved in calculating the vector motions manually. Consequently, he has more time to examine the film loops, assess the synoptic situation, identify cloud types, and measure cloud motions. Since October 1971, when the computerized technique became operational, the number of wind speed and direction vectors generated by NESS has doubled.

Improvement in quality of the vectors generated by NESS arises from the ability to (1) improve upon the precision of hand calculations and (2) compensate automatically for false motions of the viewed earth-disk. These false motions are a function of alinement errors or picture deformations caused by changes in spacecraft attitude and position.

Wind vector estimates produced by NESS have a wide variety of uses. They are both operationally significant and useful as a research tool. Wind speed and direction vectors are provided operationally to the National Meteorological Center (NMC) for use as data input for both the 0000GMT and 1200GMT Tropical Analyses. ATS cloud motion data are also input to the NMC Primitive Equation Model.

Analysis of relative vorticity and low-level divergence fields from ATS-derived cloud motion vectors have been generated independently by NESS and show promise of being operationally significant (Nagle and Dvorak 1970). Researchers at NESS are also engaged in climatological studies of cloud motion fields over data-sparse oceanic and tropical areas.

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3. Nagle, Roland, and Dvorak, Vernon, National Environmental Satellite Service, Suitland, Maryland, 1970 (personal communication).

# APPENDIX A

LUPWND - A computer program for obtaining wind vectors from cloud motion in loop movies.

This appendix describes a CDC 6600 program for computing winds from cloud motion in loop movies of spin-scan camera pictures taken from geosynchronous satellites. The projected positions of clouds in the first and last frames of a loop are converted to rectangular coordinates automatically and punched on cards by a digitizer board and associated equipment as described in the main body of this report. The method by which wind speeds and directions are obtained from these coordinates is described herein.

## GENERAL DESCRIPTION

Source Language: FORTRAN IV

Central Memory: $70_{(8)}K$

Central Processor Time: approximately 5 seconds for 100 wind vectors

## METHOD

The program solution is carried out in two stages:

1. A set of six constants is computed; by these, X-Y cloud position coordinates can be converted to angular displacements of the spin-scan camera telescope in the first picture of the loop. A similar set is computed for the last picture. These constants are:

The X-Y coordinates corresponding to the central position of the telescope (in the spin plane at the mid-earth position of the scan),

the angle from the digitizer board X-axis to a line representing the central scan of the picture. (The X-and Y-axes are rotated by this angle to obtain axes $X^1$, $Y^1$ alined with the picture (scan line, sample element coordinate system),

the increments in spin phase and telescope stepping angle corresponding to unit changes in the $X^1$ and $Y^1$ coordinates, and

the change in the $X^1$ coordinate for the mid-earth position of the telescope with unit change in $Y^1$ for points above and below the central scan.

The procedure for computing these constants is given in Appendix B.

2. For each cloud, in turn, the position coordinates in the first picture are converted into telescope displacement angles and corresponding direction cosines in a camera coordinate system (Y-axis along northern end of spin axis, X-axis right horizontal, Z-axis up). These direction cosines are converted to corresponding values in a geocentric coordinate system

(X-axis equatorial in meridian of Greenwich, Z-axis along North Polar axis). A ray with this direction is projected from the satellite location to intersect the earth spheroid. The procedure is repeated for the cloud position coordinates in the last picture to obtain a second earth intersection.

The distance between the two earth intersections is computed along the ellipse obtained by intersecting the earth spheroid with a plane containing the two points and the local vertical at the first. The wind speed is found by dividing the distance in nautical miles by the time interval between the two pictures in hours.

The wind direction is obtained by adding 180° to the azimuth of the vertical plane containing the vector.

The satellite locations are computed by an orbital prediction package (obtained from NASA) using orbital elements and time from epoch. The time from epoch is computed for each cloud point by adding to the picture start times the time increment represented by the telescope stepping position (scan number multiplied by scan period).

The conversion of camera coordinate system direction cosines to the geocentric system is accomplished by multiplication with a 3-by-3 orientation matrix. The elements of this matrix are the direction cosines of the three camera system axes in the geocentric system. The Y camera axis (spin axis) direction cosines are computed from the spin-axis declination and right ascension (which is converted to longitude using an updated Greenwich Hour Angle of Aries). The direction cosines of the local zenith are computed from the updated subsatellite-point latitude and longitude. The direction cosines for the X-axis are computed from its orthogonality to the Y-axis and the local zenith, and for the Z-axis from its orthogonality to the X- and Y-axes.

The accuracy of this procedure depends upon the correctness of the orbital elements used to compute satellite position, and of the right ascension and declination of the spin axis. It also depends on the precision with which the end pictures of the loop are fitted to the registration grid. (See appendix C).

To reduce the effect of such errors on the computer cloud motion vectors, the program includes logic for using landmarks of opportunity. The digitizer board coordinates of any landmarks are entered from the end pictures of the loop. No latitudes and longitudes are input, so the points need not be identified - only recognized as being the same in both pictures. (The time required to identify and prepare latitude and longitude inputs could prevent meeting operational deadlines in obtaining the wind vectors.) For these points, earth intercepts are computed for each picture as with cloud points. If the corresponding vectors do not have zero length, a latitude and longitude are computed for each end point and the mid-latitude and mid-longitude are assigned to the land point.

The program has options to use these points in two ways:

a. They are added to the set of nine registration points and the constants are solved for from the larger number of observation equations. Thus with three landmarks (not in themselves adequate for the solution) the modified set of constants derived from using all 12 reference points will provide a more correct set of winds (as evidenced by smaller vector lengths for the landmarks).

b. The landmark digitizer board coordinates and the computed corresponding geographic coordinates are used to compute revised spin-axis right ascension and declination, which will minimize the lengths of the corresponding vectors. This procedure has proven the more effective to date when several well-spaced landmarks are used; typical changes in spin-axis attitude are small -- on the order of a few one-hundredths of a degree in declination and a few tenths of a degree in right ascension. However, in one test case where the loop registration gave ground point vector lengths in excess of 100 miles, and only two landmarks were used near one corner of the picture, the attitude changes were much larger and the resulting wind vectors were much worse than without the correction.

The wind vectors derived from the computer program are formatted on punch cards for direct input to the NMC analysis program. The format is shown in Appendix D. The program also contains an option to produce a facsimile printer map of the cloud motion vectors on the Mercator projection.

## APPENDIX B

Procedure for computing constants used to convert digitizer board coordinates to equivalent camera telescope displacements.

1. The subsatellite point latitude and longitude, the satellite height, and camera orientation used in the original computation of the loop registration grid are input, together with the latitude and longitude of nine selected grid line intersections.

This information is used to compute two orthogonal direction angles for the ray from the satellite to each of the nine reference points on the earth.

$\alpha$ = angle out of the spin plane, Positive north

$\beta$ = spin displacement from mid-earth position of scan

2. The X-Y digitizer board coordinates of the nine reference points are input and used to form a set of nine observation equations

$$-X_i\left[\sin\theta \times \text{DALDYP}\right] + Y_i\left[\cos\theta \times \text{DALDYP}\right] - \left[Y_o^{1} \times \text{DALDYP}\right] = \alpha_i$$

where $\theta$ is the angle between the X-axis and $X^1$-axis that is parallel to picture scan lines.

DALDYP is the change in the telescope displacement from the spin plane for unit change in $Y^1$

and $Y_o{}^1$ is the value of $Y^1$ corresponding to the spin plane position of the telescope.

A set of three least squares normal equations is formed from the observation equations and solved for the quantities in brackets.

Then

$$\bar{\theta} = \tan^{-1}\left( \left[\sin\theta \times DALDYP\right] / \left[\cos\theta \times DALDYP\right] \right)$$

and

$$DALDYP = \sqrt{(\sin\theta \times DALDYP)^2 + (\cos\theta \times DALDYP)^2}$$

Note that, since

the observation equations are equivalent to

$$(Y^1{}_i - Y_o{}^1) * DALDYP = \alpha_i \;.$$

3. A second set of nine observation equations

$$X_i{}^1\left[DBEDXP\right] - \left[X_o{}^1 \times DBEDXP\right] + (Y_i{}^1 - Y_o{}^1)\left[DXODYP \times DBEDXP\right] = \beta_i$$

is solved from least square normal equations for the quantities in brackets, where DBEDXP is the change in telescope spin displacement for unit change in $X^1$, $X_o{}^1$ is the value of $X^1$ corresponding to the mid-earth position of the scan when the telescope is in the spin plane, and DXODYP is the change in the mid-earth value of $X^1$ per unit of $Y^1$ and represents the drift of the mid-earth sample number across a picture.

The constants thus computed are valid only for the satellite location, and spin axis orientation assumed in the original computation of the grid.

To relate to the actual pictures used in the loop, the following procedure is used for the first and the last pictures.

a. Find satellite location from orbital elements and picture time and convert the input spin-axis right ascension to longitude with an updated Greenwich Hour Angle of Aries.

b. Compute telescope displacement angles $\alpha^1$ and $\beta^1$ for each of the nine reference geographic points (on the spheroid).

c. Convert the displacement angles to $X^1$-$Y^1$ coordinates, and rotate to get equivalent digitizer board X-Y coordinates by an inverse use of the constants used above.

The sets of points corresponding to the manufactured X-Y can differ from the input grid intersections in position, orientation, scaling, and pattern because of satellite motion and relative spin axis motion during the time span of the loop.

4. The scaling of each picture is controlled when the loop is made by photographic reduction to make the equatorial radius in the 10- by 10-in hard copy the same as in the registration grid. If the corresponding earth angular intercepts at the satellite are the same for the grid computation and the picture in the loop, the ratio of angular displacements of the telescope to digitizer board $X1, Y^1$ should hold for the picture as well. The angular earth intercepts are computed for the gridding geometry and for the two pictures in the loop, and the $X^1$, $Y^1$ values of the reference points for each picture are rescaled as required.

5. The pattern of manufactured reference points is translated and rotated to be superimposed over the pattern of input registration point X-Y in accordance with the geometric restraints used in fitting individual pictures to the registration grid when the loop was made. (See appendix C.)

6. Finally, the two sets of observation equations are re-formed using the values of $\alpha^1$ and $\beta^1$ for the loop picture and the revised manufactured X, Y of the reference points. The corresponding normal equations are set up and solved for the sets of six constants for the first and last pictures.

## APPENDIX C

## LOOP REGISTRATION

The coastlines in the 10- by 10-inch pictures from which the loop is made differ in shape and position from each other and from the coastlines on the registration grid. Since no exact fit between pictures and grid is possible, the attainment of a "best" fit is a process of centering and rotation to balance coastline displacements over the picture. The program logic, used to relate the input digitizer board X-Y for the nine grid registration points to corresponding but not observed X-Y for the end pictures of the loop, assumed that the center of gravity of the two sets is the same. It also assumed a rotational fit such that the tangential displacement of radials from the center of gravity to corresponding registration points is a minimum. Even in landmark-rich areas such as North and South America, use of so subjective a registration procedure resulted in differences between loops in the precision with which the fit assumed by the program logic was realized. In areas with little coastline such as the Pacific Ocean, the uncertainty was even greater.

For that reason, a more objective procedure of loop registration suggested by Linwood F. Whitney and Lester F. Hubert has been adopted. In this method one landmark is selected to be held, and a second landmark is used to control the rotation. The picture image of the landmark to be held is made coincident with the corresponding position on the registration grid. The picture is then rotated so that the image of the second landmark lies on a straight line connecting the two points on the grid.

To make use of this revised method of loop registration, the latitude and longitude of the two registration landmarks are now included in the data input, and corresponding logic added to the program as a selectable option.

# APPENDIX D

## Format of Punched Cards for ATS-Derived Winds

Columns 1-5
44LSH - Indicator for "bogus" report

Columns 7-11 $YQL_aL_aL_a$
Y - day of week (1 is Sunday)
Q - Octant
$L_aL_aL_a$ - Latitude in degrees and tenths

Columns 13-17 $L_oL_oL_oGG$
$L_oL_oL_o$ - Longitude in degrees and tenths
GG - Time of day (synoptic map time for which data are used)

Columns 19-23 PPhhh
PP - Pressure level to which wind in columns 31 to 35 applies (normally 85 for 850 mb, or 30 for 300 mb)
hhh - Height of pressure level (always XXX)

Columns 25-29 $TTT_dT_dx$
TT - Temperature at level indicated in columns 19 and 20
$T_dT_d$ - Dew point at level
x - tenths indicator

This group is coded as 711// to indicate wind derived from ATS movie loop.

Columns 31-35 DDfff
DD - Direction of wind in tens of degrees
fff - Wind speed in whole knots

Columns 37-41 PPhhh
PP - Pressure level to which wind in columns 49-53 applies (normally 70 for 700 mb, or 25 for 250 mb)
hhh - Height of pressure level (always XXX)

Columns 43-47 $TTT_dT_dx$
TT - Temperature at level indicated in columns 37 and 38
$T_dT_d$ - Dew point at level
x - tenths indicator

This group is coded as 711// to indicate wind derived from ATS movie loop.

Columns 49-53 DDfff
DD - Direction of wind in tens of degrees
fff - Wind speed in whole knots

Columns 55-59 PPhhh

PP - Pressure level to which wind in columns 67 to 71 applies (normally 20 to 200 mb, not used for low level winds)

hhh - Height of pressure level (always XXX)

Columns 61-65 $TTT_dT_dx$

TT - Temperature at level indicated in columns 55 and 56

$T_dT_d$ - Dew point at level

x - tenths indicator

This group is coded as 711// to indicate wind derived from ATS movie loop.

Columns 67-71 DDfff

DD - Direction of wind in tens of degrees

fff - Wind speed in whole knots

Figure 1.--Typical picture taken by the Applications Technology Satellite, ATS 3.

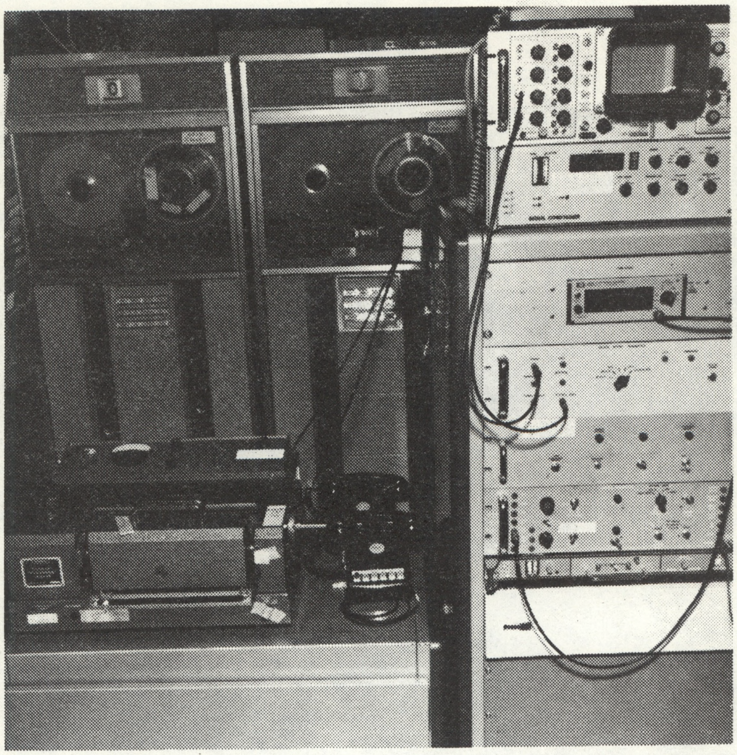

Figure 2. Photofacsimile units and associated electronics used in generating ATS images. Film is wrapped around a 10" circumference, screw driven drum which rotates in synchronism with the spinning spacecraft which, in turn, scans the earth scene.

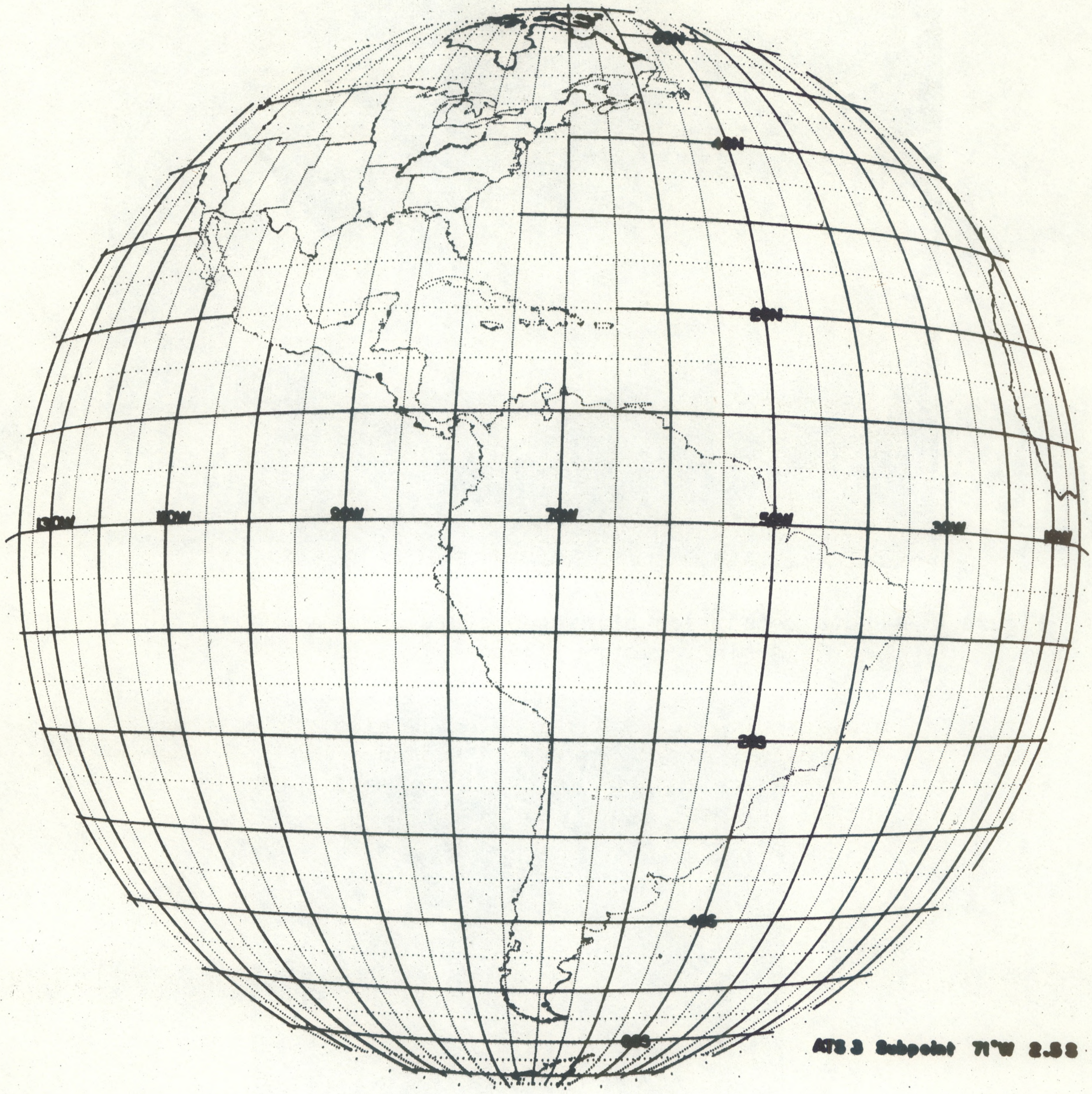


Figure 3.--Sample earth locator grid for ATS 3. Latitude and longitude lines are displayed at 5° intervals and major coastlines and other features are added for registry convenience. Hand-drawn additions are included as required.

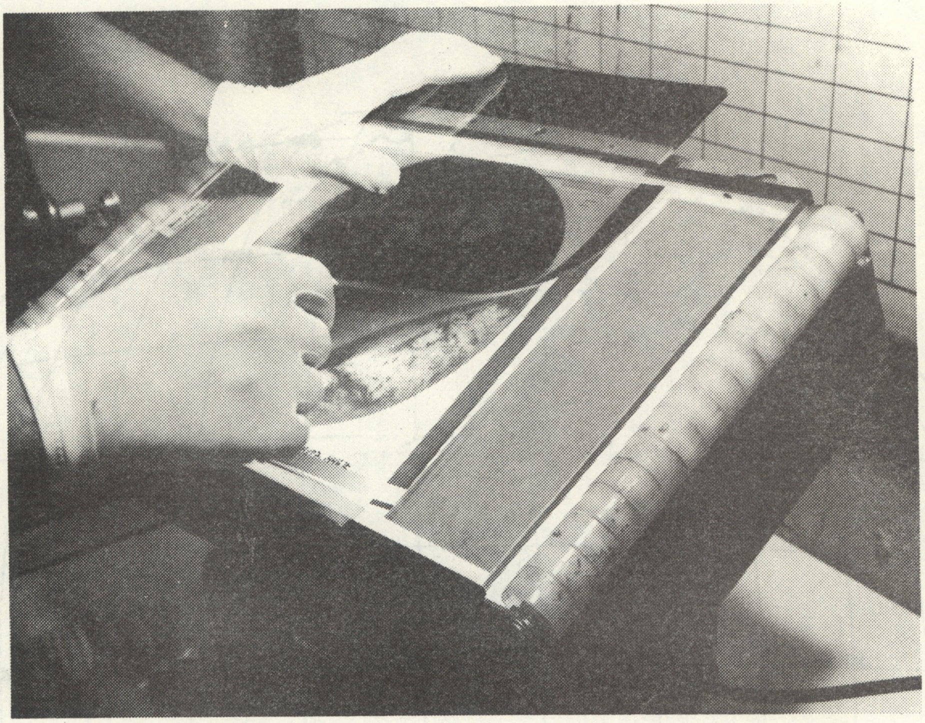

Figure 4.--Photo technician alining picture negatives with the aid of a pin registry jig and light table.

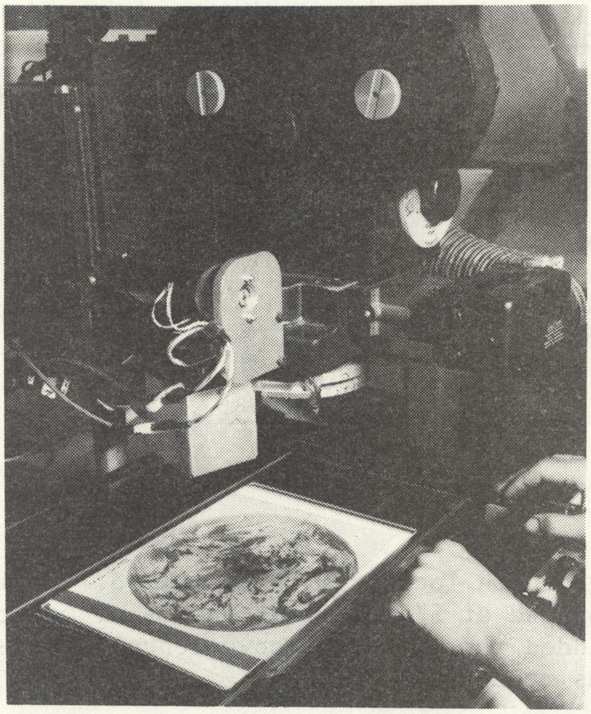

Figure 5.--Time-lapse film loop exposure station showing registry jig, back light for negatives and the adjustable cinecamera facility.

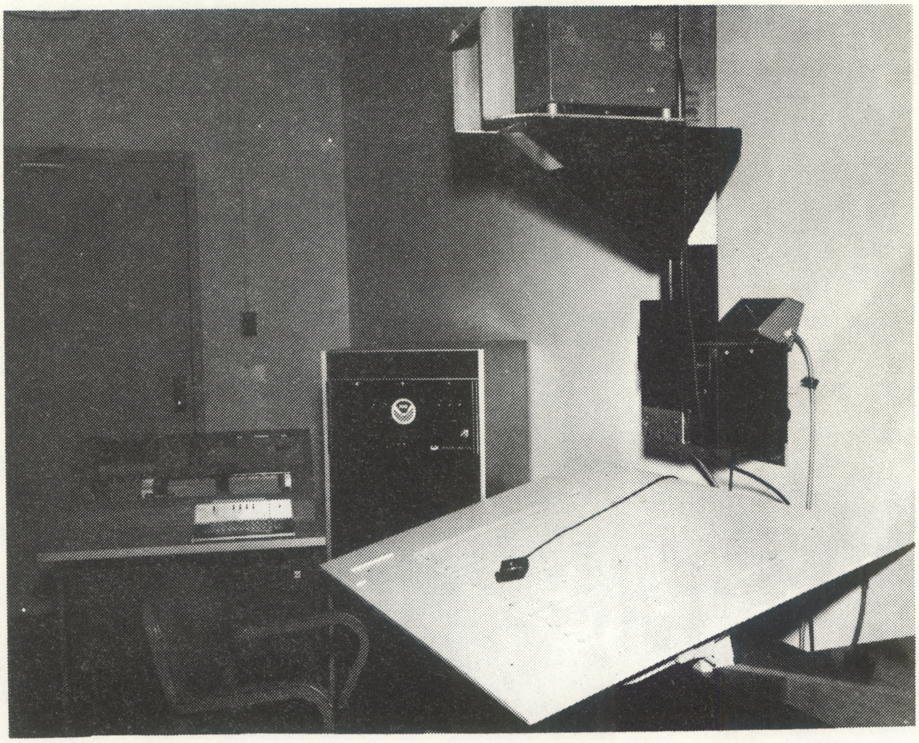

Figure 6.--Cloud vector extraction facility showing projector, work sheet and the digitizer facility.

(Continued from inside front cover)

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