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# PORTABLE AUTOMATIC CALIBRATION TRACKER: A PROGRESS REPORT

## WALTER J. CARRION

JANUARY 1968
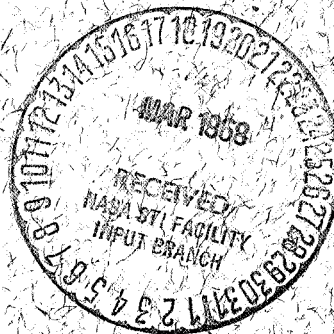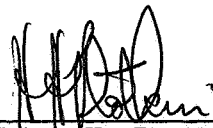
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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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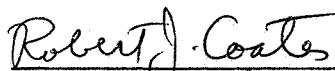



Walter J. Carrion


January, 1968




Approved:

_Henry H. Plotkin_ (signature)

Henry H. Plotkin
Head, Optical Systems Branch


_Robert J. Coates_ (signature)

Robert J. Coates
Chief, Advanced Development Division



GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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# ILLUSTRATIONS

The Portable Automatic Calibration Tracker (PACT) was developed by ITT under contract to Goddard Space Flight Center to improve the angular calibration of antennas and radio satellite tracking systems in NASA's Satellite Tracking and Data Acquisition Network. It is a significant advance in the state-of-the-art of real-time tracking and data presentation. This calibration system will be transported by the Network Calibration Airplane to the various tracking stations around the world. Therefore, it was necessary to develop a precision electro-optical system made up of modules that are easily assembled and in operation in a minimum of time (four hours).

The method now employed for the calibration of the network requires photographic records to be reduced. For instance, the large radio antennas have an optical boresight system that photographs a star field and/or the Calibration Airplane while the antenna tracks a transponder on the airplane. This method restricts calibration to nighttime and does not provide a "quick look" at the data because of time-consuming film processing and data reduction.

The design goal for PACT was to develop a reliable instrument that could perform calibration on a 24-hour schedule with real-time angular accuracy of ±5 sec of arc or better. Its alignment to station coordinates had to be a straightforward technique and easily maintained and operated by an engineering field crew.

Field evaluation tests on known stars indicate that PACT has achieved a real-time accuracy of ±7 sec of arc during operation from an hour before sunset to an hour after sunrise.

The system's hardware development is straightforward. Standard precision engineering design and good shop practices were adhered to throughout the development; therefore, only a brief description will be given. If detailed information is desired, it can be obtained from the Optical Systems Branch, Goddard Space Flight Center, or ITT, San Fernando, California.

## Mount Description

The X-Y configuration for the mount (Figure 1) is the same as that used for the network data acquisition antennas. The X-Y mount is advantageous for tracking through the local zenith where both the optical and RF reception is the best. An Az-El mount has its greatest tracking problem at zenith, while the X-Y mount has its greatest rotational velocities and accelerations on the horizon, where satellite reception is poorest.

The X-X axis is the horizontal axis that is aligned to the meridian plane of the station; the Y-Y axis is orthogonal to X-X axis. Therefore, the tracker
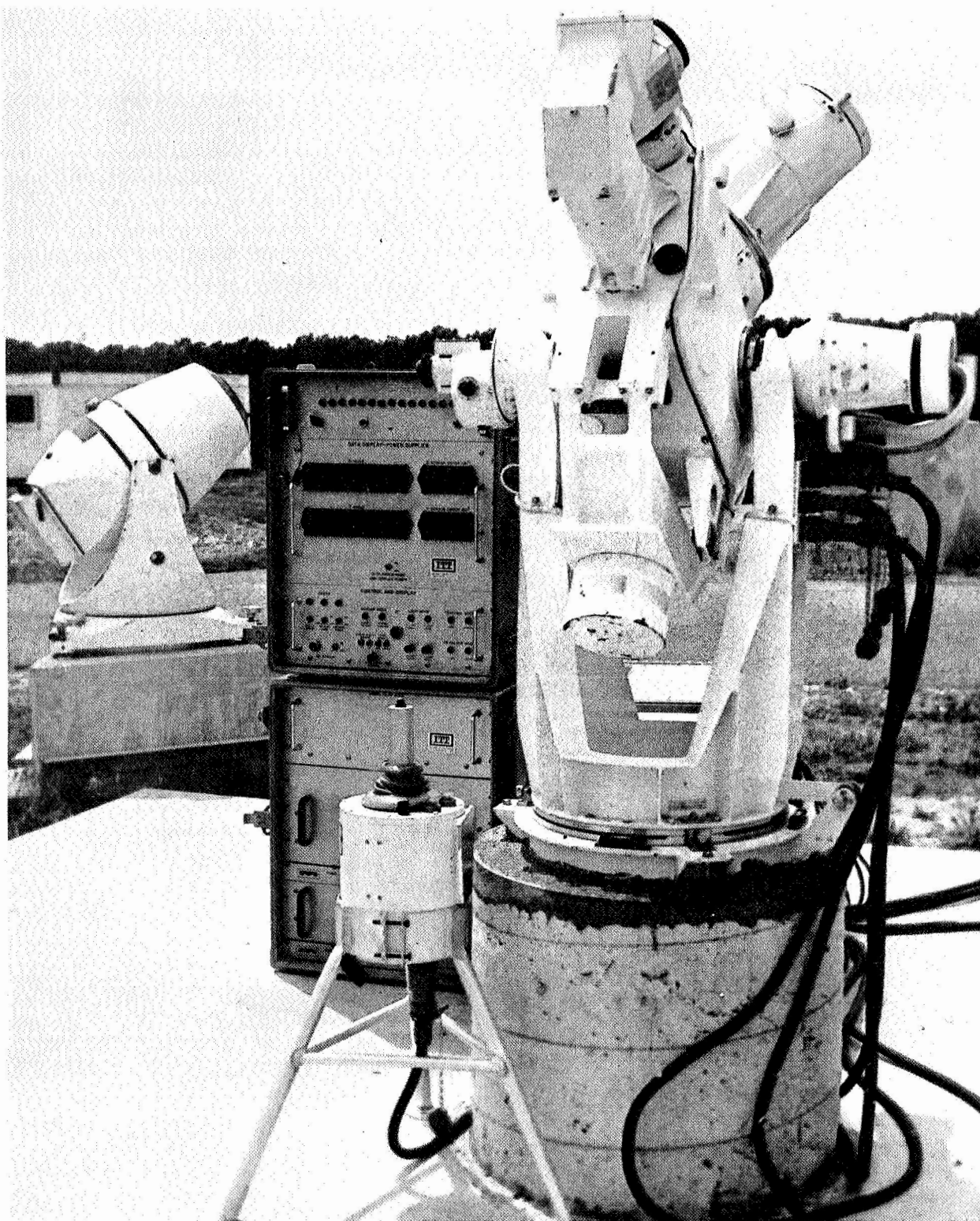
FIGURE 1 — PORTABLE AUTOMATIC CALIBRATION TRACKER

rolls about the X-X axis to point east or west and rolls about the Y-Y axis to point north or south.  This configuration is the same as an equatorial mount that is located on the equator.

The mount is a heat-treated cast aluminum structure.  The material is Alcoa's 356 alloy with a T51 temper condition which was stress relieved and heat treated prior to final machining.  Extreme care was taken to design the instrument as symmetrical as possible to minimize thermal changes.  Precision angular contact bearings were used, with one end of each axis floating to allow for thermal expansion.  The mount rests on a spherical seat that matches castings that will be permanently attached to piers at each station to be calibrated.  Adjustment screws, $120^\circ$ apart, and one second of arc levels, mounted on the gimbal along the X-X axis and the Y-Y axis, aid in initial alignment of the instrument to the station coordinates.  Each shaft has Wayne-George $2^{19}$ Digisec Encoders.  (Reference John E. Moye's paper, "An Evaluation of Precision Shaft Angle Encoders," SPIE 12th Annual Technical Symposium).

The guide scope has a fixed focal position which enables the operator to remain stationary during the operation.  To keep the sense of direction for centering the target the same, whether the operator is viewing through the guide scope or using the open sight during acquisition, the stick control which ITT developed and is patenting, has two modes.

All of the electronics for the mount, encoders, detector, etc. are housed in easily portable weatherproof containers.

The system was designed, fabricated, and checked out with a measuring precision of better than one second of arc.  See Figure 5 for the summary of the static star evaluation tests.

### Detection System

A tungsten light source with 4000 watt output that peaks near .9 microns has been mounted to the bottom of the Calibration Airplane.  The sensor in PACT is an image dissector star tracking tube.  Both S-1 and S-20 photocathode surfaces are being evaluated.  The S-1 which has a peak spectral response around .8 microns is best (but still not satisfactory) for tracking aircraft during the day but is limited in the number of stars it can track.  The S-20 surface is preferred for night operation, when it easily locks onto 4th magnitude or brighter stars.  It tracks the aircraft at night out to distances of 25 miles without losing lock.  However, with a S-20 tracker, daylight operation is seriously limited.  Even the S-1 photocathode has a daylight capability of only 7 miles (30 miles was desired).  Sun glints from the aircraft and background are the major problems.  Satisfactory daylight tracking can be done only up to one hour after sunrise and before sunset.

The optical system is a 5.7 inch aperture Dahl Kirkham with an 80 inch focal length, designed and built by Tinsley Laboratories.  The deflections

of the optical system were carefully measured by autocollimating techniques and found to be less than 1 second of arc in all orientations. This value was used in developing the error model, which is discussed later. The optical sensor assembly mounts to the gimbal by a spherical seat which has fine adjustment screws.

## Alignment to Station Coordinates (Figures 2 & 3)

The longest time-consuming function necessary to set up the system at each station is the precise alignment of the PACT axis to station coordinates. North, east, south, and west lines are set up with respect to the center of the PACT pier, by means of markers whose positions are established by first order survey. The observer's eyepiece is then removed and an optical flat is squared onto the X-X axis. A theodolite with an autocollimating (A/C) attachment is aligned to the north-south line of the station using two markers on the line south of PACT. The theodolite is then rotated approximately $180^\circ$ in elevation (the theodolite is not moved in Az unless the theodolite has a collimation error) and the line of sight is set level with reference to an optical level which has 1 second of arc precision. Level line of sight is established by autocollimating off of the optical level as in Figures 2 & 3. Removing the optical level, the X-X axis of PACT is adjusted in azimuth and leveled with reference to the A/C theodolite. The Y-Y axis which is orthogonal to X-X is then automatically aligned east-west. There is no field adjustment provided in the instrument design for correcting an orthogonality error. Field tests over a four-month period indicate that the relation of these axes stay constant.

To check or adjust the pointing axis of the optical system, two point source autocollimators are set up to the east and west of PACT on the east-west line. These need only be within a degree or so of the east-west line but must be precisely level. Using the image dissector, PACT locks onto the image of the A/C, say to the east. The angular reading is recorded. The telescope is then rotated about X-X $180^\circ$ and locked onto the west A/C and the X-X shaft angle recorded. Since both collimated beams were accurately aligned horizontal, the angle turned about the X-X axis should equal $180^\circ$ ($+90^\circ$ east, $-90^\circ$ west). When the telescope is pointing to zenith, the shaft angle readings are set at $0^\circ$. The zero angle setting is checked with reference to the one second of arc levels mounted on the gimbal along the X-X and Y-Y axis). If an angular error is noted when "dumped" $180^\circ$ in reference to the A/C, it is due to the nonperpendicularity of the optical pointing axis to the Y-Y axis. Half of the error is adjusted out by moving the entire optical-sensor assembly by means of three fine adjusting screws. This assembly mates to the gimbal by a spherical seat. The alignment is rechecked as stated above. This alignment has been repeatedly made to an accuracy of one count (3.6 sec). At this position, the pointing axis of the telescope is perpendicular to the Y-Y axis; however, its position about the Y-Y axis has to be established. This is done by locking onto Polaris and setting the Y-Y encoder to the correct angle reading.
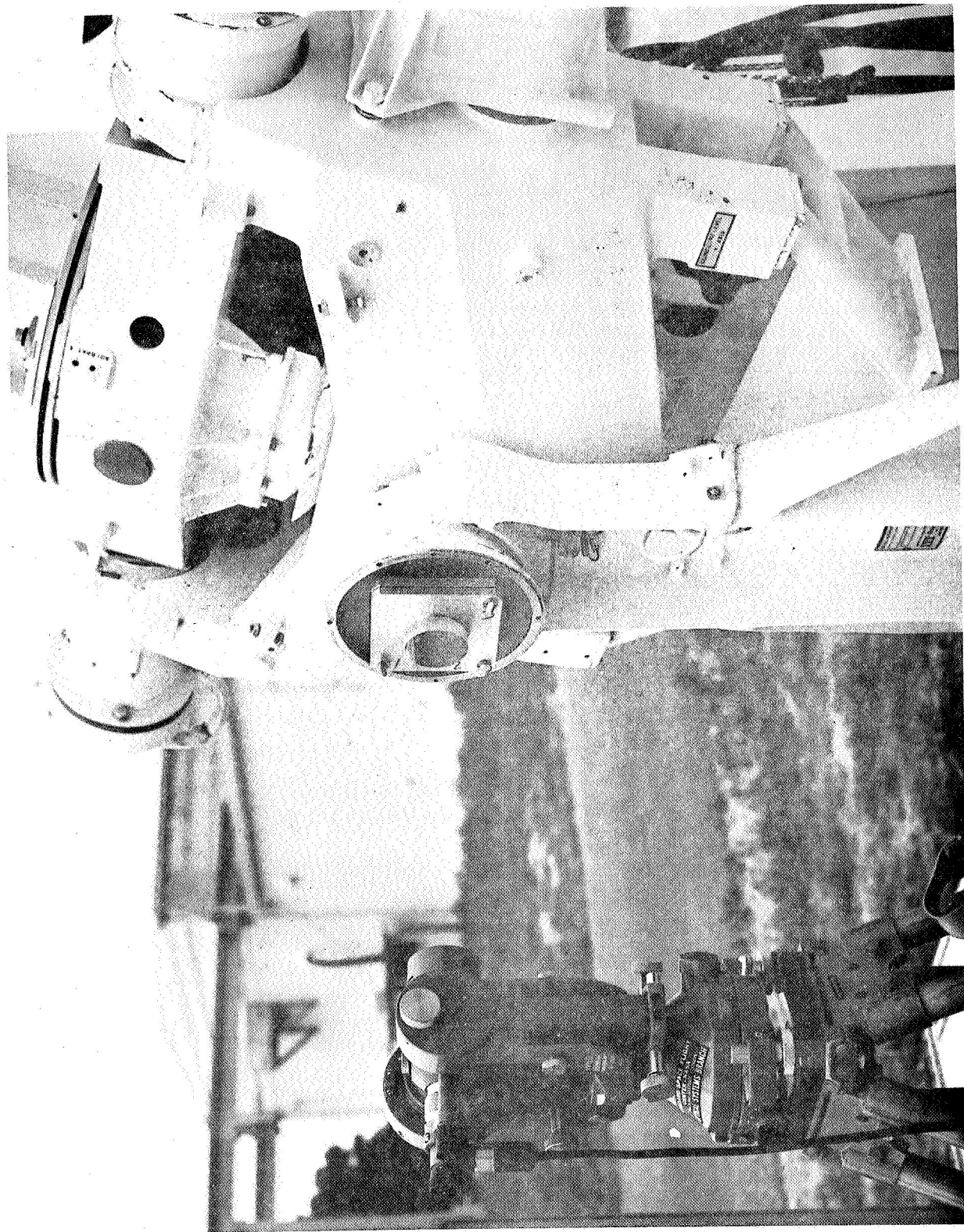
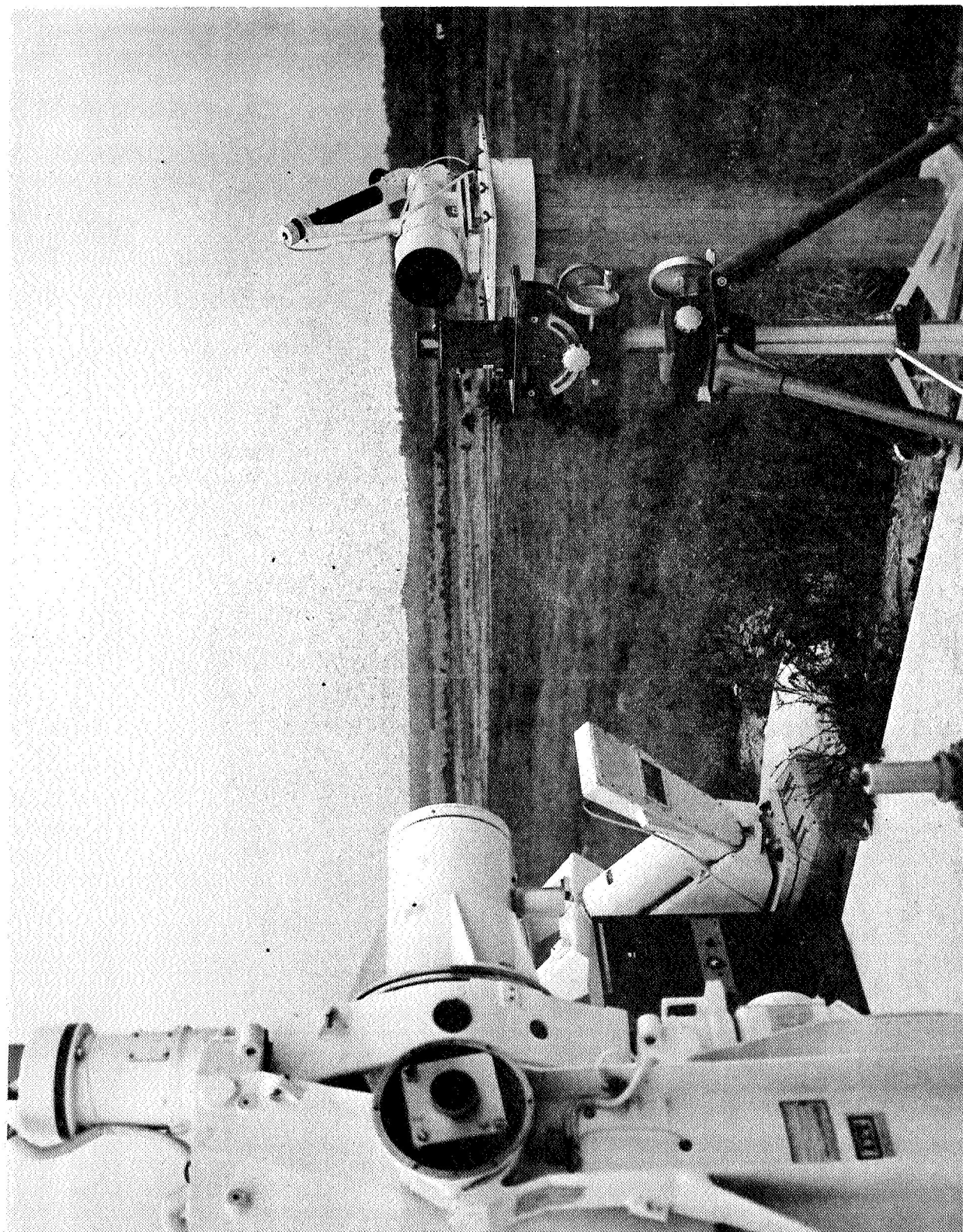FIGURE 2 - ALIGNMENT TO STATION COORDINATES

FIGURE 3 - CHECKING POINTING AXIS

## System Evaluation

Star calibration techniques have been employed to determine the pointing accuracy of PACT. After the instrument is aligned to the station coordinates, with the aid of star Ephemeris data converted to X and Y angles, PACT is set approximately to a chosen star's position by means of the shaft angle encoders. When the star gets to within four minutes of arc of the pointing axis, the instrument locks onto it and displays a light indicating that it is in auto-track. If "Lock" is lost, an audio signal sounds to warn the operator.

The X and Y encoder readings, a "Lock or No-lock" condition, a measure of tracking or servo error, time, and star identification are recorded for each second on punched tape. Each star is tracked for 20 to 30 seconds. In four or five hours, it is thus possible to record 25 to 40 stars throughout the entire hemisphere.

Computer programs have been written to analyze the data. Figure 4 shows a sample printout which gives the average delta X and Y error, the sigma delta X and Y error, and the root mean square delta X and Y difference from the predicted true star position. This data is representative of the performance of the system since it is derived from over 550 tracked points taken in all possible operation orientation. In addition, the average and standard deviation for each star is given. The standard deviation is an excellent indication of instrumentation malfunction, such as servo jitter and noise.

The data is then automatically plotted (Figure 5). The error vectors exhibit various patterns, which are directly associated with the source of the error. For instance, a pattern with all vectors pointing in the same direction and of equal or nearly equal magnitude would be an encoder bias error; if the horizontal vector increases from the zenith (or center of the plot), this indicates the optical axis is not perpendicular to the Y-Y axis. A circular pattern indicates an axial misalignment, such as the X-X axis rotated out of the meridian plane. This type of evaluation gives one a handy tool for evaluating precision tracking instruments because operator mistakes and instrumentation malfunctions can be readily detected.

## Error Model

An Error Model has been developed which analyzes the data to determine the amount of error in various components or alignments that would account for the total errors encountered in a particular track. The Error Model for PACT assigns a possible error to seven different parameters. This gives the evaluation engineers a clue to the possible source of contributing errors. It also guides the design engineers during development as well as the field alignment crew because it emphasizes the effect of a particular error on the overall system performance; therefore, the allowable error is determined.

STATISTICS
TOTAL NO. OF STARS= 25
AV DEL X= -0.00003   SIGMA DEL X= 0.00137   RMS DEL X= 0.00134
AV DEL Y= -0.00049   SIGMA DEL Y= 0.00141   RMS DEL Y= 0.00147

|     |      |        |     |         |         |         |         |         |         | STATISTICS OF AVERAGE CX AND DY | | |
| NO. | I.D. | STAR   | MAG | TRUE X  | TRUE Y  | TRUE DX | TRUE DY | DX-BIAS | DY-BIAS | SIG DX  | SIG CY  | NO. PTS |
|-----|------|--------|-----|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1   | 32   | ALIOTH | +1.7 | -38.444 | 32.081  | -0.000 | -0.003 | -0.000 | -0.002 | 0.00055 | 0.00158 | 24 |
| 2   | 34   | ALKA   | +1.9 | -36.755 | 22.158  | -0.000 | -0.001 | -0.000 | -0.001 | 0.00078 | 0.00127 | 13 |
| 3   | 37   | ARCTUR | +0.2 | -48.497 | -6.150  | 0.001  | -0.002 | 0.001  | -0.001 | 0.00060 | 0.00091 | 24 |
| 4   | 41   | ALPHEC | +2.3 | -29.612 | -6.812  | 0.002  | -0.000 | 0.001  | -0.000 | 0.00063 | 0.00171 | 20 |
| 5   | 42   | ANTARE | +3.1 | -39.465 | -6C.972 | 0.002  | -0.000 | 0.002  | -0.000 | 0.00060 | 0.00113 | 27 |
| 6   | 46   | RASAL  | +2.1 | -4.733  | -26.317 | 0.000  | 0.002  | 0.000  | 0.002  | 0.00047 | 0.00093 | 26 |
| 7   | 49   | VEGA   | +0.1 | 8.056   | 0.190   | -0.001 | 0.001  | -0.001 | 0.001  | 0.00073 | 0.00054 | 26 |
| 8   | 53   | DENEB  | +1.3 | 27.407  | 12.076  | -0.001 | 0.002  | -0.001 | 0.002  | 0.00052 | 0.00056 | 12 |
| 9   | 54   | ENIF   | +2.5 | 55.594  | -13.184 | -0.002 | 0.002  | -0.002 | 0.002  | 0.00068 | 0.00134 | 25 |
| 10  | 34   | ALKA   | +1.9 | -41.342 | 25.398  | -0.002 | -0.003 | -0.002 | -0.002 | 0.00054 | 0.00095 | 7  |
| 11  | 37   | ARCTUR | +0.2 | -54.969 | -2.179  | 0.002  | -0.003 | 0.000  | -0.002 | 0.00081 | 0.00119 | 25 |
| 12  | 40   | KOCHAB | +2.2 | -16.013 | 39.903  | -0.001 | -0.002 | -0.001 | -0.002 | 0.00041 | 0.00174 | 19 |
| 13  | 41   | ALPHEC | +2.3 | -38.371 | -3.064  | 0.001  | -0.001 | 0.001  | -0.001 | 0.00114 | 0.00211 | 12 |
| 14  | 42   | ANTARE | +3.1 | -55.389 | -55.943 | 0.002  | -0.002 | 0.002  | -0.001 | 0.00050 | 0.00092 | 18 |
| 15  | 40   | KOCHAB | +2.2 | -17.694 | 41.073  | -0.001 | -0.001 | -0.001 | -0.001 | 0.00043 | 0.00108 | 23 |
| 16  | 42   | ANTARE | +3.1 | -59.743 | -54.103 | 0.002  | -0.002 | 0.002  | -0.002 | 0.00036 | 0.00095 | 16 |
| 17  | 46   | RASAL  | +2.1 | -20.349 | -24.318 | 0.001  | 0.000  | 0.001  | 0.000  | 0.00077 | 0.00126 | 25 |
| 18  | 47   | ELTAN  | +2.4 | -8.845  | 13.145  | -0.000 | -0.001 | -0.000 | 0.001  | 0.00070 | 0.00125 | 25 |
| 19  | 49   | VEGA   | +0.1 | -3.463  | -0.183  | -0.001 | 0.001  | -0.001 | 0.001  | 0.00057 | 0.00115 | 26 |
| 20  | 51   | ALTAIR | +0.9 | 15.016  | -29.140 | -0.002 | 0.001  | -0.002 | 0.002  | 0.00051 | 0.00091 | 25 |
| 21  | 58   | POLAR  | +2.1 | 1.374   | 51.180  | -0.003 | 0.001  | -0.003 | 0.001  | 0.00038 | 0.00073 | 25 |
| 22  | 49   | VEGA   | +0.1 | -5.785  | -0.032  | 0.001  | -0.000 | 0.001  | 0.000  | 0.00059 | 0.00093 | 25 |
| 23  | 53   | DENEB  | +1.3 | 15.785  | 8.084   | -0.000 | 0.001  | -0.000 | 0.001  | 0.00054 | 0.00098 | 26 |
| 24  | 1    | ALPHER | +2.1 | 58.740  | 12.209  | 0.001  | 0.001  | 0.001  | 0.001  | 0.00076 | 0.00184 | 35 |
| 25  | 58   | POLAR  | +2.1 | 1.400   | 51.096  | -0.001 | -0.001 | -0.001 | -0.001 | 0.00047 | 0.00098 | 27 |

FIGURE 4 - STAR TRACK SUMMARY

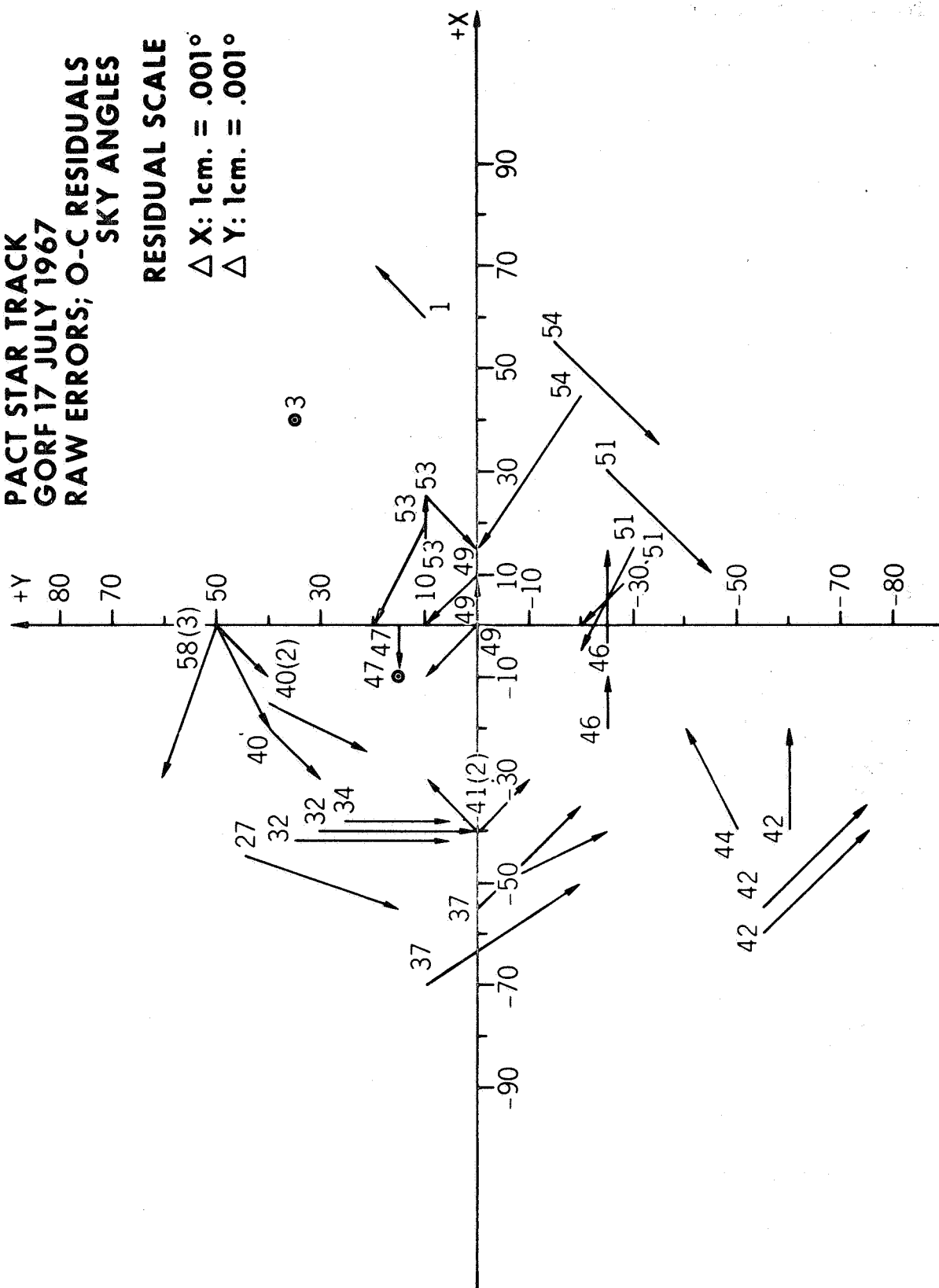FIGURE 5

The seven parameters for the X-Y configuration of PACT are:

1. X axis encoder bias     These are the errors in the zero setting of
                                      - the encoders. When the pointing axis is
2. Y axis encoder bias     pointing to zenith, the encoders should read
                                      zero.

3. X axis tilt - The X-X axis, which is aligned to the meridian plane,
                       must also be level.

4. X axis rotated west - This is the azimuth rotation of the X-X axis
                               out of the meridian plane.

5. Optical axis to Y axis - This is the nonperpendicularity of the
                                   pointing or optical axis to the Y-Y axis.

6. Rotation of Y axis to X axis - This is the nonorthogonality of the
                                     Y axis to X axis.

7. SAG - This is the deflection of the telescope tube sag or the amount
                 of variation of the pointing axis with reference to the Y-Y
                 axis.

The validity of the error model has been verified by rechecking the various parameters, correcting or adjusting out the misalignments and re-running the evaluation tests. By this means, the importance of the two categories of errors is easily seen; namely, the inherent instrument errors (6 and 7 above) and the alignment errors (1 through 5 above). It is significant to note that the PACT system has reached an accuracy that is limited more to the ability of a field crew to align the system to particular station coordinates if absolute pointing angles are to be obtained, then the inherent accuracy of the instrument.

## Results of the Star Evaluation Test

Figure 6 is a summary of the results of the raw data (no error model correction applied) of the star track statistics for five tests. Each night's test contains at least 30 to 40 stars with over 600 data points, because each star is tracked for at least 20 seconds. In addition to the data shown, our examination of the data for July 17 revealed that the peak error was no greater than three counts or approximately 10 seconds of arc. The overall accuracy of PACT is represented by the rms, which is better than 7 seconds of arc.

## Aircraft Evaluation Test

The star evaluation tests are considered to be static tests and are relatively easy to conduct and analyze the data. PACT's primary function is for the calibration of the network. In this role, it will be determining

# SUMMARY OF STAR TRACK STATISTICS

| DATE OF TRACK | NUMBER OF STARS | $\overline{\Delta X}$ | $S_x$ | $RMS_x$ | $\overline{\Delta Y}$ | $S_y$ | $RMS_y$ |
|---|---|---|---|---|---|---|---|
| MAY 17, 1967 | 31 | -.0006 | .0030 | .0031 | -.0005 | .0017 | .0018 |
| MAY 19, 1967 | 40 | -.0004 | .0025 | .0025 | +.0012 | .0011 | .0017 |
| JULY 10, 1967 | 36 | +.0013 | .0017 | .0021 | +.0019 | .0014 | .0023 |
| JULY 17, 1967 | 35 | -.0002 | .0015 | .0015 | -.0003 | .0016 | .0016 |

ALL STATISTICS SHOWN IN DEGREES.

FIGURE 6

the angle (corrected for parallax) of the Calibration Aircraft from a given station, while network tracking instruments, such as an 85 foot dish, are autotracking on a transponder mounted on the aircraft near the tungsten source target for PACT. The aircraft is flown in prescribed patterns around the station to simulate satellite rates. In order to evaluate PACT under its actual field operation, photogrammetric techniques are employed. During the night evaluation tests, the aircraft is photographed against a star field. Two types of plate cameras are used: the fixed PTH-100 camera (in background of Figure 1) and the MOTS-24 camera, which is on a sidereal mount. The PTH-100 camera requires Pre and Post calibration star plates. The MOTS-24 requires just the chopping of the aircraft lights by the shutter exposure. (All exposures are precisely timed). These tests have been performed, and the plates are being measured. The results will be published in the final engineering report.

Presently, the system is being temperature cycled from $+120^{\circ}$ to $-60^{\circ}$ F to determine physical changes or damage that may occur from environment since it will be operated at both far northern and desert sites.

## Summary

The Portable Automatic Calibration Tracker development has advanced the state-of-the-art of Optical Technology in two areas. Absolute pointing accuracy has been achieved to an accuracy of 7 seconds of arc. Error Model has been developed, evaluated, and applied to the data for precision tracking instruments. In addition, the improved real-time handling of the data not only expedites calibration of tracking instruments, but it makes available technology necessary for deep space optical communication mission. PACT has demonstrated the ability to autotrack a celestial target to an accuracy better than 3 seconds of arc.

To date, PACT's main deficiencies are in its ability to track the aircraft during daylight hours and the time-consuming alignment procedures for aligning PACT to the station coordinates. Both of these problems are under consideration.

It is felt that cooling the detector will not give a sufficient gain to achieve full daylight capability. Although considered in the earlier phases of this development program and discarded because of safety and reliability, a laser retroreflector system should be reconsidered.

The station alignment procedures are being improved. The system will be rechecked in the field after it has completed the temperature test.

## <u>ACKNOWLEDGMENTS</u>