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PROTOTYPE DEVELOPMENT AND TESTING AUTOMATED ASTRONOMIC POSITIONING SYSTEM

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Control Data Corporation

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The Automated Astronomic Positioning Systems (AAPS) is a portable astro-geodetic field instrument developed to provide astronomic latitude and longitude. It is impersonal, automatic, and performs most of the computations at the site using a miniature 469 computer. These features substantially reduce the training and office computations currently required for conventional methods. This is the Final Report for Contract No. F19628-72-C-0265 covering the fabrication and testing of two prototype systems. Field tests have thoroughly demonstrated the ease of operation and environmental survival originally

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20. Continued

hoped for in the design. Major site equipment items weigh a total of 65 kg (144 lbs.) and come in three pieces: a Sensor Head, containing optics, leveling system, and photodetectors; a Control Unit, containing computer, clock, and control-display panel; and a battery pack capable of a minimum of 10 hours system operation. Position accuracy has been demonstrated to the ± .35 arc second (one sigma) level after averaging six reversal pairs of data and correcting for instrument biases.

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ABSTRACT

The Automated Astronomic Positioning System (AAPS) is a portable astro-geodetic field instrument developed to provide astronomic latitude and longitude. It is impersonal, automatic, and performs most of the computations at the site using a miniature 469 computer. These features substantially reduce the training and office computations currently required for conventional methods. This is the Final Report for Contract No. F19628-72-C-0265 covering the fabrication and testing of two prototype systems. Field tests have thoroughly demonstrated the ease of operation and environmental survival originally hoped for in the design. Major site equipment items weigh a total of 65 kg (144 lbs.) and come in three pieces: a Sensor Head, containing optics, leveling system, and photodetectors; a Control Unit, containing computer, clock, and control-display panel; and a battery pack capable of a minimum of 10 hours system operation. Position accuracy has been demonstrated to the ± 0.35 arc second (one sigma) level after averaging six reversal pairs of data and correcting for instrument biases.

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AAPS FINAL REPORT

I. INTRODUCTION

This is the Final Report for AF Contract No. F19628-C-72-0265, the fabrication and testing of two prototypes of the Automated Astronomic Positioning System (AAPS.)

AAPS is an optical sensor/computer combination capable of deriving astronomic latitude and longitude in a relatively short observation time. Both observations and computations are automatic and are performed at the site. Highly trained observers are thus not required and each site can be abandoned with confidence that the final adjusted values (calculated later and incorporating polar and time corrections) will be accurate.

A. Contract Background

The concept upon which AAPS is based was presented in the early sixties as an outgrowth of related starmapper studies at Control Data [1, 2, 3, 4]. These studies concentrated on the determination of spacecraft attitude; AAPS is similar in that the system is passive, deriving its information from the transits of stars past a known pattern of slits.

By 1966, the concept had taken explicit form, resulting in a patent [5] and two published papers [6,7]. During the period from October 1970 through June 1971 a design study (Contract No. F19628-71-C-0036) was performed [8]. Based upon this study, a Critical Breadboard Fabrication effort (Contract No. F19628-72-C-0015) was undertaken during the period from September 1971 through February 1972 [9].

The present prototype effort, reported on here, is a direct outgrowth of the previous contracts and covers the period from March 1972 through March 1974. All three contracts have been under the sponsorship of AFCRL.

B. Survey of Contract Requirements and Achievements

Basically, the effort described herein was aimed at developing two prototype hardware systems capable of undergoing extensive field evaluation. Related peripheral equipments and software packages were also provided; all of this equipment was supplied as described in detail in this report. Table 1 summarizes the desired and achieved performance characteristics.

TABLE I. COMPARISON OF ACHIEVEMENT AND GOALS FOR AAPS PROTOTYPE CONTRACT

Specifications	Contract Goals	Contract Achievements
1. Operation and Time	Easy to use; average observation and data reduction time not to exceed 6 hrs.	Easy to use; ~9 hrs. to achieve ± 0″.36 after systematic corrections
2. Weight (Major site items)	C.U. not to exceed 23 kg, S.H. not to exceed 32 kg (including batteries)	C.U. = 18 kg, S.H. = 30 kg, NICAD batteries = 17 kg; total weight 144 lbs. (65 kg)
3. Portability	Each unit transportable by one man	Control unit and battery pack OK; sensor head may require two men for distance and safety
4. Power	24-32 vdc rechargeable battery for 10 hrs. (minimum)	28.8 vdc, 21 AH NICAD battery supplies 15 hrs. at 25°C
5. Environment (Site equipment, operating)	-30°F to +120°F (-35°C to +50°C): 0-95% humidity; 0-14000 feet (0-4267m)	Achieved all goals except PMT channel saturation above +40°C (100°F)
6. Accuracy	± 0″.3, one sigma, at $\phi = 45^\circ$	± 0″.36, one sigma, at $\phi = 45^\circ$

II. AAPS SYSTEM DESCRIPTION

The object of this section is to supply the reader with an overview of the AAPS concept and of its operational and hardware implementation. Sections III and IV provide a more detailed description of the two principal pieces of hardware, the Sensor Head and the Control Unit.

A. Basic Concept

The entire AAPS configuration derives from the star detection concept illustrated in Figure 1 (1). Earth rotation carries the pattern of stars past the fixed slit pattern, thereby creating output pulses from the photodetectors (four photomultipliers in the case of the present prototypes). These pulses are filtered and their peaks detected via a differentiator and zero-crossing detector. The logic level output from this latter stage interrupts a computer which reads a precision clock and stores this "transit time" in its memory. (2) This is the "starmapper" detection technique used extensively by Control Data for spacecraft attitude determination and control [1,2,3,4]. The passive transit of a star image across a slit provides a constraint at the time of transit between sensor latitude, longitude, and azimuth and star position. This constraint is illustrated in Figure 2 and is

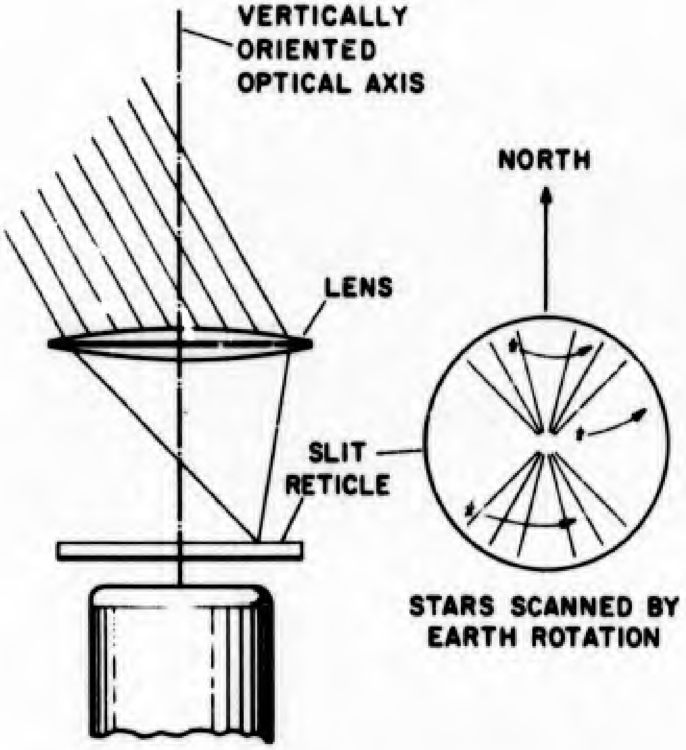

Figure 1. Star Transit Measurement Concept

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(1) The utilization of a radial slit pattern in Figure 1 makes the measurement technique similar to that suggested by Gougenheim [10,11,12], White [13], and others [14,15] for use with theodolites.

(2) The hardware details of these processes are discussed in Sections III and IV.

expressed by the standard four-parts formula of the "azimuth technique":

$$\sin h_i \cot \gamma_j = \sin \bar{\varphi} \cot \bar{\delta}_i - \cos \bar{\varphi} \cos h_i$$

where h_i is the local hour angle of the ith star, $\gamma_j = \beta_0 + \beta_j$ the azimuth of the jth slit, δ_i the stellar declination and φ the site latitude. The super bar refers to the co-angle. The measured time of transit enters into h, as does the star's right ascension α_i and the site longitude λ. The slit angle β_j and star coordinates α_i and δ_i are determined by identifying the star/slit combination. A solution is obtained by adjusting the parameters φ, λ, and β_0 to achieve a best-fit to the aggregate of these equations generated by the star transits.

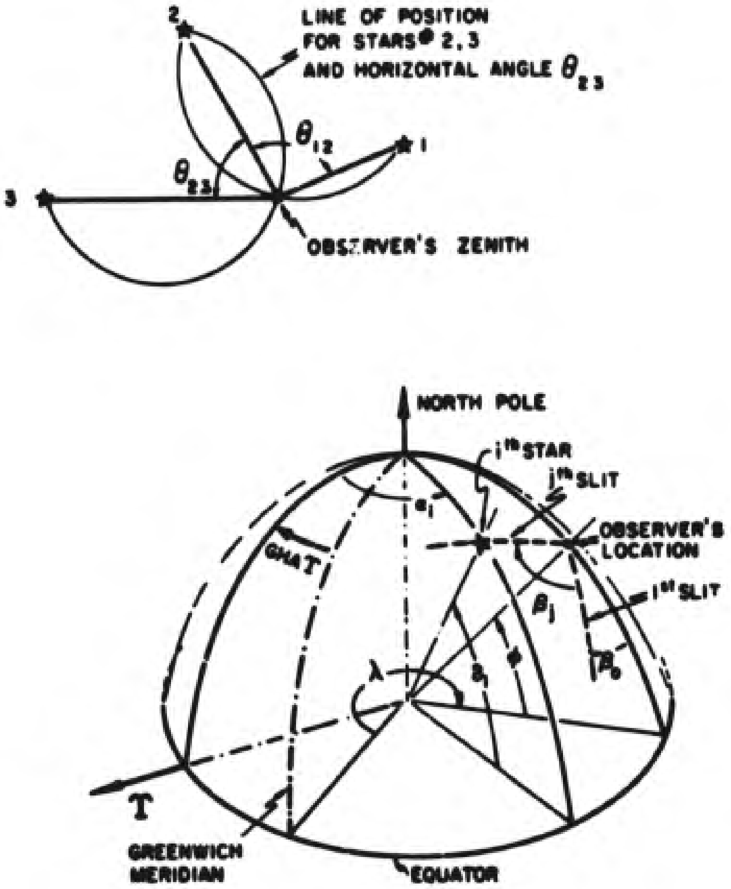

Figure 2. Star-Slit Geometry at Transit

B. Summary Description of the Prototype Hardware

Two sets of prototypes were constructed under the present contract. Each set consists of the following pieces:

Sensor head and soft-pack
Control unit and soft-pack
Battery pack and soft-pack
Sensor head/control unit cabling (2 pieces, 26' and 22' lengths)
Magnetic tape transport
Printer
Battery charger
Cables for peripheral equipment interconnection
Transport cases

These are divided into site and base portions. The site equipment includes sensor head, control unit, and battery pack and is shown in field deployment in Figure 3; there the sensor head is being coarse leveled prior to operation. Figure 4 gives a closer view of the grouped instrumentation. In both figures the transport soft-packs for the sensor head and the control unit are also shown. The sensor head contains the optics, slit reticle, and photodetectors required for the measurement of star transits as shown in Figure 1; it also contains filter and detection electronics and an active leveling system provided by Hughes Research Laboratories, Malibu Beach, California. The control unit contains a 469 miniature computer, precision clock, and a control panel for operation and monitoring.

The base equipment consists of tape deck, impact printer, and battery charger; these are shown connected to the control unit in Figure 5 and are used for the following tasks: (a) loading system programs and computing apparent places of stars prior to leaving for a night's work, (b) outputting the site data and field results onto magnetic tape and/or hard copy after completion of a night's work, and (c) performing direct/reverse combinations and data averaging on selected sets from past observations.

To effect 469 software changes or maintain the computer, a console is required as shown in Figure 6.

C. System Software Description

The 469 software is composed of four major sections, all stored on a single system tape: (a) apparent place or site preparation program, (b) site program, (c) dump and utility programs, and (d) star catalog. The latter contains all stars down to 6.3 visual magnitude over the entire celestial sphere. Some stars, such as those with poor positions or unresolvable doubles, are marked for deletion from a set solution. The FK4 coordinate system is used, about half of the stars being from the FK4 or its supplement. The remainder are taken from the SAO Star Catalog with parallax and radial velocity added where necessary and possible.

The AAPS 469 software task required 2½ man years of effort and resulted in 20,000 words of program and 47,000 words of star catalog.

Figure 3. AAPS Site Deployment

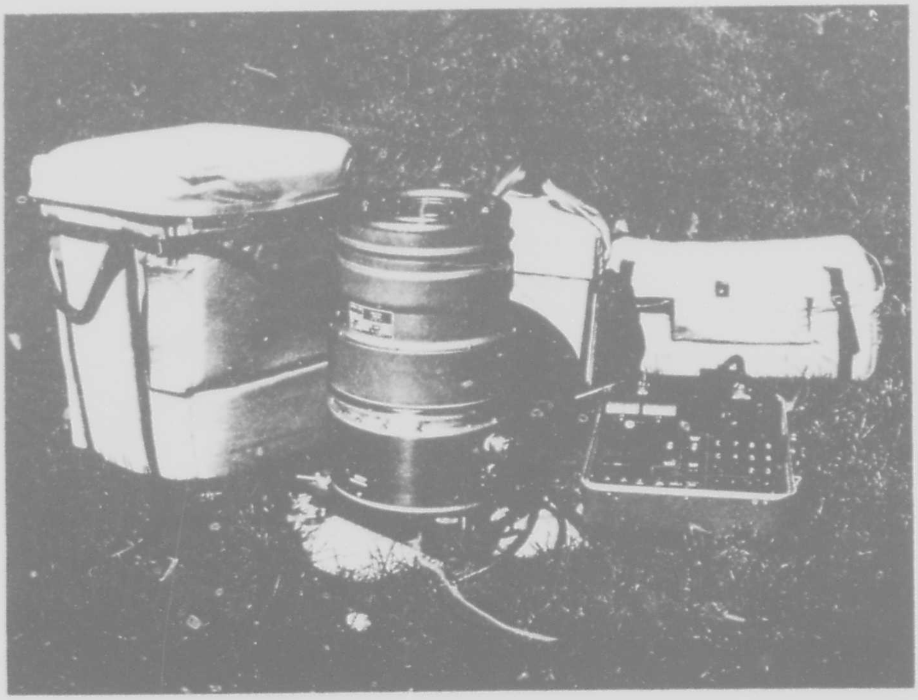

Figure 4. Site Equipment, Grouped

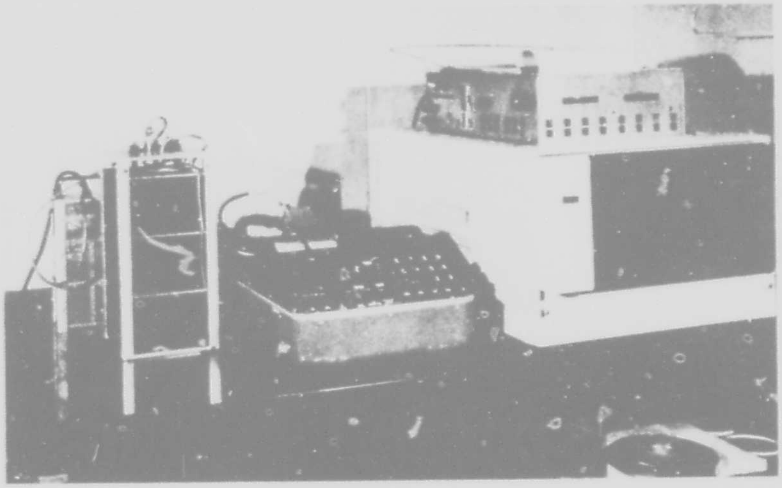

Figure 5. Field Base Equipment (Charger, NICAD Battery, Control Unit, Printer, Tape Deck)

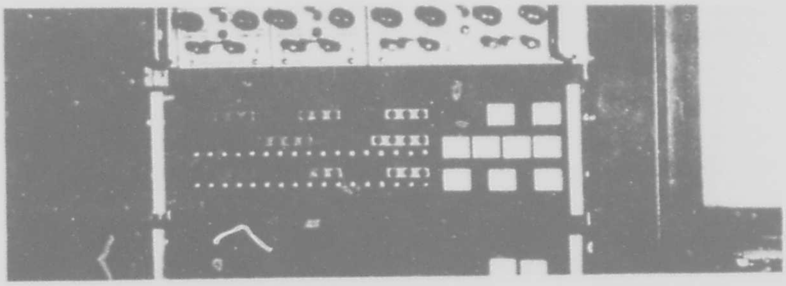

Figure 6 469 Programmer's Console

The apparent place and dump programs provide various outputs to the operator, via the printer, as shown in the annotated reproductions in Figure 7. To reduce memory, various approximations are made in the apparent place program resulting in the use of "constants" good only for the decade of the 1970's. Simple revisions will have to be introduced for operation after 1980 or more expanded versions of the equations employed. The site program is the most memory-limited of the three and has been constructed so as to eliminate stars which can no longer be seen from the night's catalog and to store site data (star transit times and computed results) in their vacated positions. The dump program has seven options of which three are shown in Figure 7. This program also permits the blank labeling of tapes for their introduction to the system.

D. Overall AAPS Operation (3)

Operation starts with the setup of the base equipment as shown in Figure 5. The clock is synchronized against a locally available time standard using controls described in Section IV. (This is usually a one-time task; subsequent actions amount only to monitoring the clock and performing small adjustments when necessary.)

To prepare for a night's observation, the operator enters the approximate coordinates (latitude and longitude accurate to one or two minutes of arc) through the keyboard for each site to be occupied. The system tape is then automatically searched to find those stars likely to be detected during the night. These are reduced to apparent place and stored in the computer memory, taking up about 4K words. A total of 330 stars (or twelve hours of observing, whichever comes first) are so reduced. The site program is then loaded into the remaining 4K of memory from the tape. An example of the printer output during this task is shown in the lower left corner of Figure 7.

The control unit, sensor head, and battery are then transported to the first site to be occupied and set up in a manner similar to that depicted in Figure 3. (A maximum separation of 50 feet is allowed between control unit and sensor head. During cold weather, the operators and control unit could remain in a heated vehicle.) The sensor head is mounted on a relatively stable base (concrete pier, sidewalk, roadway, blocks, etc.). It is then aligned within 5° of celestial north and coarse-leveled using the footscrews and external bubble levels. A screen is erected around the sensor head after alignment to protect it from wind gusts and to provide shielding from neighboring lights.

Following this, the system is powered up and the footscrews readjusted to minimize the power required of the active level system. Upon identifying the site and initial orientation (north or south, direct or reverse) through the keyboard, the computer takes over to automatically acquire and process the star transits. Generally about 30-33 transits are recorded, of which some 28-30 are identified and a minimum of 25 retained in solution. Such a collection of transits is called a "set" and requires 30-60 minutes to acquire depending on star density, atmospheric opacity, and cloud cover. The upper left portion of Figure 7 lists data from such a set.

At the completion of each set, the operator records in the log nine quantities from the display for later confirmation of the data dumped. He then reverses the sensor head (upper portion only) about 180° – the motor is controlled from a switch on the control panel – and executes the next set. Sets are accumulated in pairs (direct and reverse) for later combining. As many such

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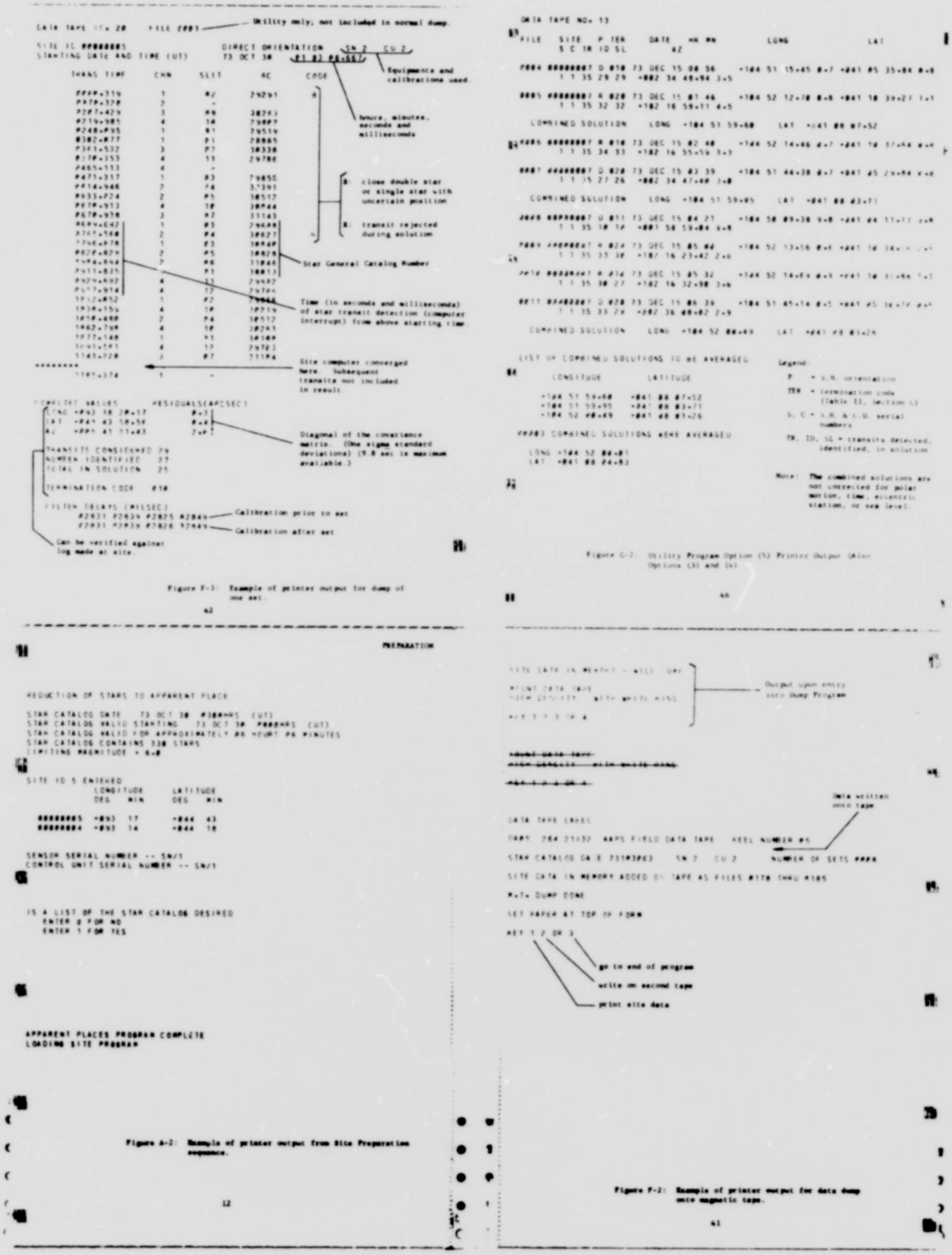
(3) Detailed operational instructions and suggestions for equipment care are contained in the R & D Equipment Information Report, dated 8 February 1974 and supplied as part of the present contract.



```
DATA TAPE NO. 20    FILE 0001

SITE ID 00000005                    DIRECT ORIENTATION   SN 2   CU 2
STARTING DATE AND TIME (UT)         73 OCT 30   01 03 06.667

     TRANS TIME      CHN     SLIT       AC      CODE

     0000.319         1       02      29291      A
     0070.320         2       -
     0207.429         3       09      30203
     0219.985         4       10      29807
     0248.095         1       01      29519
     0302.077         1       01      28865
     0361.532         3       07      30338
     0370.353         4       11      29708
     0465.113         4       -
     0471.317         1       03      29850
     0614.946         2       04      30391
     0633.024         2       05      30512
     0670.913         4       10      30044
     0670.930         3       07      31143
     0694.042         1       03      29600
     0761.560         2       04      30627      R
     0746.070         1       03      30040
     0820.829         2       05      30828
     0904.944         2       06      31046
     0911.835                 01      30013
     0929.692         4       11      29882
     0957.914         4       12      29706
     1012.052         1       02      29066
     1030.159         4       10      30219
     1050.400         2       04      30512
     1062.790         4       10      30263
     1077.140         1       01      30100
     1091.501         4       12      29703
     1143.720         3       07      31104
********
     1185.374         1       -

COMPUTED VALUES        RESIDUALS(ARCSEC)
 LONG +093 18 20.17          0.3
 LAT  +044 43 50.50          0.4
 AZ   +005 41 21.03          2.0

 TRANSITS CONSIDERED 29
 NUMBER IDENTIFIED   27
 TOTAL IN SOLUTION   25

 TERMINATION CODE   010

 FILTER DELAYS (MILSEC)
      02031 02034 02025 02049
      02031 02039 02026 02049
```

Utility only; not included in normal dump.

Equipments and calibrations used.

hours, minutes, seconds and milliseconds

A: close double star or single star with uncertain position

R: transit rejected during solution

Star General Catalog Number

Time (in seconds and milliseconds) of star transit detection (computer interrupt) from above starting time.

Site computer converged here. Subsequent transits not included in result.

Diagonal of the covariance matrix. (One sigma standard deviations) (9.0 sec is maximum available.)

Calibration prior to set

Calibration after set

Can be verified against log made at site.

Figure F-3: Example of printer output for dump of one set.

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```
DATA TAPE NO. 13

FILE   SITE     P TER     DATE      HR MN          LONG                    LAT
       S C TR ID SL             AZ

0004 00000007 D 010 73 DEC 15 00 56     +104 51 15.45 0.7 +041 05 35.04 0.8
          1 1 35 29 29   +002 34 48.94 3.5

0005 00000007 R 020 73 DEC 15 01 46     +104 52 12.70 0.8 +041 10 39.27 1.1
          1 1 35 32 32   +102 16 59.11 4.5

  COMBINED SOLUTION    LONG  +104 51 59.60    LAT  +041 00 07.52

0006 00000007 R 010 73 DEC 15 02 40     +104 52 14.46 0.7 +041 10 37.54 0.4
          1 1 35 34 33   +102 16 55.59 3.3

0007 00000007 D 020 73 DEC 15 03 39     +104 51 44.38 0.7 +041 05 29.94 0.8
          1 1 35 27 26   +002 34 47.40 3.0

  COMBINED SOLUTION    LONG  +104 51 59.95    LAT  +041 00 03.71

0008 00000007 D 011 73 DEC 15 04 21     +104 50 09.38 9.0 +041 04 11.17 [illegible]
          1 1 35 10 10   +001 50 59.04 9.0

0009 00000007 R 024 73 DEC 15 05 04     +104 52 13.56 0.6 +041 10 34.[illegible] [illegible]
          1 1 35 33 30   +102 16 23.42 2.6

0010 00000007 R 014 73 DEC 15 05 32     +104 52 14.69 0.9 +041 10 3[illegible] 1.1
          1 1 35 30 27   +102 16 32.90 3.6

0011 00000007 D 020 73 DEC 15 06 39     +104 51 45.14 0.5 +041 05 3[illegible] [illegible]
          1 1 35 33 29   +002 36 00.02 2.9

  COMBINED SOLUTION    LONG  +104 52 00.49    LAT  +041 00 03.26

 LIST OF COMBINED SOLUTIONS TO BE AVERAGED

        LONGITUDE          LATITUDE

     +104 51 59.60      +041 00 07.52
     +104 51 59.95      +041 00 03.71
     +104 52 00.49      +041 00 03.26

 00003 COMBINED SOLUTIONS WERE AVERAGED

   LONG +104 52 00.01
   LAT  +041 00 04.83
```

Legend:

P = S.H. orientation

TER = termination code (Table II, Section C)

S, C = S.H. & C.U. serial numbers

TR, ID, SL = transits detected, identified, in solution

Note: The combined solutions are not corrected for polar motion, time, eccentric station, or sea level.

Figure G-2: Utility Program Option (5) Printer Output (Also Options (3) and (4)

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PREPARATION

```
REDUCTION OF STARS TO APPARENT PLACE

STAR CATALOG DATE    73 OCT 30  0300HRS  (UT)
STAR CATALOG VALID STARTING    73 OCT 30  0000HRS  (UT)
STAR CATALOG VALID FOR APPROXIMATELY 06 HOURS 06 MINUTES
STAR CATALOG CONTAINS 330 STARS
LIMITING MAGNITUDE + 6.0

SITE ID 5 ENTERED
               LONGITUDE       LATITUDE
               DEG   MIN       DEG   MIN

  00000005    +093   17       +044   43
  00000004    +093   14       +044   10

SENSOR SERIAL NUMBER -- SN/1
CONTROL UNIT SERIAL NUMBER -- SN/1


IS A LIST OF THE STAR CATALOG DESIRED
   ENTER 0 FOR NO
   ENTER 1 FOR YES


APPARENT PLACES PROGRAM COMPLETE
LOADING SITE PROGRAM
```

Figure A-2: Example of printer output from Site Preparation sequence.

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```
SITE DATA IN MEMORY - WILL DUMP

MOUNT DATA TAPE
HIGH DENSITY   WITH WRITE RING

KEY 1 2 3 OR 4


~~MOUNT DATA TAPE~~
~~HIGH DENSITY   WITH WRITE RING~~

~~KEY 1 2 3 OR 4~~


DATA TAPE LABEL

DAPS  204 21132  AAPS FIELD DATA TAPE    REEL NUMBER 05

STAR CATALOG DATE 73103003    SN 2   CU 2        NUMBER OF SETS 0008

SITE DATA IN MEMORY ADDED ON TAPE AS FILES 0178 THRU 0185

M.T. DUMP DONE

SET PAPER AT TOP OF FORM

KEY 1 2 OR 3
```

Output upon entry into Dump Program

Data written onto tape

go to end of program

write on second tape

print site data

Figure F-2: Example of printer output for data dump onto magnetic tape.

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Figure 7. Four Examples of Program Output

"reversal pairs" as are required to meet accuracy are observed at the site. The equipment is then transported to the next site and the above sequence repeated.

At the end of the night, the control unit and battery are returned to the base (the sensor head can be stored at ambient temperature). Connected again as in Figure 5, the dump program is read from the system tape into the computer. All the night's data is then recorded onto a data tape and can also be printed if desired (upper left portion of Figure 7). This completes the cycle; the next night's operation begins as did the first night's operation, except that it usually is not necessary to synchronize the clock again.

At any convenient time, the utility program can be input to the computer to permit the output of other computations. Specifically, the combining of direct and reverse sets to generate site coordinates and the averaging of these reversal pairs for a night's work are accomplished with this program. An example of the output is shown as the upper right portion of Figure 7.

Precise final values of the site latitude and longitude must await the publication by BIH (4) of UT1-UTC and polar coordinates. This currently occurs one or two months after the observation date.

---

(4) Bureau International de l'Heure, especially their Circular D, distributed in the U.S. by the U.S. Naval Observatory.

III. SENSOR HEAD DESCRIPTION

The sensor head is an important piece in the AAPS system and has been shown in the field photos of Figures 3 and 4; it is also shown in outline form in the drawing of Figure 8. It is 19 3/4 inches high by 12 1/2 inches in diameter (50.1 x 31.8 cm), weighs 30 kg (66 lbs.), and fits into a soft-pack having outside dimensions 17 x 17 x 24 inches (43.2 x 43.2 x 60.9 cm). Its major constituents are: optics, leveling system, photodetectors and electronics, reversal bearing, and motor. These are each described separately in subsequent paragraphs.

A. Optical System

Detailed dimensions of the AAPS optics are shown in Figure 9. It is a 23° field of view concentric two-mirror reflecting system with an image diameter of approximately 25 arc seconds. This unconventional arrangement of optical elements is inherently free from astigmatism, coma, and chromatic aberrations, suffering only from spherical aberration which is minimized by the appropriate selection of element radii.

Because of the completely concentric nature of the system, there is no axis of symmetry (5), hence no optical axis and no off-axis condition which can cause additional aberrations. An instrument axis is, of course, present and consists of the projection of the center of the reticle pattern out towards the celestial sphere.

The aperture stop is physically located immediately below the common center of the elements. Light is accepted in an annulus which strikes first the primary and then the secondary mirrors and is finally focused at the reticle.

Another novel feature of this optical system is the single-piece structure upon which are mounted the primary and secondary mirrors and the reticle holder. This piece is a solid block of CER-VIT(6) which was cored out by E & W Optical Company (Minneapolis, Minnesota). References [8] and [9] contain details of the coring, various photos of the process, and the rationale for selecting this material and technique. CER-VIT was chosen for its near-zero expansion coefficient, and a solid-block structure approach was used to minimize interfaces.

Both the primary and secondary mirrors are also of CER-VIT, as is the reticle holder. The secondary mirror blank was pressed into a mold at Owens-Illinois. Severe difficulties were encountered during this task due to differential cooling, mold release problems, and voids. Two mold redesigns were required and about 25 pressings before satisfactory blanks could be obtained. This resulted in a two-month delay in optical testing.

The primary mirror assembly is shown in Figure 10. A precision thickness washer (stainless steel) is placed between the mirror and its spider support. Focusing of the optical system was accomplished by trial and error selection of the thickness that produced optimum imagery as determined by star transit pulse shape. The structure to the right in Figure 10 holds the primary mirror in place and also serves as a light baffle; it can be seen more clearly in Figure 8.

---

(5) Note, however, that there is a point of symmetry; all elements are concentric to a point centered in the aperture.

(6) Owens-Illinois, Toledo, Ohio. All non-reflective surfaces of the CER-VIT materials were painted a flat black. This virtually eliminated stray light conducted through the material to the region of the PMTs.

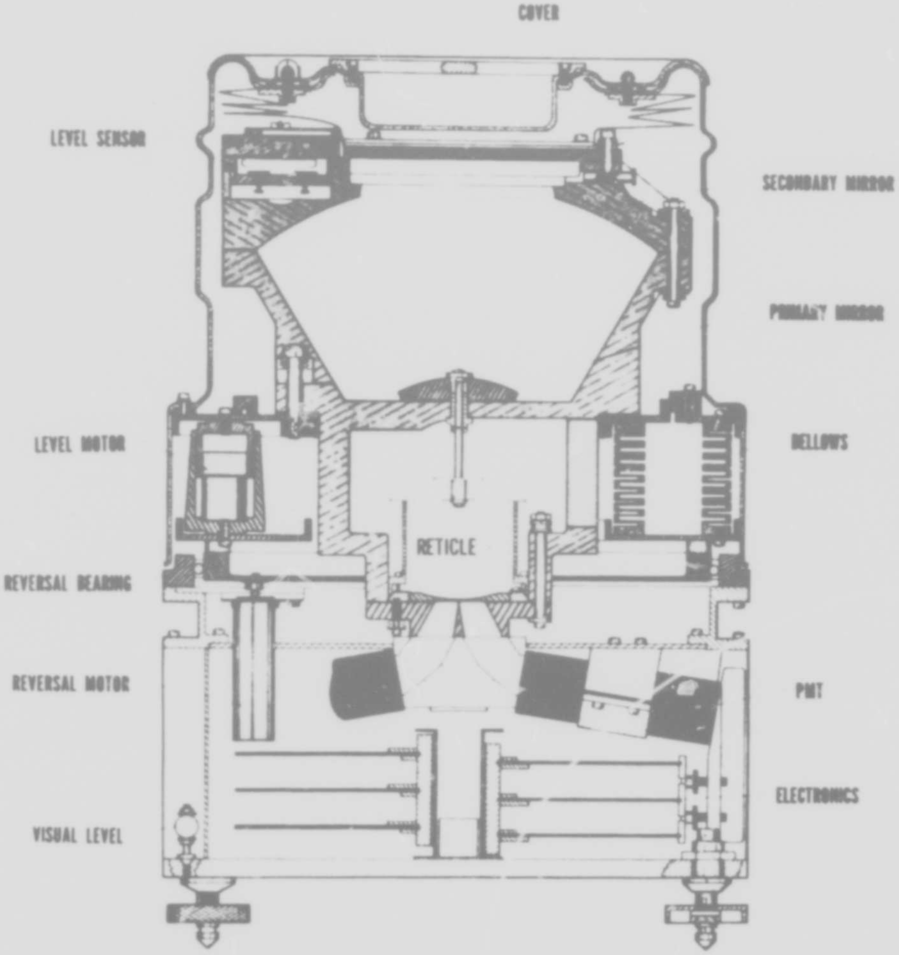

Figure 8. Sensor Head Outline Drawing

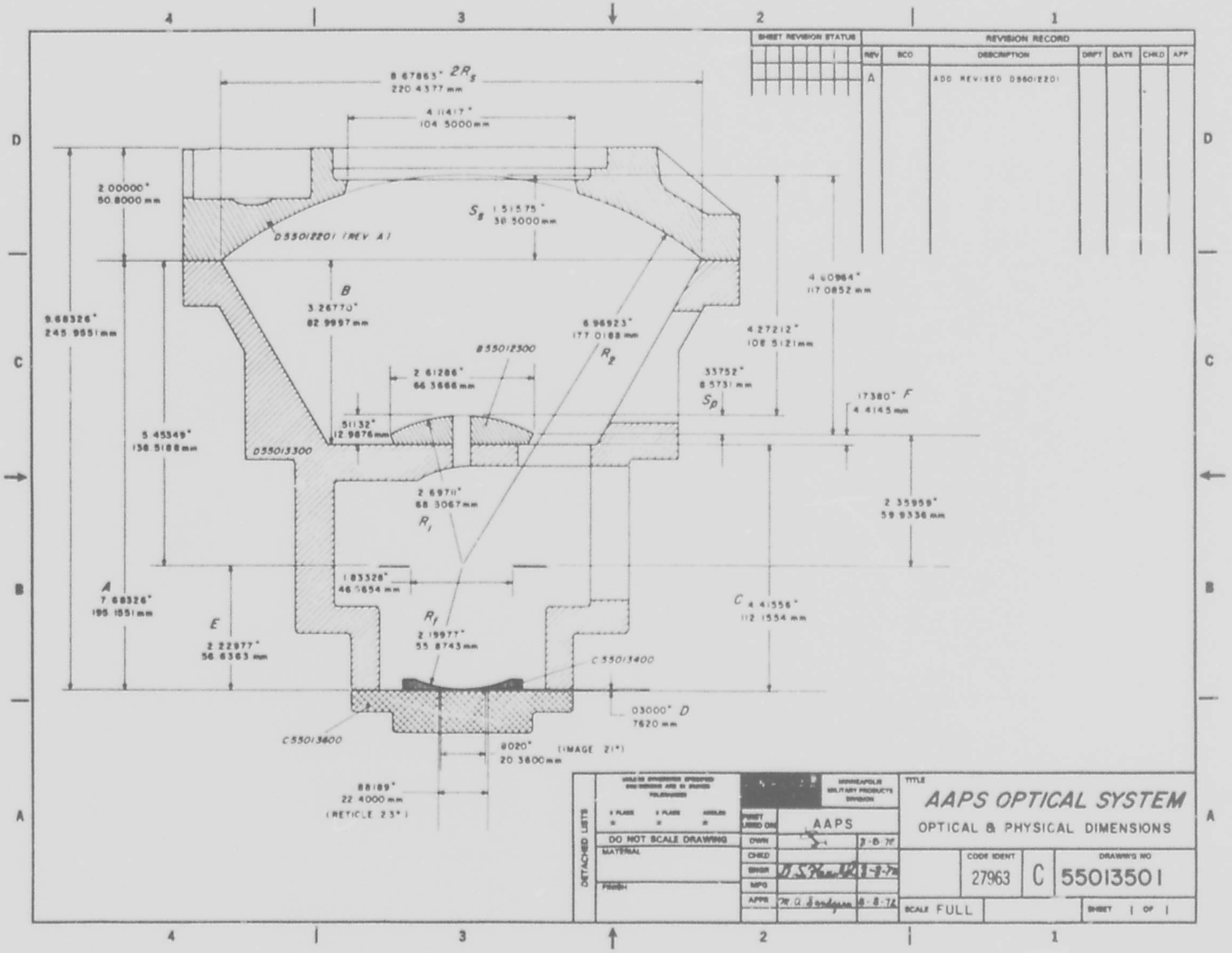

Figure 9. AAPS Optical System

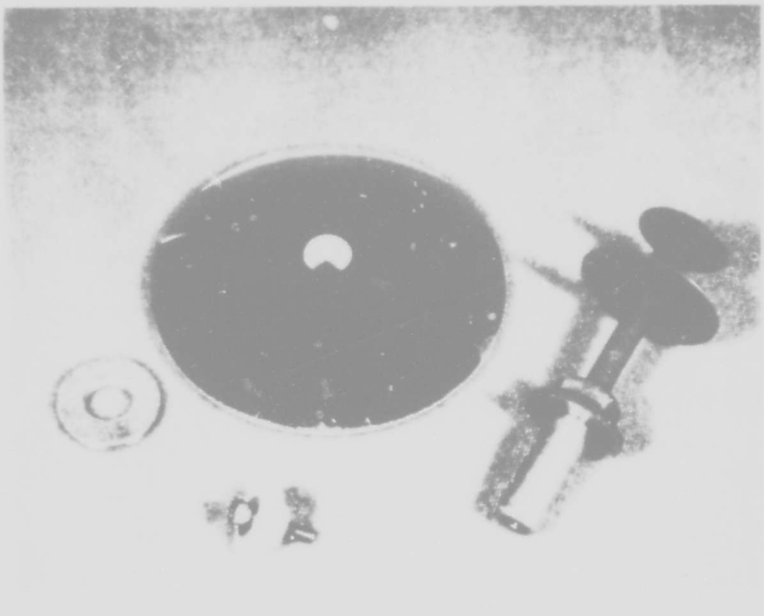

Figure 10. Primary Mirror and Components

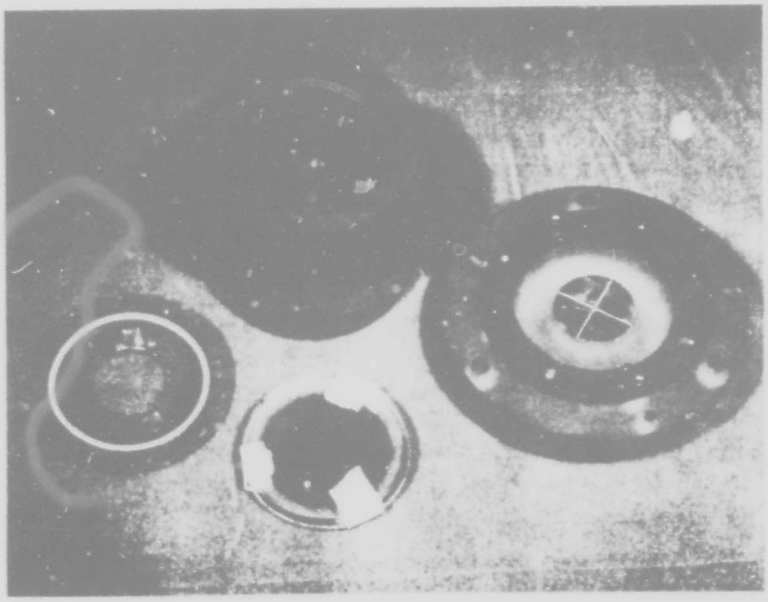

Figure 11. Reticle Assembly

Figure 11 depicts the reticle assembly attached to the bottom of the optical structure. The cylinder shown in the upper portion of the figure is the aperture assembly, which serves principally to define the aperture stop and to block out unwanted stray light. The reticle itself (temporarily covered with a plastic protector) pictured just below the cylinder was supplied by Dynamics Research Corporation, Wilmington, Massachusetts. It fits into the circular ring on the reticle holder shown to the right in the figure, and is then clamped using the piece to the left (the white annulus is a rubber ring used to exert clamping pressure on the reticle (7)).

In the center of the reticle holder is the mouth of the light guide with the crossed vanes delineating the four quadrants. Referring back to Figure 8, one sees that this is the first stage of a two-stage light guide diverting light toward each of the four PMTs. Subsequent test data showed that the variation in light collection efficiency as a function of the off-axis angle of the star is less than 20 per cent. In the reversal process, only the upper stage of the guide rotates. The lower stage, along with the PMTs, HV supplies, and electronics, remains stationary; the slits rotate, but the channels of electronics do not. This is accounted for in the software bookkeeping process.

B. Active Level Controller

The optical system rests by means of three bolts on a level control base which is driven from a sensor located atop the secondary mirror. The level sensor, base, and associated electronics were furnished by Hughes Research Laboratories, Malibu Beach, California.

The operation of the leveling subsystem is illustrated in Figure 12. The level sensor participates

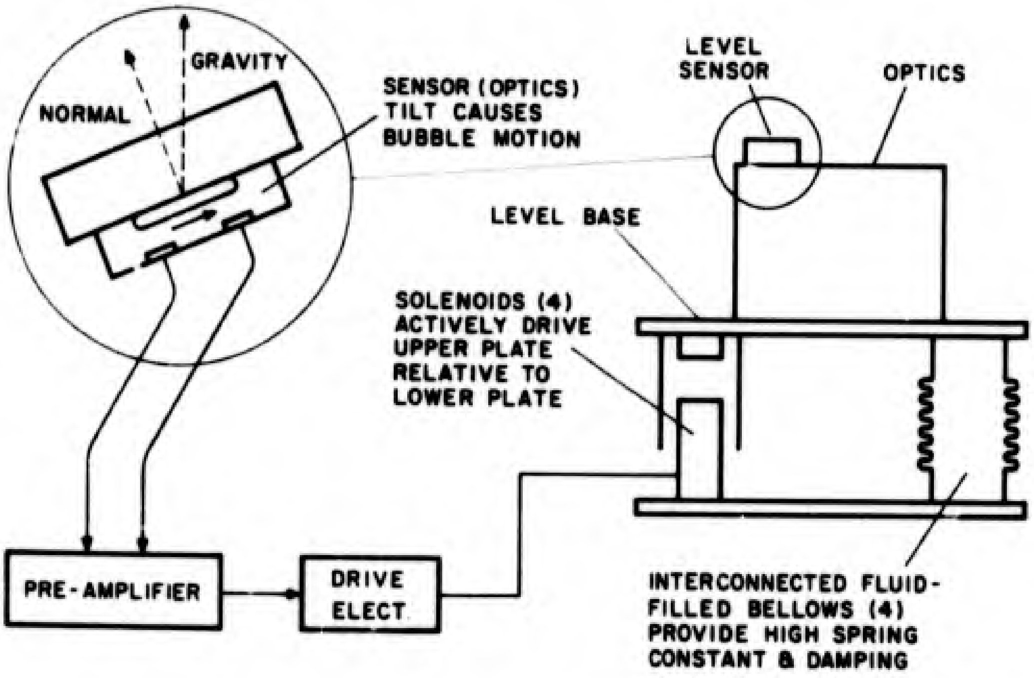

Figure 12. Hughes Level Control Subsystem

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(7) This pressure was insufficient in SN/1 sensor head resulting in reticle slippage and out-of-focus conditions. Corrective action was required in December, 1973.

in any tilt of the optical structure, the two being intimately clamped together (see the top portion of Figure 13), such a tilt causes bubble displacement which is sensed electrically, causing appropriate countering current through the solenoids. These combine in a Type 1 servo loop to center the bubble. The four fluid-filled bellows are interconnected by a ring (top of level base in Figure 13) to allow fluid exchange through the orifices; this provides damping of the loop.

If the bubble were contained under a curved surface, the centering would depend upon the locations of the four sensing elements and, more importantly, upon their positional stability. The bubble is in fact contained under an optically flat quartz plate, hence it is only metastable and independent of precise centering. As a result, placement of the electrodes or even slow drift of the electrodes will not affect tilt even though it may affect bubble position.

The optical elements and level subsystem are shown assembled in Figure 13. This portion of the sensor head is covered during operation by the light-colored top seen in Figures 3 and 4.

The performance of this leveling system is crucial to the accurate operation of AAPS since any errors couple directly into final position. Temperature and time changes can be tolerated in the level electronics and in the level base (solenoids and bellows) since their only function is to keep the bubble centered; similar variations in the bubble itself, however, are intolerable to the extent that they allow tilt changes. Thermal gradients, perhaps caused by shifting winds at the site, may constitute a current limitation of accuracy (refer to Section V).

For a time during the prototype development, it was thought that the fluid in the bellows system could be eliminated. This was because of slow (10-20 second period) oscillations observed on site and their cessation once the fluid was removed. Later analysis showed, however, that the fluid was needed to reduce high frequency instabilities. Transient response measurements such as those shown in Figure 14 revealed the true advantage of the fluid in permitting a rapid response to transient loads without excess bubble disturbance. (The level oscillations are probably due to differences in the sensor head and ambient temperatures upon initial occupation of the site, and are currently under investigation.)

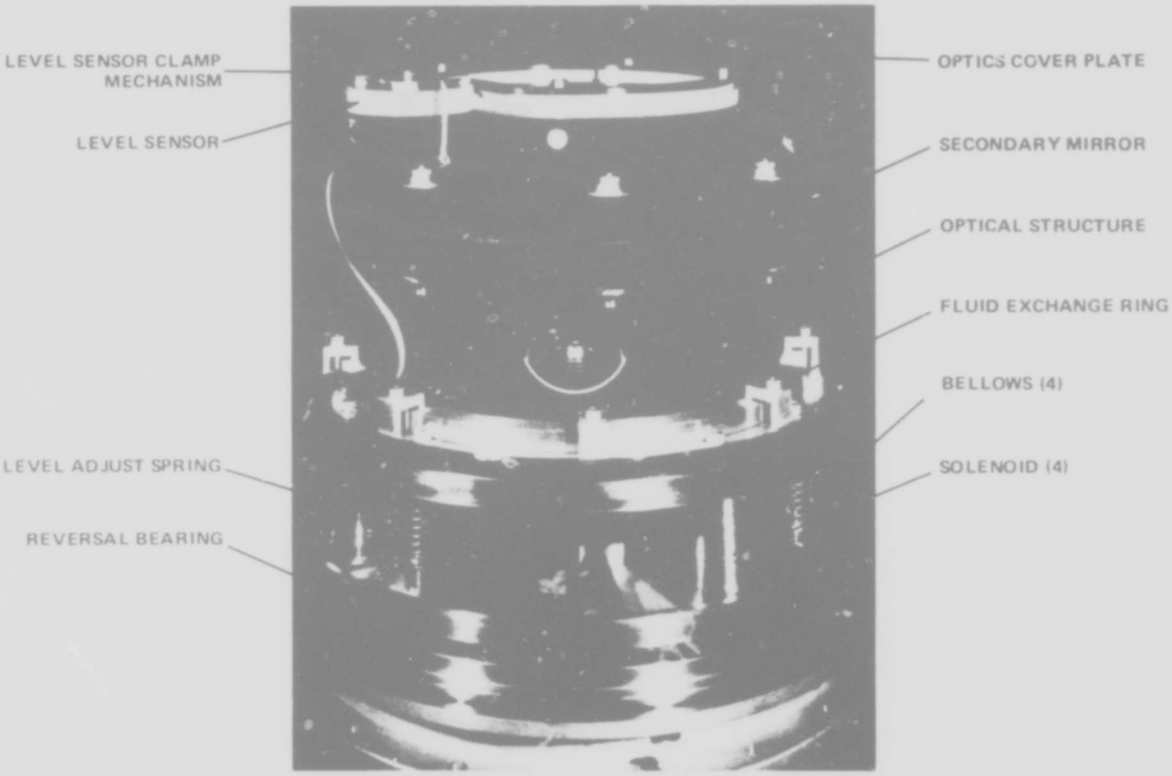

Figure 13. Sensor Head, Upper Portion (Cover Removed)

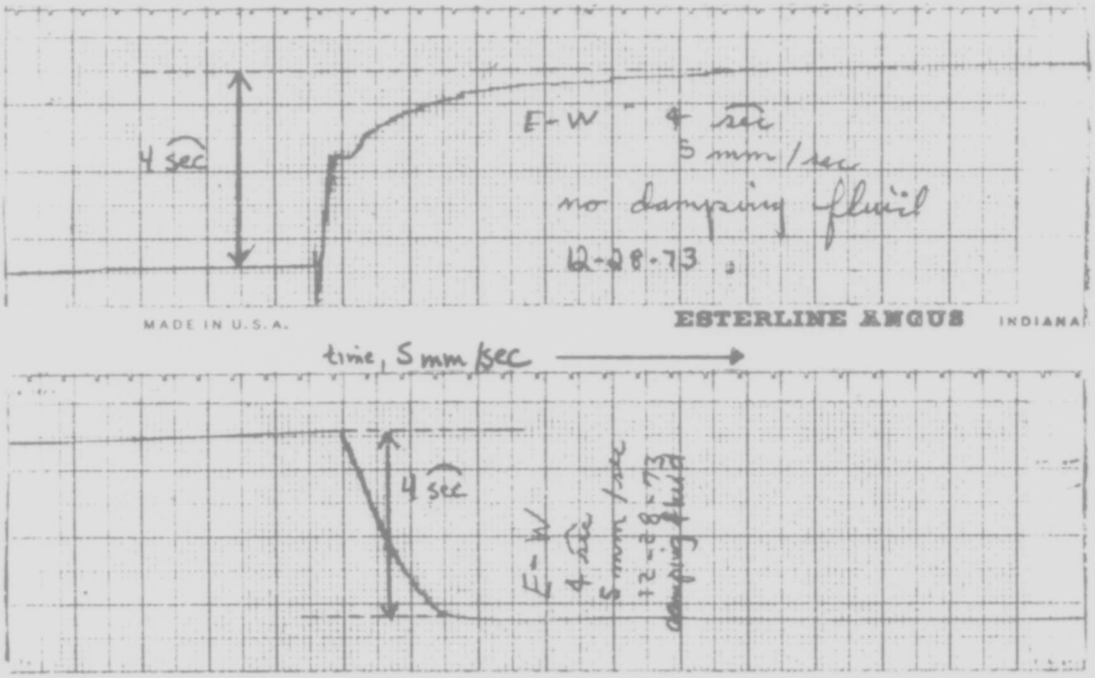

Figure 14. Transient Response of Level System With and Without Damping Fluid

C. Photodetector and Electronics

In operation, the leveled optical system focuses the near-zenith star field onto a reticle containing 12 slits arranged in radial fashion and grouped in quadrants of three each (see Figure 1). Behind each quadrant, as shown in the sensor head outline drawing of Figure 8, is a two-stage light guide leading to an EMR 541E photomultiplier tube. Each of these tubes is powered by a separate high voltage supply (EMR Model 638K) and is followed by an independent signal filtering and detection channel.

The electronics are housed in the base of the sensor head as pictured in Figure 15. There are six semicircular cards mounted three to a side on the mother-board structure depicted in the center of the base. Four of the cards contain the filtering and detection circuits for the four channels, one card contains the H.V. gain controls and calibration pulse generator, and the final card contains level sensor amplifier circuits.

The operation of each of the four channel cards is illustrated in the block diagram and waveform photos of Figures 16 and 17. In Figure 16 the action proceeds generally from left to right across the upper line of blocks. The top photo in Figure 17 is that of a star transit waveform out of the preamplifier (showing noise caused by background light, dark current in the PMT, and the random generation of photoelectrons at the cathode surface) and after processing by the six-pole filter.(8) The filtered pulse is delayed by approximately 2.8 seconds; this delay is calibrated before and after each set of data to take account of temperature and aging effects on the components.

The filtered pulse is then simultaneously sent to a baseline follower circuit (center left of Figure 16) and a differentiator. The outputs of these circuits are shown in the second and third photos of Figure 17. The baseline follower serves to subtract out (at the input to the gate detector) the dc signal from the star pulse and also to permit operation in a slowly varying dc light environment (due to changing cloud and haze conditions, local lighting, or near twilight). The baseline follower has a maximum rate of rise. When a star pulse comes along, it rises at a more rapid rate until the separation reaches 100m volts at which point the gate detector is tripped, preparing the circuits for a coming star transit.

The differentiator serves to locate the peak of the filtered pulse. When it passes through zero, the transit detector emits a pulse which is finally translated to the $\overline{\text{STAR}}$ pulse (bottom photo, Figure 17). This is the pulse which interrupts the computer in the control unit, causing it to read the clock and store the time of transit. It is 5 volts high but only 100 µsec long and therefore hardly visible in the figure.

The logic circuits in the lower right portion of Figure 16 control the flow of signals, detect excessive light levels, and return the analog circuits to normal after detection of a transit. (Note the rapid slewing of the baseline follower in the second photo of Figure 17 after the filter peak has passed and the $\overline{\text{STAR}}$ pulse transmitted.)

From an accuracy standpoint, the key element is the time delay caused by the filter. This is calibrated using a symmetric triangular pulse ("Test Video" in Figure 16) input to the preamplifier. This is commanded from the control unit which then measures the time difference

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(8) See references [8] and [9] for a discussion of filter design and testing.

between the peak of the triangular pulse and the peak of the filtered pulse. A complete discussion of this with measurement results at various temperatures and pulse heights is contained in reference [9]. The only difference is the doubling of the delay from 1.4 seconds to 2.8 seconds to accommodate the longer pulses observed in the prototypes.

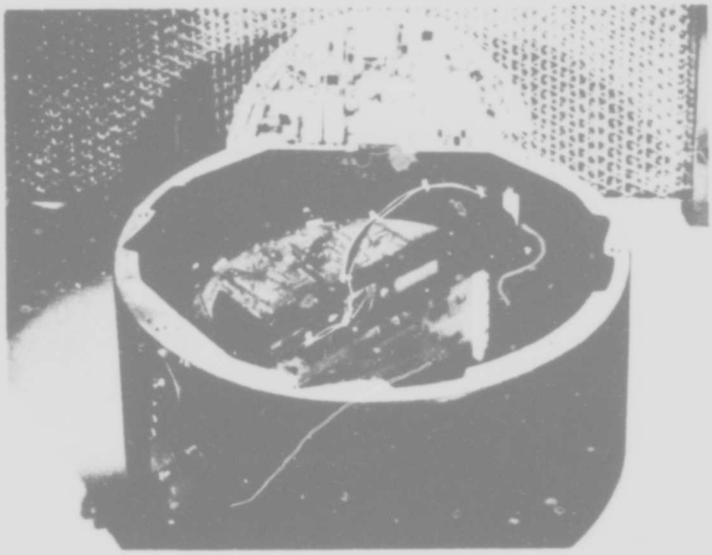


Figure 15. Sensor Head Base Showing Electronic Cards

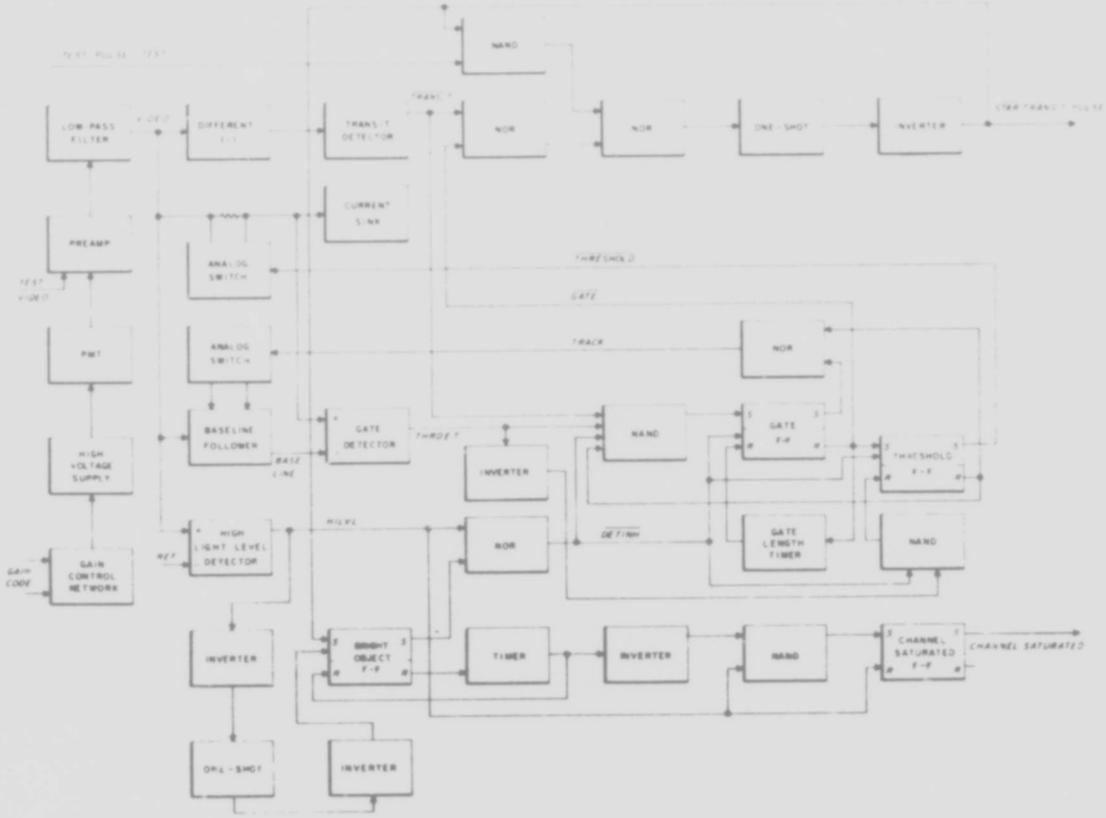
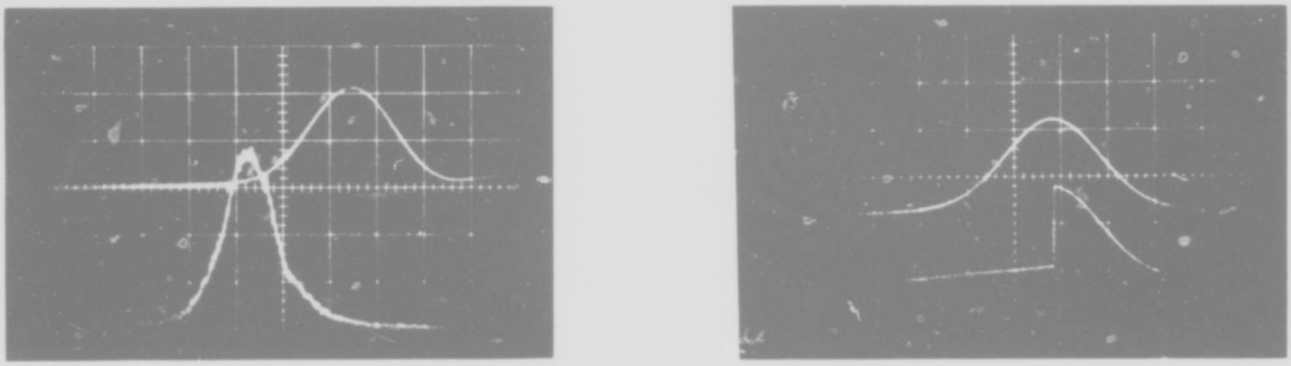


Figure 16. Detection Electronics Block Diagram

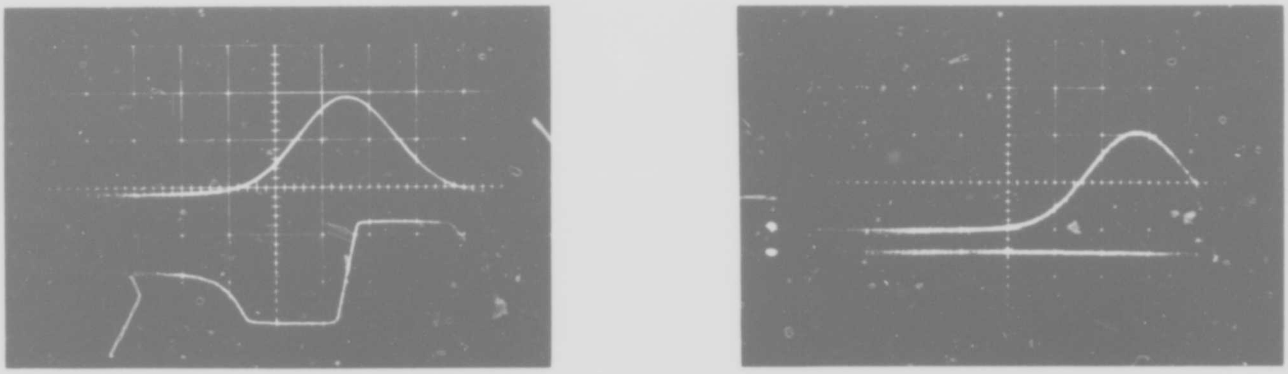


Filter (.1v/cm)

Preamplifier (.1v/cm)

Filter (.1v/cm)

Baseline Follower (.1v/cm)



Filter (.1v/cm)

Differentiator (10v/cm)

Filter (.1v/cm)

$\overline{\text{STAR}}$ (5v/cm)

Figure 17. Output Waveforms from Test Connector Pins (Sweep: 1 sec/cm)

IV. CONTROL UNIT DESCRIPTION

The control unit is shown in plan view in Figure 18. It contains a Control Data 469 computer with 8192 words of plated wire memory (16 bits apiece), a Motorola precision oscillator, a NICAD clock battery (24 volts, 7 AH, 6.4 kg), computer interface and clock electronics, and a control-display panel. Principle characteristics of the computer are as follows:

- Model No. 469-1-1.0-36-D-12-K
- 8192 16-bit words of plated-wire memory
- 1.0 MHz clock frequency
- 5 watts input power from +12v, +5v, -12v
- Temperature range -55°C to +65°C
- Reliability level – D
- Case style – K

Photos of some of the components and the interior of the assembled control unit are shown in Figures 19 and 20. The rear of the control unit, shown in Figure 20, contains three inserts. On the right is a pressure release; next is an actual port for access to the oscillator fine and coarse frequency adjustments; and to the left is an interior humidity indicator.

A. Clock

A precision clock is an integral part of the control unit, maintaining continuous time for accurate recording of the star transits. This clock is kept running at all times except during prolonged transport (several days) when the battery is disabled to prevent its complete discharge. A totally charged clock battery will sustain operation for about 28 hours at 25°C.

The oscillator is shown in both Figures 19 and 20 between two boards of electronics which form the first portion of the count-down chain. Major characteristics of the oscillator are as follows:

- Motorola model No. S1081A-1231AA
- 3.0 MHz
- Aging rate: 2×10^{-10}/day
- Thermal (-55°C to +77°C): -1.6×10^{-8}
- 30 minutes warmup time to 1×10^{-9}
- 2-1/2 – 4-1/2 watts input power

The time resolution available to the computer is one millisecond. The total clock capacity is 999 days; it should, however, be reset after the first of each year.

Required stability through one night is 2 milliseconds for AAPS. Operational use has shown that errors of much less than 1 millisecond occur during one night and that a stability of better than a millisecond per week can be maintained with careful attention to the oscillator frequency adjustments (accessible through a port in the rear of the control unit).

Controls for the clock itself are located on the control/display panel on the front of the control unit. Figure 21 shows the controls along with waveform photos used in clock alignment. The clock is simply set by putting the RUN/STOP switch into the STOP position and incrementing the upper four buttons until the display shows the proper day of the year, hour, and upcoming minute. When a time service broadcast, such as WWV, is listened to, the RUN/STOP switch may

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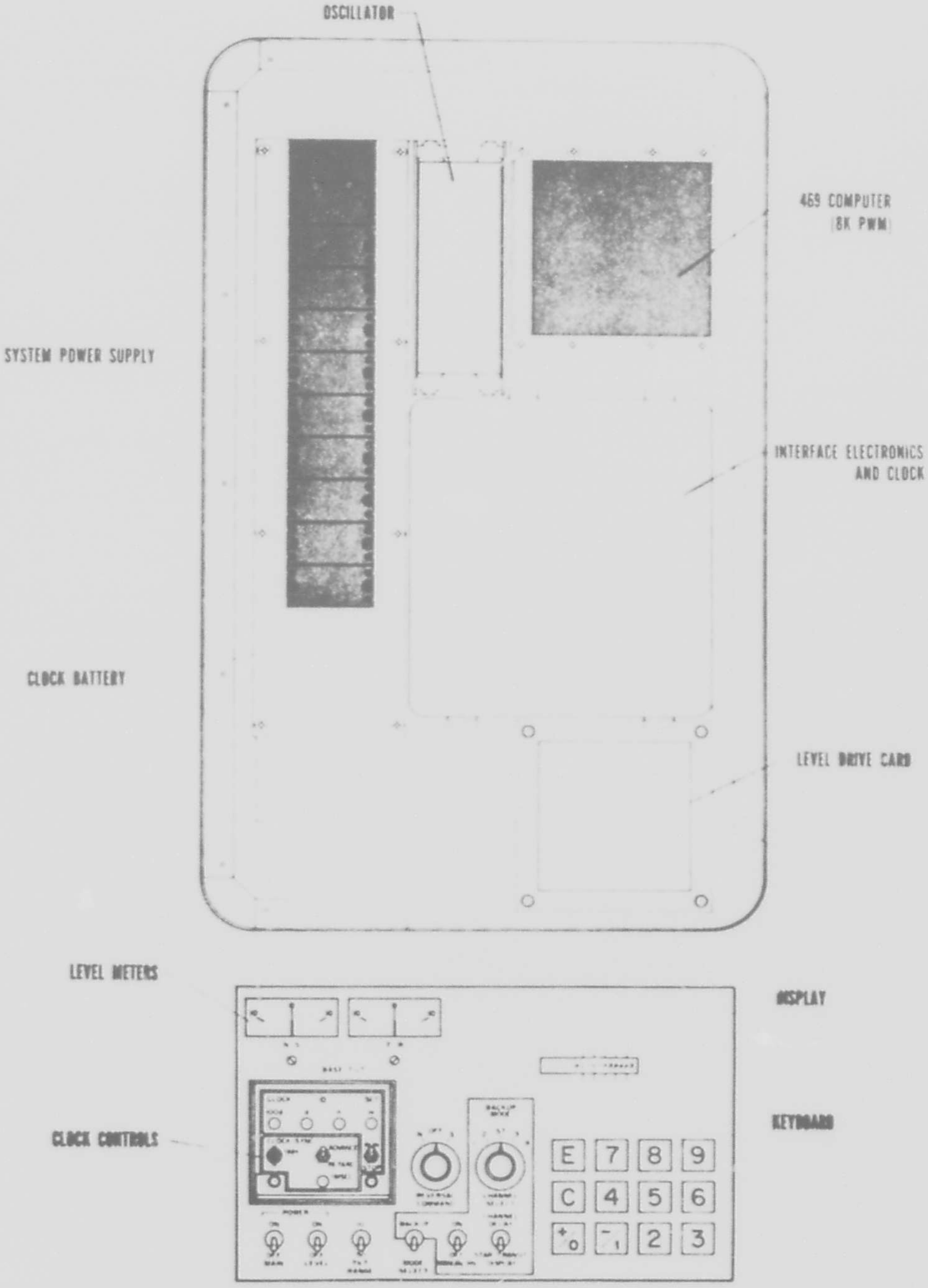


Figure 18. Control Unit Outline Drawing

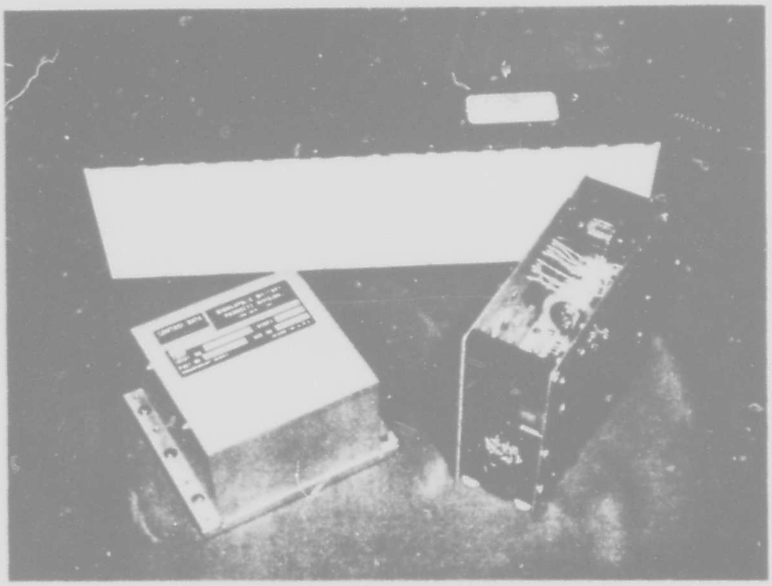


Figure 19. NICAD Clock Battery, 469 Computer, and Oscillator Assembly

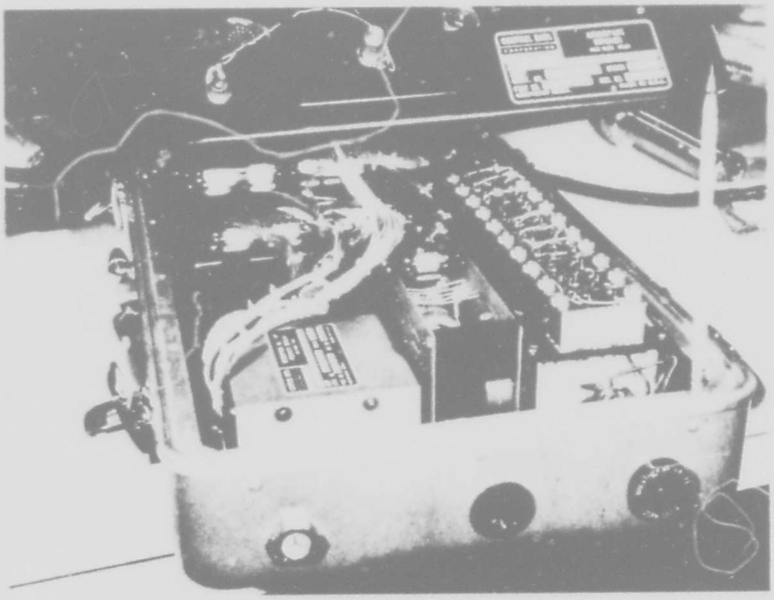
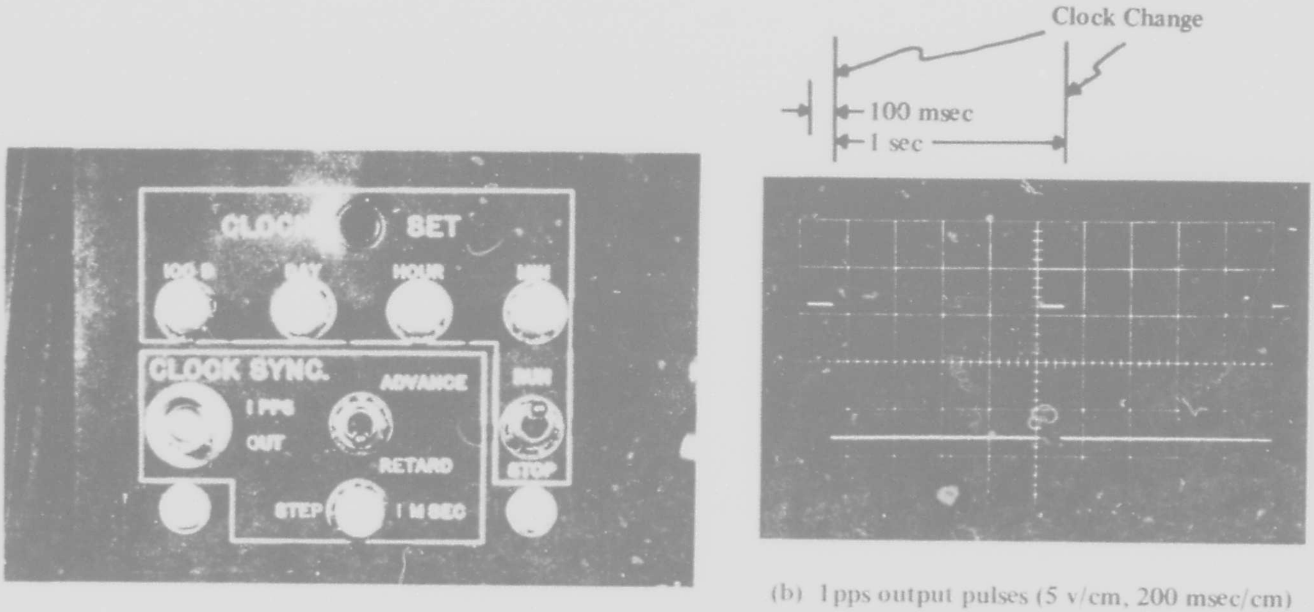


Figure 20. Control Unit, Interior View (Rear)



(b) 1pps output pulses (5 v/cm, 200 msec/cm)

(a) Clock controls on front panel of control unit

(c) Two views of WWV "Tick" reception

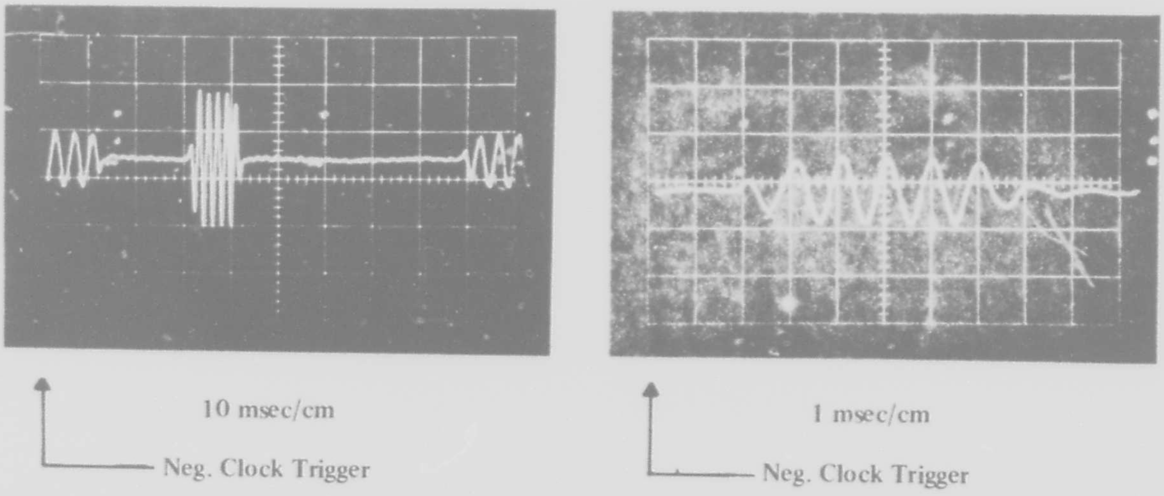


Figure 21. AAPS Clock Controls and Waveforms

be put to the RUN position as close to the audible minute start as possible.

Preparatory to field observations, synchronization is accomplished by displaying on an oscilloscope the time service broadcast triggered (negative) by the 1pps output from the BNC connector. The clock can then be slewed (advance or retard) in 1 millisecond steps to set the "tick" as close to the sweep start as possible.

B. Electronics

The main control unit electronics consists of seven multilayer boards stacked in the large black box in the approximate center of the control unit as shown in Figures 18 and 20. Figure 22 shows the stack partially unfolded.

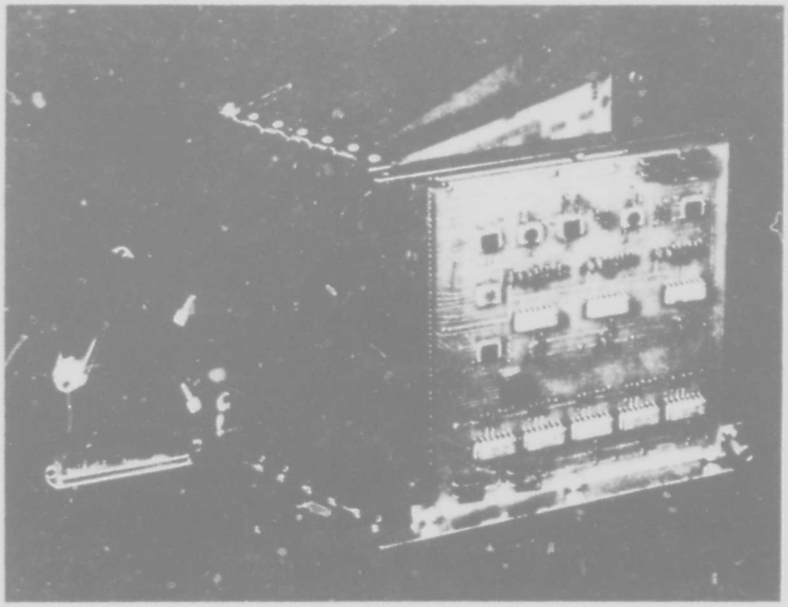


Figure 22. Control Unit Electronics Assembly

The seven boards are labeled A through G. Boards A, B, C, and D each contain four bits of the 16-bit computer input/output word. Board E contains the I/O timing and channel select circuits. It also contains the control electronics for the back-up mode of operation. The display decoder and multiplexer electronics are on board F. The final board G holds the interrupt receivers and the 469 power up/down sequencer.

C. Power Distribution

Figures 18 and 20 each show a row of small power regulators and supplies from Powercube, Inc. These are interconnected as shown in Figure 23 to convert a 24-36 volt input to the precision voltages needed for effective operation of the control unit and sensor head. The main system battery actually consists of three 7 AH, 28.8 volt units in parallel; the diodes in Figure 23 prevent these batteries from charging each other. Pin A on the input comes directly from the charger (when it is attached) to maintain the clock battery. A small meter to the rear of the display panel provides a readout of system and clock battery voltages. (This is not a very accurate indication of their charge status, since they are NICADs, but it does provide the operator with some monitoring capability.)

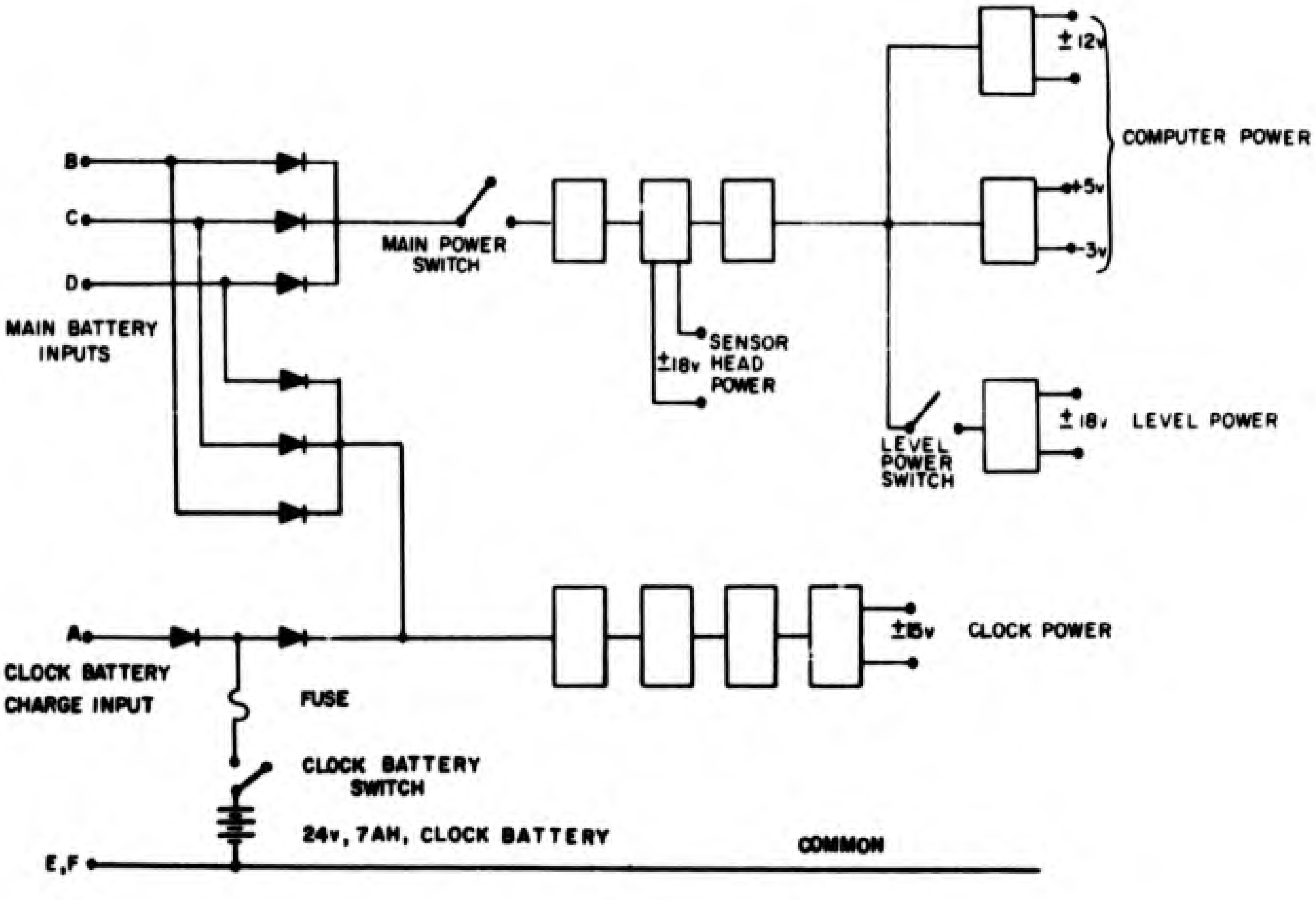


Figure 23. Power Distribution

D. Control/Display Panel

The control-display panel is shown in Figure 24 and contains all necessary information for operation of the equipment once erected. The meters in the upper left hand corner show the current (calibrated in arc seconds of base tilt) passing through the level solenoids to maintain the level sensor normal to the vertical. The area marked "Backup Mode" is used for manual recording of the transit times should computer failure occur. This has not, to date, been necessary. The sensor head is reversed from the control panel when the display indicates the end of a set.

The single row of display LED elements provides coded messages and computed data results during the monitoring of each set's operation. In addition, input information from the keyboard is displayed for operator sanction prior to entry. It is the usual practice to record nine displayed quantities at the end of each set. This permits a check on the data dumped upon return to base.

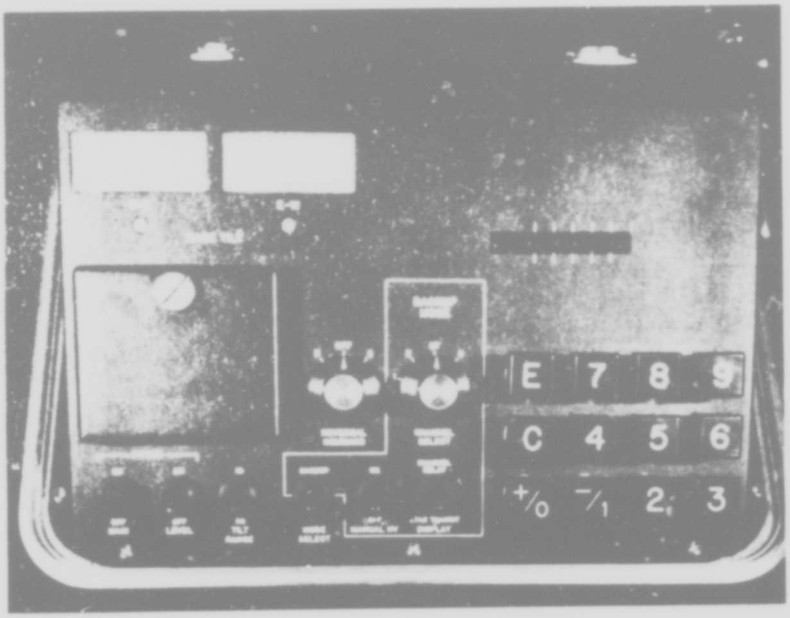


Figure 24. Control-Display Panel

V. AAPS TESTING

By progressive stages, the AAPS prototypes were brought to operational status early in 1973; preliminary and then full field testing were started soon after. During mid-1973, environmental testing was interleaved with field testing. Calibration and final acceptance testing were accomplished during the first quarter of 1974. From the beginning, field operation of the equipment was performed almost exclusively by personnel from the DMA AC/GSS (Geodetic Survey Squadron, Warren AFB, Cheyenne, Wyoming).

A. Environmental Testing

Environmental testing of the AAPS prototypes consisted of formal and informal phases. The formal phase took place between July and October of 1973 and was mostly performed at Environ Laboratories, Minneapolis, Minnesota. Informal environmental testing consisted of natural exposures during field operations: vibration and shock encountered during handling and transportation, temperature cycling, and exposure to humidity, dust, and sand. These environments, to which the system was exposed over the last 10 months of the contract, did not adversely affect the equipment.

The present section will concentrate on the formal environmental tests. The contract specifications stated the following operational environments:

Temperature:	-30°F to +120°F (-35°C to +50°C)
Humidity:	0 to 95%
Altitude:	0 to 14,000 feet (0 to 4267 meters)

The method of demonstrating that the AAPS met these environments was detailed in the "R&D Test and Acceptance Plan" submitted to and approved by AFCRL as part of the contract data requirements list. This plan used Mil Standard 810B, "Environmental Test Methods," as a guide where applicable. Table II lists the tests performed along with all pertinent supporting information and a summary of the results. The text following expands on some of the more significant events. SN/2 system was the principal object of the tests with SN/1 control unit also participating at times.

In general, both the formal and informal tests have fully demonstrated the environmental survivability of these prototypes.

1. Level Sensor Rupture

During the first formal test at Environ, a planned two-cycle temperature/humidity non-operating exposure, examination of the equipment on 12 July 1973 after one cycle revealed an excessive amount of moisture inside the sensor head. Subsequent electrical malfunctions caused return of all the equipment to Control Data where it was dismantled for closer examination. The following failures were noted:

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TABLE II. AAPS ENVIRONMENTAL TESTING (Environ Labs, Inc.)

Test	Appropriate Portion of 810B*	Dates and Equipment	Brief Description	Results
Humidity	507, Procedure I	7/11-12/73 SH/2 CU/2	In 2 hrs. raise temp. and humidity to 71°C, 95%; hold for 6 hrs.; temp. return to 25°C over next 16 hrs. at 85% humidity. Two cycles intended, only one completed because of failures.	Level sensor rupture because of high temp. rate; reticle destruction due to condensation of level sensor vapor; loss of power supply in control unit (see text).
Low Temperature (storage)	502, Procedure I	8/13-14/73 SH/2 CU/2 (no level sensor)	-54°C non-operating for 10 hours; return to -35°C for operation.	No problems upon return to ambient. Extensive condensation and puddling on equipments; no effect from this. Computer malfunction at -35°C; ok upon return to ambient.
High Temperature (storage)	501, Procedure I	9/10-11/13 SH/2 in soft-pak CU/2 covered (no level sensor)	+71°C for 10 hr., non-operating	No problems upon return to ambient.
Low Temperature (storage)	502, Procedure I	9/10-11/73 level sensor only	-54°C non-operating for 10 hours (did not exceed 10°C/hr.)	No problems upon return to ambient
High Temperature (storage) **	501, Procedure I	9/10-11/73 level sensor only	+71°C for 10 hr., non-operating (did not exceed 10°C/hr.)	No problems upon return to ambient
High Temperature (operating)	501, Procedure I, Steps 4-8	9/13-14/73 SN/2 system with level sensor	+50°C, 3 hrs.	All ok except channels 1, 2, 3 saturated. Normal upon return to ambient (see text)
Altitude	500, Procedure I except Step 2	10/4/73 SN/2 system	14,000 feet, one hr.	All ok at altitude and after return to ambient
Low Temperature (operating)	502, Procedure I except Steps 2, 3	10/9-11/73 SH/2 CU/1	-35°C, 4-1/2 hrs; -40°C, 2-1/2 hrs.	All ok at low temperatures and after return to ambient
Shock	–	10/23/73 SH/2 only	Manual handling, outside soft-pack, vertical and horizontal	30 + g recorded at various places during collisions.

* Used only as a guide. Several revisions were necessary for practical and cost considerations.

** Performed at Hughes Research Laboratories, Malibu Beach, California

(a) The level sensor mounted atop the secondary mirror had ruptured (i.e., the cup holding the electrodes and fluid had parted from the quartz reference plate), releasing the fluid and/or its vapors throughout the sensor head interior. A great deal of condensation was found throughout the optical portion (none was found in the electrical base cavity), especially on all optical surfaces.

(b) The slit reticle was "torn" in several places at its center with resultant widening of most of the radial slits in the pattern. This was probably caused by absorption of the vapor released by the level sensor and subsequent drying-out over one or two days. (This failure was not discovered until the optical system was examined on the test stand. The failure was confined to the reticle coating; the substrate and other mechanical relationships were undisturbed.)[9]

(c) The electrical failures were traced to a power supply failure in the control unit. Its mate in the other control unit had already failed previously under normal use, signifying a marginal design. A more off-the-shelf supply was procured for each control unit at lower cost but slightly reduced conversion efficiency. Condensation was also present in the control unit and traced to voids in the seal around the control/top panel. These were subsequently sealed with RTV.

The excessive amount of moisture inside the sensor head[10] did not by itself produce any damage other than tear the slit reticle as described above. The optical surfaces returned to normal after drying and have not been subsequently touched or resurfaced. Residue from the moisture was found only at the joining surfaces of various mechanical parts: between the secondary mirror and the optical structure, and between various parts of the reticle assembly.

The subsequent ability of the system (including reticle) to survive 95 per cent humidity conditions has been amply demonstrated both as a by-product of other environmental tests and as the result of field tests. Upon return to ambient from the low temperature tests, frost and condensation (on the outer portions of the equipment) certainly represented exposure to 95 per cent and higher humidities. Similarly, in the field, on nights of high humidity, condensation occasionally occurred. In none of these cases was any damage (even to the reticle) observed.[11]

The rupture of the level sensor itself was caused not by the humidity in the test room (which never exceeded 95 per cent) but by the high rate of temperature climb (25°C to 71°C in 100 minutes). That is, thermal shock produced internal stresses in the level sensor which sheared the epoxy seal between the cup and quartz flat.

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[9] The unusable reticle was replaced by a spare that had been used extensively during initial testing and alignment. The many scratches on it were carefully painted over, eliminating in the process about 5 per cent of the slit length. SN/2 operation does not seem to be degraded by this less-than-perfect reticle.

[10] Clearly in excess of the 95 per cent maximum called for in the test.

[11] Future versions of AAPS can greatly increase reticle survivability by fabricating the slit pattern from an etched chrome surface. The current prototypes use an hygroscopic material for the surface.

It was originally thought that an error had been made in the selection of the type of epoxy employed. Hughes Research Laboratory (HRL) therefore provided a replacement sensor. However, when both this sensor and the one remaining at Control Data were tested in an oven to 80° C (again a fast rise) they both ruptured (August 7, 1973). These were again replaced by HRL and separately tested at high and low temperatures with maximum rates of 10° C/hour imposed. No failures occurred.(12)

A thermal blanket consisting of alternating layers of aluminum foil and tissue paper wrapped around each sensor as it is mounted in the sensor head prevents any rapid changes in can temperature from being transmitted to the level sensor. Essentially the level sensor temperature is now slaved to that of the optical system which has large mass and hence will not change temperatures quickly even if subjected to rapid air temperature change. In addition, operating procedures specify that the sensor head not be subjected to thermal shocks in excess of 20° C. If such a change is anticipated, the sensor head should remain in its soft-pack for approximately one hour for each 5° C anticipated change.

With the addition of the thermal blanket and conservative operating procedure, no further complications have arisen with the level sensor.

2. Channel Saturation At High Temperatures

During the high-temperature (50° C) operating test, the sensor head and control unit were located inside the chamber near a port which could be opened for access to the controls. At assorted chamber temperatures the port was opened, power turned on, and various portions of equipment exercised. The level system was checked by noting whether the meters could be nulled by appropriate adjustment of the sensor head foot screws (temperature deformed the chamber and sensor head mount considerably, requiring significant foot screw motion to achieve null). The sensor head was also reversed, and several computer sequences checked out by running a mock set of "data." These "data" were generated by lifting the sensor head cover momentarily to permit light to actuate the PMTs, thereby producing "star transits."

These operating exercises were performed whenever such checkout was required as part of the environmental tests. Difficulties were encountered during the high-temperature test only when Channels 1, 2, and 3 did not produce "transits" above 40°C. Channel 4 produced "transits" until 50° C was reached, and then it too ceased to function. After return to lower temperatures, operation returned to normal. The difficulty was quickly traced to the fact that the dc outputs of the channels were positive functions of temperature and reached saturation levels (12-14 volts) in the 40° C to 50° C temperature range. These in turn were traced to the PMT dark currents which are known (approximately fourth power) functions of temperature. At room and lower temperatures, these dark currents produce no more than one or two volts of dc signal. As the temperature rises, the dark current and dc voltage levels rise, leaving progressively less room for star transits. The dc level eventually reaches saturation and no star transits are possible.

Apart from the loss of functionality, this is not a damaging factor for the PMTs. Damage can occur only when the tubes are on and a high light level is present to produce currents many times in excess of the saturation dark currents experienced at 50° C. (A dark current equivalent to +15 volts is approximately 100 microamps. Tube damage occurs only after prolonged exposure in minutes of time to currents in excess of one milliamp, ten times the saturation dark current.)

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(12) It is noted with appreciation that these level sensors were replaced at no additional expense.

Because AAPS operation occurs only at night when the sky is clear, the ambient temperature will probably never reach 50° C. A potential initial problem could result from storage of the sensor head during the day above 50° C. The sensor head requires some time to adjust to ambient temperature. During this time it is possible for the PMTs to be above 50° C, and one or more of the channels may be saturated. To date such a situation has not been encountered; testing has taken place only in the midwest, and primarily during the winter.

No specific steps have been taken to eliminate this potential problem from the prototypes. Several alternatives are available, however, should future experiences warrant their use. Most obvious is the selection of PMTs with low inherent dark currents; this is feasible though expensive. Furthermore, there is no assurance that this parameter would remain low throughout the life of the tube. Electronically, one could either reduce the overall gains of the PMTs (thereby losing some dim stars because their pulses are too low) or introduce a dc voltage subtraction between the PMT outputs and channel inputs. Either approach could be manual or automatic and each would require additional circuitry. Mechanically, of course, the PMTs could be cooled either thermoelectrically or by forced air. Both of these methods would require additional equipment, and would disturb the natural internal temperatures of the sensor head.

It is recommended, if action is required in this area, that it be done electrically and that the circuitry take account of high dc light levels (such as those caused by twilight or the moon). A PMT gain change would probably be the easiest to introduce and the approach more in line with the results of noise error analyses performed under Contract No. F19628-71-C-0036.

B. Initial Field Testing

In the first half of 1973, the field tests took place at various locations near the Control Data Minneapolis facilities and were generally restricted to data gathering. Pulse shapes from the PMTs were monitored, data rate compared to expected values, and an effort made to manually identify transits. This latter proved completely fruitless as the computer could always perform better and, of course, much more rapidly than anyone attempting manual identifications.

During this time the gains on each PMT were approximately adjusted to get detection down to 6.0 visual magnitude. This could only be determined from later (6600) data processing and so required several nights' iteration to achieve stability.

By June of 1973, the software and hardware had been sufficiently checked out to the point that it was decided to begin environmental and full field testing. The start of field testing was delayed until mid-September of 1973 due to environmental failures already described. When they did begin, both prototypes were exercised near stations BUCK (located on the Buck Hill Ski area just south of Minneapolis) and FARIBAULT (located just east of the city of Faribault about 40 miles south of Minneapolis) through the end of October. The coordinates of these stations (reduced to sea level) and the eccentric reductions from the locations of the AAPS prototypes were: (13)

BUCK: 93° 17' 02".80 west longitude
44° 43' 19".20 north latitude

Reductions:	BUCK - SN/1	BUCK - SN/2
Δλ	+0".113	0
Δφ	-0".220	-0".062

---

(13) All standard coordinate values were supplied as per contract by DMAAC/GSS.

FARIBAULT:	93° 14' 31".60	west longitude
	44° 18' 03".48	north latitude

Reductions:	FARIBAULT - SN/1	FARIBAULT - SN/2
$\Delta\lambda$	+3".793	+3".752
$\Delta\varphi$	-1".027	-1".028

These include a sea level correction of -0".064 at FARIBAULT and -0".062 at BUCK.

The characteristics of and results for each station and prototype are listed in Table III. One can see that considerably more sets were observed than ever became useful reversal pairs. This was due principally to the operational learning curve wherein all environments were tried (clouds, dew, moon, wind) to determine the range of operability.

Early in November, 1973, the prototypes were transferred to the DMAAC/GSS in Cheyenne, Wyoming. They were both operated initially until early December near station THEODORE located on the F. E. Warren Air Force Base. The established coordinates for each location were: (14)

THEODORE ECCENTRIC	104° 51' 55".17	west longitude
(SN/1)	41° 08' 05".33	north latitude
AAPS	104° 51' 55".48	west longitude
(SN/2)	41° 08' 05".10	north latitude

These are not corrected to sea level.

An examination of the data summarized in Table III shows a significant amount of scatter and a systematic southeast offset or bias (except in Wyoming). These characteristics persisted into the final period of acceptance testing and are discussed in Section V-D.

This initial phase of the testing was terminated in December to correct a serious defect in each of the sensor heads. SN/2 optics became defocused on or around December 1, 1973 as indicated by a drastic drop in data rate. Upon return to Control Data, it was discovered that the secondary mirror had slipped out of alignment. After realignment, the mirror was bonded to the structure to prevent a recurrence. (SN/1 mirror had been similarly bonded late in July.) SN/2 was returned to operation on January 11, 1974.

SN/1 system was found to have a loose reticle. This caused changes in the offsets (deviation of instrument axis from true vertical) from night to night or whenever the instrument was significantly disturbed. Because the amount of travel was limited to one or two thousandths of an inch, defocusing did not occur. The reticle was more securely attached and SN/1 system returned to operation on December 15, 1973. A recurrence of the shift (this time of the entire reticle holder) occurred over the Christmas - New Year's period and again late in March. After realignment, the holder was cemented in place. No further motions have been noticed and no reticle shift was evidenced during the acceptance data collection period (14 February 1974 through 6 March 1974).

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(14) Supplied as per contract by DMAAC/GSS.

TABLE III

RESULTS OF INITIAL AAPS TESTING

System	SN/1			SN/2		
Station	Buck	Faribault	Theodore Eccentric	Buck	Faribault	AAPS
Dates	Sept-Oct/73	Sept-Oct/73	11/10/73 through 12/10/73	Sept-Oct/73	Sept-Oct/73	11/10/73 through 11/30/73
Total observed sets	54	34	157	49	51	77
Total finally usable reversal pairs*	17	9	28	19	20	23
<u>Latitude</u>						
Obs. average	19".015	03".256	05".370	18".72	03".38	05".314
Dev. from station	−0".18	−0".22	+0".04	−0".48	−0".10	+0".21
Standard Error of one R.P. ±	0".71	1".14	0".90	0".52	0".57	0".82
<u>Longitude</u>						
Obs. average	02".371	30".219	54".492	02".39	30".91	55".295
Dev. from station	−0".43	−1".38	−0".68	−0".41	−0".69	−0".18
Standard Error of one R.P. ±	0".80	0".81	0".84	0".73	0".99	0".66

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*Two adjacent, well-converged sets per reversal pair.

C. Acceptance Testing

Upon the return of each of the sensor heads, it entered final calibration and acceptance testing. This phase generally covered the period from 15 December 1973 to 6 March 1974 and took place at stations THEODORE ECCENTRIC (SN/1) and AAPS (SN/2) on the Warren AFB, Cheyenne, Wyoming. The photo in Figure 25 shows the relative arrangement of the test area, looking approximately to the northwest. At the far right is the pier called station THEODORE. To the far left is station AAPS, showing sensor head No. 2 in a square cinderblock enclosure. This was constructed during December, 1973 as an experiment to evaluate full wind protection. In the middle of Figure 25 is station THEODORE ECCENTRIC (showing sensor head No. 1 backed by its black plywood windscreen). About 6 meters behind THEODORE ECCENTRIC is a white shelter used by the operators during the test period, containing sufficient space for both control units (with batteries), a heater, lights, shelving, and chairs. Power for lights and heat was obtained from a generator located behind a second shelter off the left edge of the photo. The shelters and generator are not required for AAPS field operation.

Each of the stations consisted of a round concrete slab 60 centimeters in diameter and 30 centimeters deep. The tribrack for SN/1 was cemented to the slab of THEODORE ECCENTRIC as the result of an azimuth stability experiment conducted in December. The tribrack on Station AAPS was left loose.

The results of this testing are shown in Figures 26 and 27 as scatter plots. Each plotted point (dot or cross) represents the result of a single pair of direct/reverse sets. The crosses represent reversal pairs which were later rejected on a Halperin basis (see the discussion in Section V-D). Those crosses or dots enclosed in circles (acceptance data, Figure 27 only) were associated with anomalous sky or weather conditions (again, refer to Section V-D).

Data recorded up to February 13 (Figure 26) was used to derive slit calibrations and offsets using the 6600 computer at Control Data Corporation in Minneapolis. A final AAPS system tape was generated in early February including these calibrations. From that point on, the 469 computers in the control units were the only source of computation (acceptance data, Figure 27).

On January 28, 1974, the outer cans of both sensor heads were replaced by versions that mounted below the level platform. This freed the platform from the immediate effects of wind gusts.

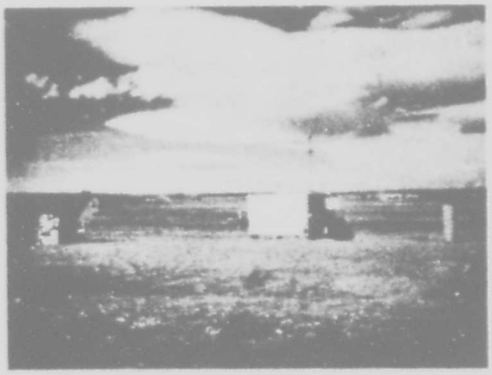

Figure 25. AAPS Test Area at Warren AFB, Cheyenne, Wyoming

D. Analysis of Data

The principal desired derivative from the data shown in Figures 26 and 27 is the extent to which the AAPS meets the accuracy and time goals set forth in the contract specifications. As with all collections of experimental data, there are several ways to proceed and criteria to apply toward obtaining this derivative; thus, an explanation of the criteria and procedures used is given in paragraphs 1) and 2) following. Paragraph 3) provides the actual data analysis while 4) examines a potential correlation with weather.

1. Statement of Accuracy Criteria

Paragraph 1 of Attachment No. 1 to the Contract Work Statement states:

> "Average observing and data reduction time (total) shall be two hours. This time may be relaxed . . . but shall not exceed six hours." And, in paragraph 6: "Each system shall be . . . capable of producing astronomic latitude and longitude accurate to ± 0.3 arc seconds, one sigma, at latitude 45°."(15)

It is well known that errors are both systematic and random. Systematic errors are presumably characteristic of the equipment (bias) and, once determined, can be applied to the data as corrections. The remaining error terms are thus random and it is these components to which the ± 0.3 arc second one-sigma criterion applies. Hence, from an accuracy standpoint, we are interested in "precision" or in the scatter of the data about its average. From a usage standpoint, however, one also needs the bias terms in order to compute, from the measured data, the true station coordinates.

Both bias and scatter will have to be computed in the AAPS data analysis. The bias thus determined is, of course, uncertain: hence, a characterization of the overall AAPS accuracy must include scatter (standard deviation about the average) plus uncertainty in bias.

2. Halperin Rejection Procedure

In what follows, individual data points (reversal pairs or RPs) will be rejected based upon a scheme developed by Halperin.

The Halperin scheme is discussed in reference [16]. Table III.1 of that reference is reproduced here as Table IV. The table essentially says that given, for example, 13 observations and an a priori knowledge that the standard deviation of each observation is 1.000, then any observation deviating from the group mean by more than ± 2.769 is rejected as a "mistake." That is, there is less than a 5 percent probability that the rejected measurement is valid and also a greater than 95 percent probability that each of the "kept" measurements is valid. Hence, this scheme presents a criteria for rejecting mistakes provided that sufficient experience has been accumulated to specify the expected or a priori standard deviation.

The standard error selected for the AAPS data is ± 0″.7 in each coordinate. This selection is somewhat subjective but supported as follows: Table III, summarizing the results of observations in Minnesota and initial observations in Wyoming, shows an average standard error of about 0″.8.

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(15) Modification No. P00003, 25 April 1973. These specifications were treated as design goals to be achieved if possible within the available resources. Since the calibration and acceptance measurements were made at latitude 41°, a slightly more stringent longitude requirement should be applied (± 0″.28) if it is interpreted that a fixed linear error criteria is to be applicable over the whole globe.

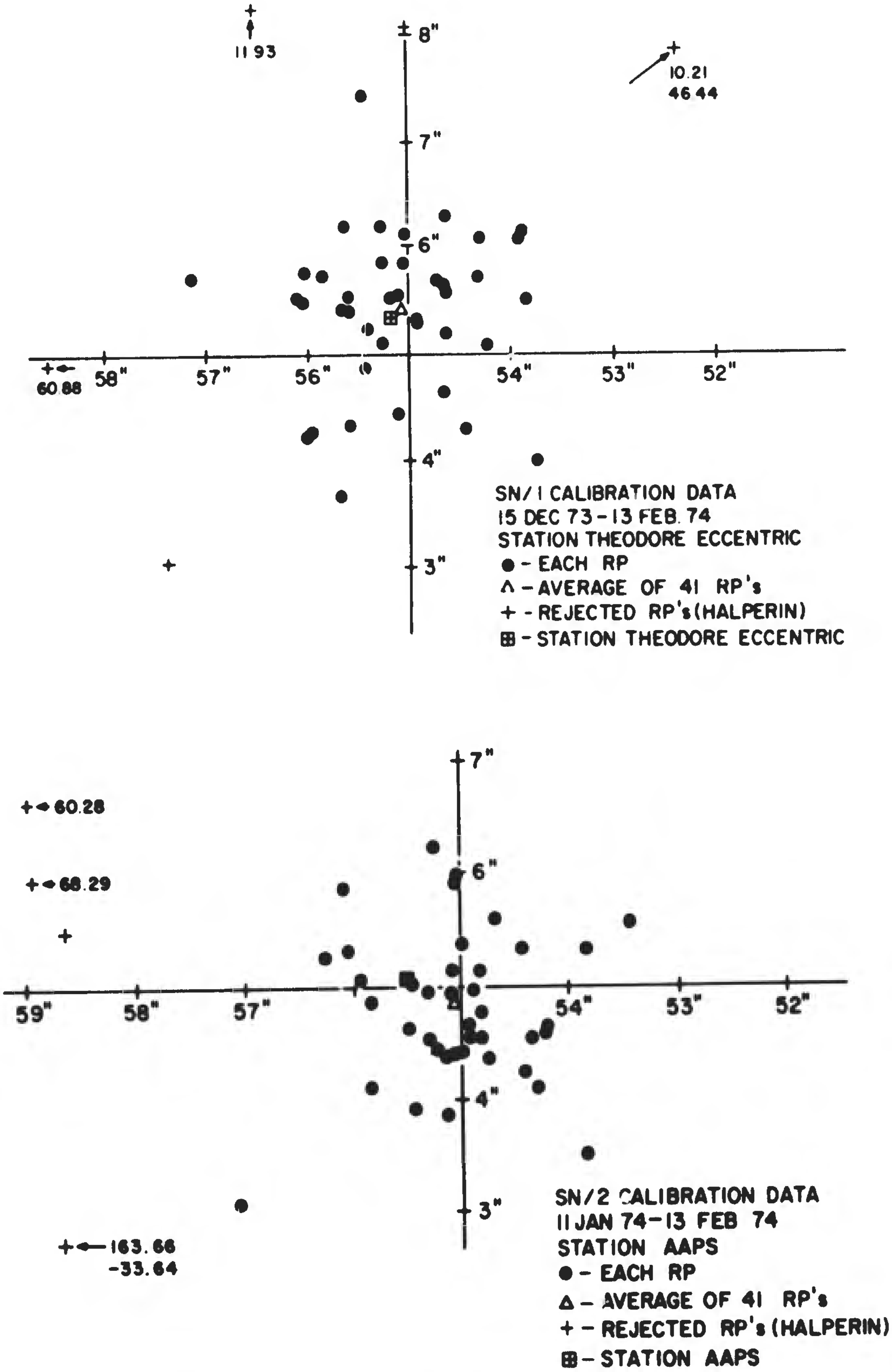

Figure 26. Calibration Test Results: December 15, 1973 through February 13, 1974

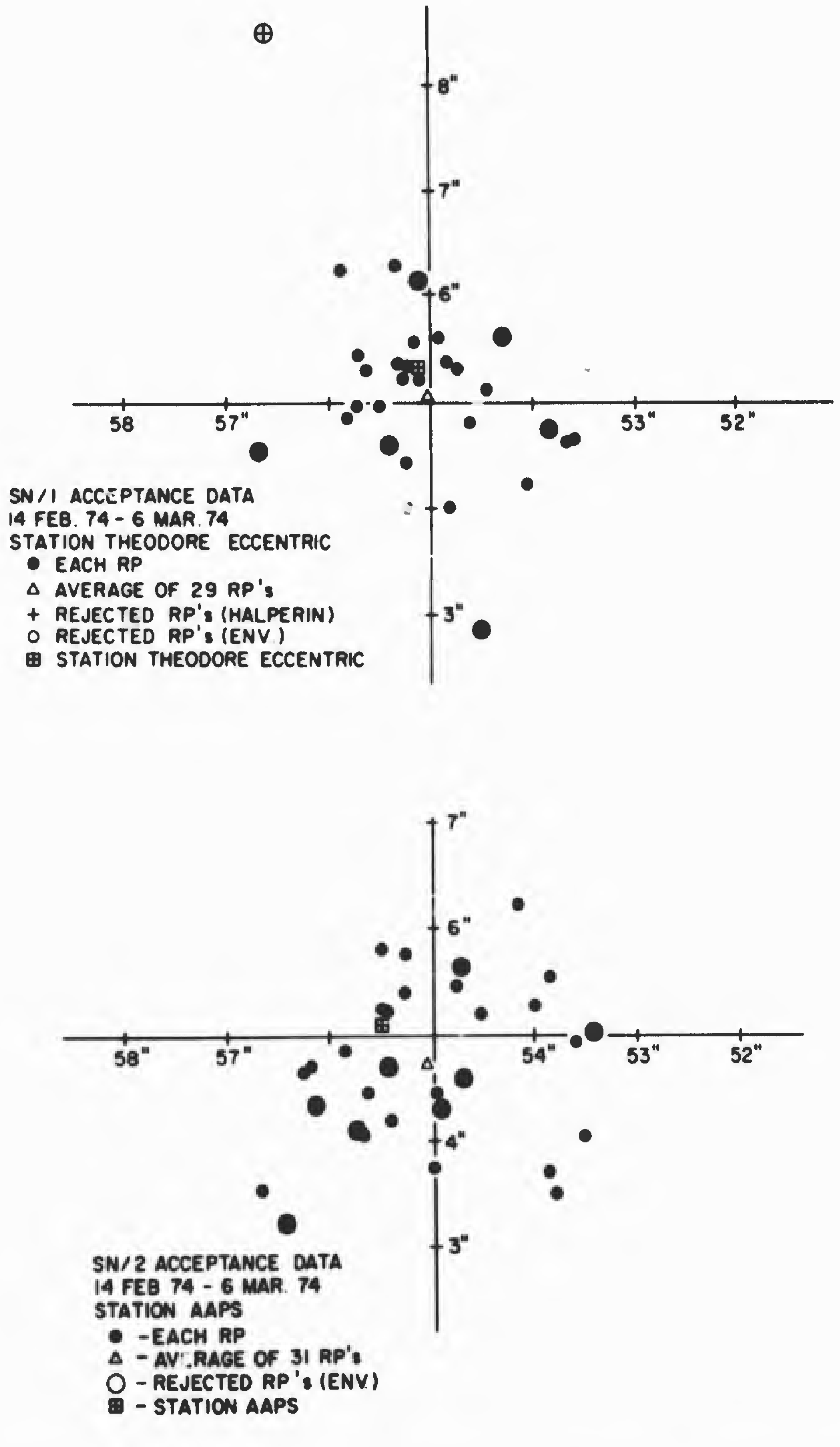

Figure 27. Acceptance Test Results: February 14, 1974 through March 6, 1974

TABLE IV

HALPERIN MAXIMUM ABSOLUTE DEVIATES*

(Test Level .050, Table III.1 of Reference [16])

Number of Observations	Maximum Deviate	Number of Observations	Maximum Deviate
3	1.949	22	2.974
4	2.156	23	2.990
5	2.297	24	3.005
6	2.401	25	3.020
7	2.483	26	3.034
8	2.550	27	3.047
9	2.607	28	3.060
10	2.655	29	3.072
11	2.698	30	3.083
12	2.735	31	3.095
13	2.769	32	3.105
14	2.800	33	3.116
15	2.828	34	3.126
16	2.853	35	3.135
17	2.877	36	3.144
18	2.899	37	3.154
19	2.920	38	3.163
20	2.939	39	3.171
21	2.957	40	3.179

*Using a trial and error method, it was determined that this data could be fit above eight observations within ± .01 by the expression:

$$y = 0.604 \cdot \sqrt{x} - 6 \cdot \frac{(x - 25)}{(x + 100)} - 2 \cdot 10^{-4} (x - 30)^2 + 0.01$$

where x is the number of observations and y the maximum absolute deviate. A simpler form was utilized in the 469 to reject individual transits within a set solution:

$$v = 0.01x + 2.78.$$

This fits the above data to within ± .1 for 15 or more observations. It is always conservative in the sense that it will retain more observations in a solution than will the table.

This is probably high due to the inclusion of all data with no rejections. The results (shown in Table V) of applying the ± 0″7 level yields about ± 0″.7 standard errors.(16) The use of ± 0.70, then, is approximately representative of the true performance of the prototypes in their state of development and usage at the time this data was obtained. (One could have argued for the determination of separate criteria for latitude and longitude and also for each of the two systems. It was not felt that the amount of data was sufficient to perform this with confidence.)

3. The Data Analyzed

Table V summarizes all of the data gathered during the calibration and acceptance periods at Cheyenne. (The individual RPs have already been plotted in Figures 26 and 27.) Comparing SN/1 with SN/2 and calibration with acceptance reveals several conflicting conclusions. On the one hand, the standard deviation of one RP is just over 0″.7 in each coordinate. This seems con-

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(16) Actual average is ± 0″.75. If the SN/2 acceptance longitude is left out (arguing contamination from an unknown source), then the result is 0″.72.

sistent throughout the data except for SN/2 acceptance longitude (see the paragraph following). On the other hand, the deviations from station (or offsets or biases) are different for the two systems and also differ for SN/1 between the calibration and acceptance periods, though for SN/2 there is consistency between the two periods. It is not apparent why these biases should be present. Had there been consistency, they could have been treated as instrument constants and applied as corrections; the lack of consistency, however, raises the possibility of an as yet unknown systematic error.

The large scatter in the case of SN/2 acceptance longitude is due to excessively east (about 1.5 arc seconds) longitudes on the first two nights of observation (seven RPs).(17) If it is argued that a large error source contaminated that data, then a recomputation of the SN/2 acceptance data with these two nights left out gives the values shown in parentheses in Table V. It is seen that the standard deviations are now consistent across the whole table but the biases are no longer consistent between calibration and acceptance for either instrument.

The biases thus do not appear to possess sufficient consistency to be classified as instrument constants. However, judgment should be reserved until more observations are available from other stations and seasons.(18)

As just noted, the random error is consistent at slightly more than 0″.7 for each RP. To achieve the contract specification accuracy requirement of 0″.3, then, requires six RPs or more, assuming the applicability of a $\sqrt{N}$ decrease. Combining the acceptance data in groups of (consecutive) six RPs each (using Halperin rejection) results in Figure 28, which is plotted using the true station as origin. In that figure we see that SN/1 achieves two of the four points within ±0″.3 of the grand average in longitude and three out of four in latitude.(19) (About the station, the result is three out of five in each coordinate.) Eliminating as before the first two days of data from SN/2 produces the open indicators. These show three out of four in longitude and two out of four in latitude (within ±0″.3 of the new grand average). Neither system, then, meets the 68 percent (one sigma) criteria for both coordinates, though each system has one coordinate at 75 percent. The actual standard deviations of the six RP averages about the grand averages, as computed from the data, are:

	Latitude	Longitude
SN/1	±0″.18	±0″.44
SN/2	±0.42	±0.64
SN/2 (first two days deleted)	±0.40	±0.25

The average scatter in each coordinate could be characterized by ±0″.30 or ±0″.29 in latitude and ±0″.54 or ±0″.35 in longitude depending on whether the first two days of SN/2 are retained or deleted.

The length of time taken to accumulate six RPs is determined from Table V as 1.59 x 6 = 9.5 hours for SN/1 and 1.32 x 6 = 7.9 hours for SN/2. The individual six RP times ranged from a low of 7 to a high of 10 hours, both of which exceed the 6 hours contract specification.

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(17) These nights were separated by one night during which no observations were made. Not all the RPs in each observation night were low.

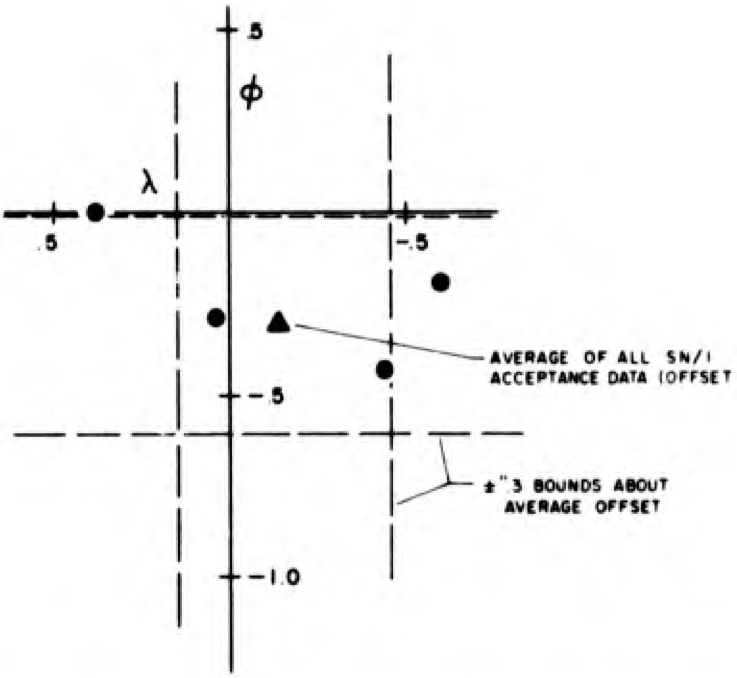
(18) Preliminary reductions of the Washington, D.C. and Richmond, Florida observations reveal biases or offsets which continue to be inconsistent between instruments and between locations. It may be concluded that these offsets are not instrument constants but are systematic errors caused by an as yet unknown agent (or agents). They are, however, not completely random in the sense of being scattered equally on either side of the correct value. Thus it is partially valid to introduce an instrument correction, but this correction is itself uncertain.

(19) The grand averages are determined using all RPs with Halperin rejection (29 in the case of SN/1 and 31 (24) for SN/2). Deviations from the station (Tables V and VI) are determined from these grand averages. All data have been corrected for final pole and UTC values. SN/2, however, shows two out of five in longitude and one out of five in latitude.

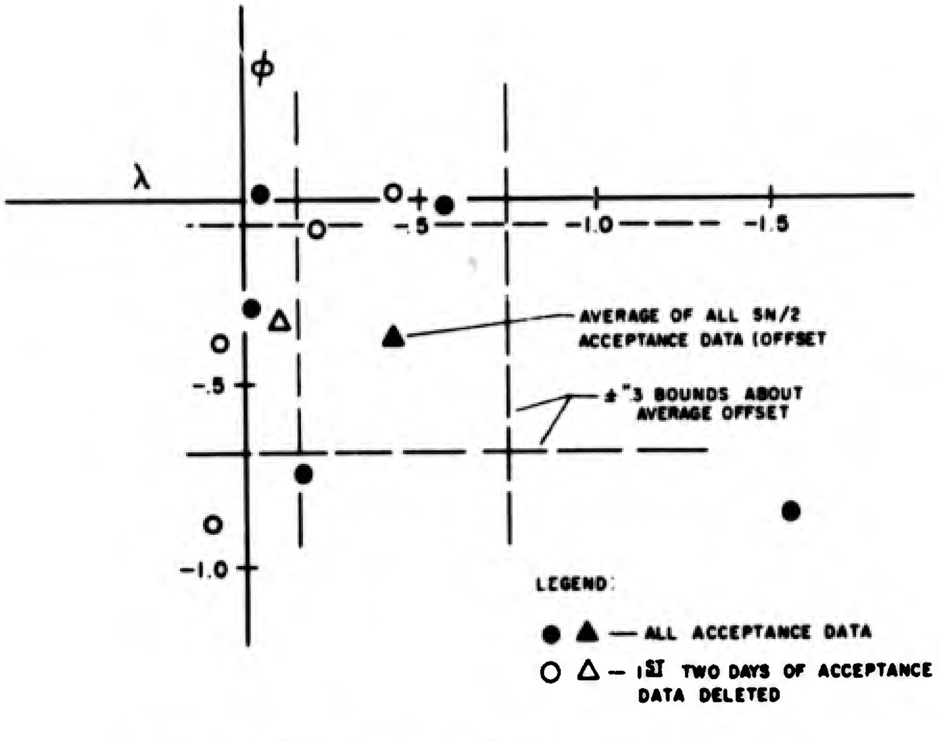
TABLE V
BULK ANALYSIS OF CALIBRATION AND ACCEPTANCE DATA

	SN/1				SN/2			
	Calibration		Acceptance		Calibration		Acceptance	
Reversal Pairs: Original Rejected*	46 5		30 1		45 4		31 (24) 0 (0)	
Averages per accepted RP			49.6 transits 1.59 hours				50.6 transits 1.32 hours	
Projected monthly RP production rate	21		42		38		46	
	Lat.	Long.	Lat.	Long.	Lat.	Long.	Lat.	Long.
Final average**	05".38	55".14	05".02	55".03	04".81	55".05	04".71 (4.77)	55".05 (55.36)
Deviation from Station***	+0".05	-0".03	-0".31	-0".14	-0".29	-0".43	-0".39 (-0".33)	-0".43 (-0".12)
1_σ scatter about average	± 0".75	±0".71	±0".72	±0".70	±0".66	±0".70	±0".76 (±0".71)	±0".92 (±0".73)

* Indicated by crosses in Figures 26 and 27
** Indicated by Δs in Figures 26 and 27
*** In the sense: AAPS – Station



(a) SN/1, Six RP Groupings Plotted Relative to Station THEODORE ECCENTRIC



(b) SN/2, Six RP Groupings Plotted Relative to Station AAPS

Figure 28. Acceptance Test Results – Average of Six Reversal Pairs

In summary, the combination of accuracy and time requirements (0".3 in 6 hours) is not satisfied by either of the two AAPS prototypes in their physical and operation status existent in early 1974. One could conservatively characterize the overall one sigma AAPS performance as being composed of:

(a) 0".32 scatter after averaging six RPs, and

(b) 0".15 uncertainty in the bias term used to correct the six RP average (0".72 / $\sqrt{24}$). Hence, a total error characterization is

$$\sqrt{(0.32)^2 + (0.15)^2} = 0''.35$$

using a six RP measurement period.

The "production rate" entry in Table III indicates that about seven stations (six RPs/station) per month accurate to 0".35 or better can be established for SN/2. The number for SN/1 is about five stations per month. This amounts to an annual production rate of 60-80 stations.(20)

4. The Influence of Weather

During examination of the data, the contract monitor noticed an apparent correlation between certain sky and moon conditions and large residuals in the data. A thorough analysis of the acceptance data records (records for the calibration data were not as detailed and hence are not discussed here) showed that, in many cases, data taken in the presence of haze and/or clouds coupled with about a 50 percent or more illuminated moon possessed large residuals, especially in the case of SN/1 system. In addition, high gusty winds also produced large residuals.

Reversal pairs measured during these "bad weather" times are shown circled in the plots of Figure 27. For SN/1, it is seen that weather can be blamed for most of the data scattered far from the station. All RPs within about 0".5 of the station were taken under "good weather" conditions. The SN/2 plot, however, contradicts this conclusion since circled points are scattered somewhat uniformly throughout the "good" points.

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(20) As an additional operational note, about two-thirds of the nights during the Cheyenne test period were sufficiently clear to obtain at least one reversal pair. About 2.1 (SN/1) to 2.8 (SN/2) RPs per clear night were obtained as an average. The maximum was five RPs on one night (SN/1). The production rate projected from the Washington, D.C. data is also about 60 stations per year. From the Richmond data, however, a rate of 100 stations for SN/1 to 180 stations for SN/2 resulted.

Numerically, Table VI shows the effect of rejecting all "bad weather" RPs. This merely verifies the visual picture of Figure 27. The residuals are decreased for SN/1 but unaffected for SN/2 (as compared with Table V). The annual production rate drops to about 60 stations for each system (six RPs per station). Combining the RPs in groups of six only gives three stations for SN/1 and three (two) for SN/2. Two of the three for SN/1 are within ± 0.3 of the average while only one is so located for SN/2. The weather-rejection technique is thus not universally supported but does seem to possess some validity.

TABLE VI

ANALYSIS OF ACCEPTANCE DATA (RPS REJECTED ON WEATHER)

	SN/1		SN/2*	
Reversal Pairs:				
Original	30		31 (24)	
Weather rejected	7		8 (7)	
Halperin rejected	0		0 (0)	
Averages per Accepted RP	49.8 transits 1.41 hours		51.3 transits 1.15 hours	
Projected monthly RP production rate	33		33	
	Lat.	Long.	Lat.	Long.
Final average	05".08	55".04	04".79 (4".91)	54".99 (55".32)
Deviation from station	-0".25	-0".13	-0".31 (-0".19)	-0".49 (-0".16)
1σ scatter about average	±0".59	±0".63	±0".78 (±0.68)	±0".92 (±0.76)

*Parenthetical values indicate results with first two days of data deleted.

VI. CONCLUSIONS AND RECOMMENDATIONS

Perhaps the most significant and far-reaching result to come out of the AAPS development over the past few years has been the introduction of a new approach to astro-geodetic instrumentation. The conclusions which can be derived from the contract work reported on here are as follows:

(a) The AAPS equipment has conclusively demonstrated its ease of handling and automatic measurement and computation features.

(b) The AAPS equipment has demonstrated survivability and operability under a wide range of environmental conditions, including: operation from -40°C to +40°C (-40°F to +100°F), shock to 30g vibration encountered in normal handling and transit, external humidity to condensation (100 percent), and altitude to 4267 meters (14,000 feet).

(c) Accuracy performance is characterized as follows: Six RPs are averaged and corrected for bias. Each resulting latitude and longitude component scatters about the reference station coordinate by ± 0.35 arc second, one sigma. To obtain the six RPs requires between seven and ten hours of site observations.

(d) Analyses of various AAPS subsystems demonstrates that the star detection, signal processing, and data reduction chain is operating to an accuracy which exceeds the design goal. An as yet unknown error source is affecting each instrument as a unit.

In view of the significant contribution AAPS can make to astrogeodesy and the considerable advancements made to date, it is recommended that further developments and testing be undertaken. Specifically, it is recommended that:

(a) Operation and usability aspects be improved by investigating potential software changes and also by familiarizing the users with the software through a formal training course.

(b) Maintenance aspects be improved by: providing spare components, conducting a maintenance training course, and investigating alterations of the hardware to permit easier maintenance and adjustment.

(c) A deliberate search for error sources be conducted, specifically: thermal gradients within the level system, star catalog variations, sky background gradients, and filter delay calibration technique.

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VII. ACKNOWLEDGEMENTS

Major John C. Herring, USAF, was the initial AFCRL contract technical monitor. Upon his reassignment during July of 1973, Mr. Mahlon S. Hunt, AFCRL/LWG, became the contract technical monitor.

At Control Data, the personnel assigned to this program and their responsibilities were as follows: Paul Nurkkala, filter fabrication and system test; Darrol Herold, sensor head mechanical design (upper portion) and HRL interface; John Berk, control unit electrical design; Marvin Sandgren, sensor head base mechanical design; Charles Eumerian, control unit mechanical design; Harlan Paetznick, 6600 system software; Ray Rigles and Larry Kane, 469 system software; Louis Wilson, star catalog; Dave Koch, mechanical technician; and Dick Hanson and Ken Golden, electrical technicians.

DMAAC/GSS personnel responsible for providing resurvey data on stations BUCK and FARIBAULT in Minnesota and who were also responsible for accumulating field data both at these stations and at stations THEODORE ECCENTRIC and AAPS in Wyoming were: Capt. John D. Rushing, Sgt. Tracy W. Johnson, and A1C Edward J. Lopes.

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