

THE AUTOMATED ASTRONOMIC POSITIONING SYSTEM (AAPS)

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ABSTRACT

The Control Data Corporation, Minneapolis, Minnesota, under contract to Air Force Cambridge Research Laboratories, L. G. Hanscom Field, Bedford, Massachusetts, has recently delivered two prototype systems of The Automated Astronomic Positioning System (AAPS) to DMA. The AAPS was developed to automate and expedite the determination of astronomic positions (latitude and longitude). This equipment is capable of defining astronomic positions to an accuracy of $\sigma = 0.3$ in each component within a two hour span of stellar observations which are acquired automatically. The basic concept acquires observations by timing stellar images as they cross a series of slits, comparing these observations to a stored star catalogue, and automatically deducing position and accuracy by least squares using pre-set convergence criteria. An exhaustive DMA operational test program has been initiated to evaluate the capabilities of the AAPS in a variety of environments (both climatic and positional). Status of the operational test is discussed and participation is invited.

BACKGROUND THEORY AND TECHNICAL DESCRIPTION

The idea of automating astronomic position determination has been actively pursued for at least two decades. To date, however, no one has come up with a portable field instrument. Current first order observing instruments such as the Wild T-4 and Kern DKM 3AX do not readily lend themselves to automation without serious redesign and the probability of performance degradation.

Following a series of feasibility studies supported by Air Force Cambridge Research Laboratories (AFCRL), the Air Force directed AFCRL to initiate development and design studies in 1970 for an Automatic Astronomic Positioning System (AAPS). As a result, a development and fabrication contract for two (2) prototype AAPS is awarded to Control Data Corporation.

The current instrument represents a radical departure from past astronomic positioning instruments. It is based on the timing of the transits of star images past slits in a focal surface reticle. While developed independently during the 1960's at Control Data Corporation, such a detection technique had been pioneered in the 20's and 30's by Pavlov (1946) in Russia. He employed such measurements in the accurate determination of time at a fixed observatory. Since

then, Liang Tseng-Yung (1963), Moreau (1966), and Abby (1969) have separately experimented with field versions, usually theodolites with photoelectric attachments. At the present time, Hog in Germany is developing an interesting meridian transit instrument based on the same principle.

The present instrument system is the first which combines a truly automatic field instrument with a portable computer. The AAPS was designed with the following specifications in mind:

- a. The portable-field equipment should not exceed 45 kilograms in total weight. Any individual portion of the system should not exceed 25 kilograms.
- b. The system should provide an astronomic position within a two hour observing and computing period.
- c. The accuracy of astronomic latitude and longitude should be within ± 0.3 arc sec, one sigma, at 45° latitude.
- d. The system should contain its own internal battery capable of supplying power for ten hours of continuous operation.

The AAPS was conceived to be a totally automated system. This quantum jump in relation to present systems was deemed necessary to provide greater efficiency in operations and to eliminate operator mistakes and errors caused by the "personal equation". In addition, increased data rate and on-site data reduction holds out the promise of rapid, reliable, and accurate site surveys.

The theory involved in the AAPS is based on a star detection concept (Fig. 1) where the transit of a star passes through a lens, whose optical axis is vertically oriented, onto the slits of a reticle. This star transit is detected photoelectronically as its image passes across the slits of the reticle.

The constraint for one such transit is shown in Figure 2. A spherical triangle equation is used in the AAPS computation both to (1) predict transit times for an assumed position in order to identify actual transits, and (2) to solve for the true position from the identified and measured transits.

For the purpose of prediction, the equation is rewritten as shown here. This equation is then solved using the negative portion of the quadratic equation.

The transit time for the given slit and star is determined by Equation 3 (Fig. 3).

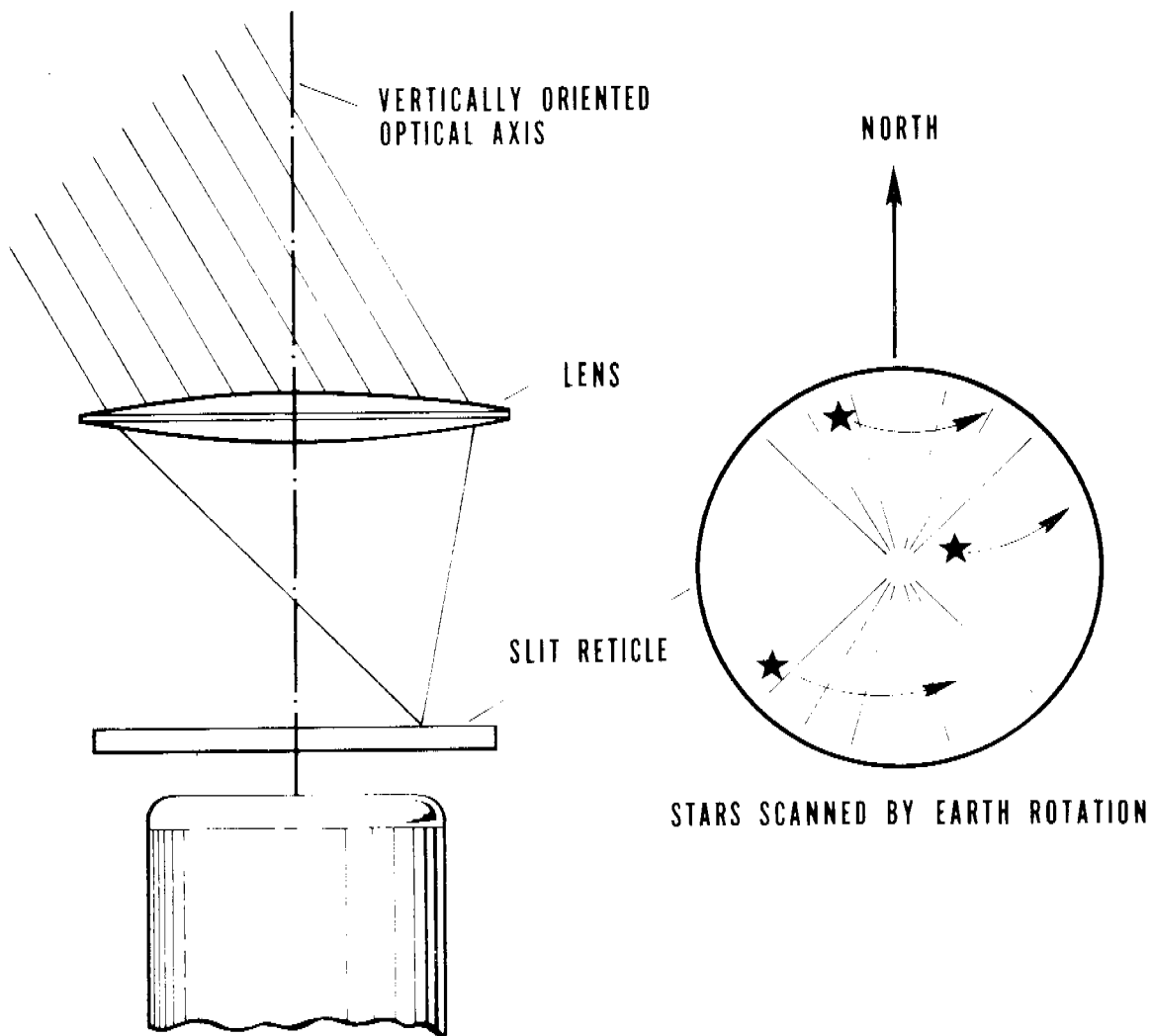


Figure 1

The basic identification process then becomes one of matching a measured transit with a predicted transit (for a given slit). Since small errors in azimuth orientation create large errors in the transit time, a preliminary course matching procedure is followed to produce a more accurate estimate of azimuth.

Upon identification of the transits, the assembly of the equations are solved for astronomic position in a least squares sense using an iterative technique.

After the first solution has been obtained, measurement residuals are calculated and the standard deviation found. Some multiple of the standard deviation is then used as a rejection limit and all observations with residuals exceeding this limit are momentarily deleted from the measurement set and the computation is repeated.

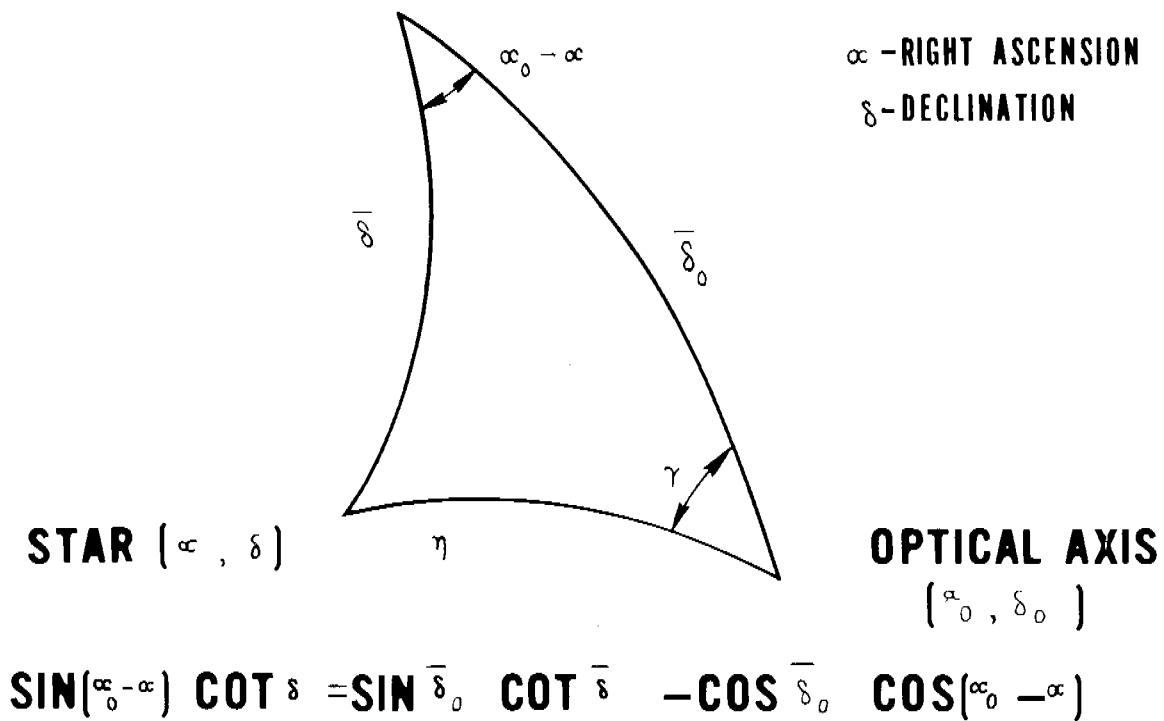


Figure 2. AAPS Geometry

$$(1) \quad \alpha_0 = \alpha_z + \dot{\alpha} t$$

$$(2) \quad \text{SIN} [\alpha_0 - \alpha] = \frac{-BC + A \sqrt{A^2 + B^2 - C^2}}{A + B} = X$$

$$(3) \quad t = \frac{\alpha_z + \text{SIN}^{-1} X}{\dot{\alpha}}$$

Figure 3

As the computed solution converges towards its final value, the predicted transits approach the measured ones. This permits the rejection limits to be successively reduced, thereby achieving finer resolution in the identification process and perhaps admitting previously ambiguous data to the solution.

How do we design an instrument which will use the theory to the best possible advantage? In addition, the position must be computed in real time excluding the effects of polar motion and any other unknown time off-set errors. Using the constraints previously discussed, the AAPS has evolved into a system containing two units, the sensor head, which weighs about 25 kilograms, and the control unit, which weighs about 15 kilograms. (Fig. 4)

The sensor head is a single package composed of: optical system, four photomultiplier detectors, filter and detection electronics, level control system, and reversal mechanism. (Fig. 5)

The design of the optical system was considered to be the most important, since analysis showed that it had to maintain an image size under 10 arc sec over a 23° field of view to meet the system accuracy and data rate requirements. That such a system has to operate over a temperature range of -35°C to +50°C without the luxury of field focusing posed an additional major problem. The optical concept chosen was a two-mirror concentric configuration. Concentric systems have all, or most, of their element radii concentric to a common point at the aperture. This means inherent freedom from astigmatism, coma, and distortion. Spherical aberration is minimized through the appropriate placement of stops and the ratio of primary to secondary mirror radii.

Optimum optical characteristics were derived from many computer simulation runs using different fields of view, focal lengths, number of slits, number of photo-multipliers, and star patterns over a 140° latitude range (70°S to 70°N). The final criteria were: sensor physical size, star transit data rate, and accuracy. The resulting optical characteristics are now shown. (Fig. 6)

The optical system is fairly unique. Thermal stability of the optical dimensions is achieved by employing a unique structural design. (Fig. 7) All structural members as well as the primary and secondary mirrors are fabricated from CER-VIT, a glass ceramic substance whose temperature coefficient is an order of magnitude smaller than that of INVAR. After considering a number of different configurations for the mirror supports, it was decided that a single major piece presented the fewest overall problems.

The AAPS level system keeps the sensor in the vertical and the top portion of the secondary mirror contains a level sensor. (Fig. 8) The base of the optical system rests on the releveing drivers. The electronics for the level system is



Figure 4

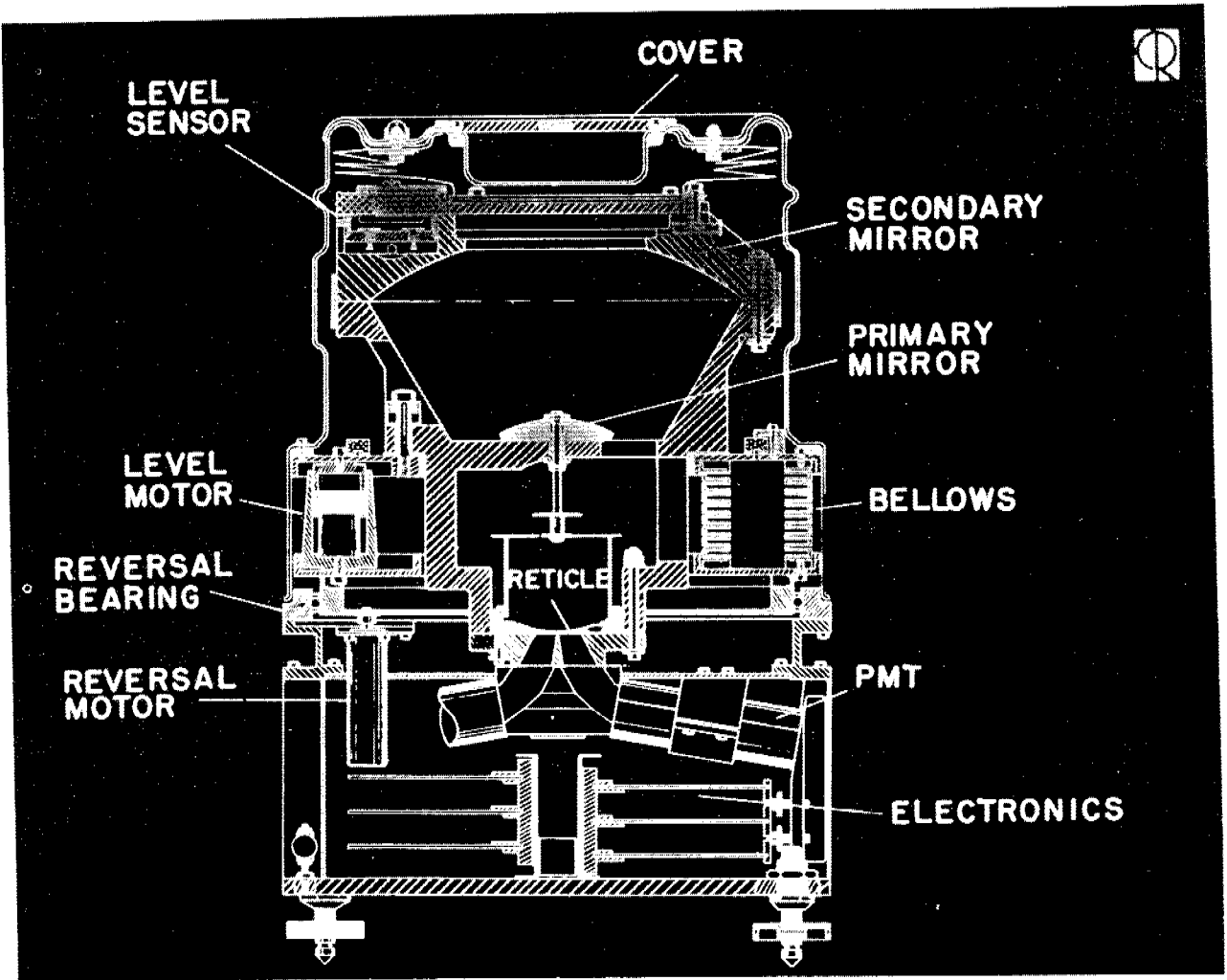


Figure 5

(1) FIELD OF VIEW :	23°
(2) FOCAL LENGTH :	5.58 CM
(3) APERTURE DIAMETER :	3 CM (CLEAR)
(4) OPTICS :	f/1.6
(5) IMAGE DIAMETER :	10 ARC SECONDS

Figure 6. Optical System Characteristics

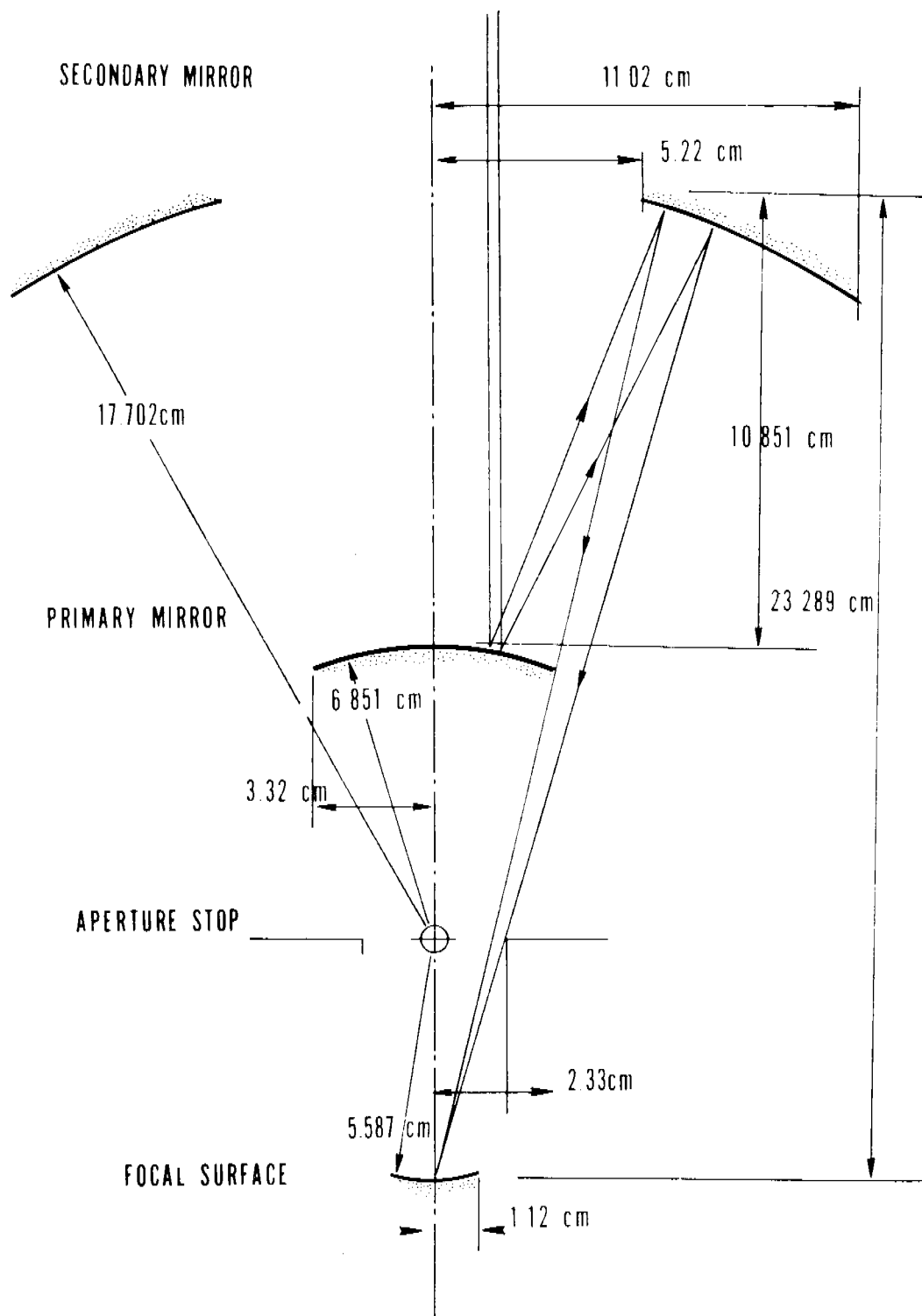
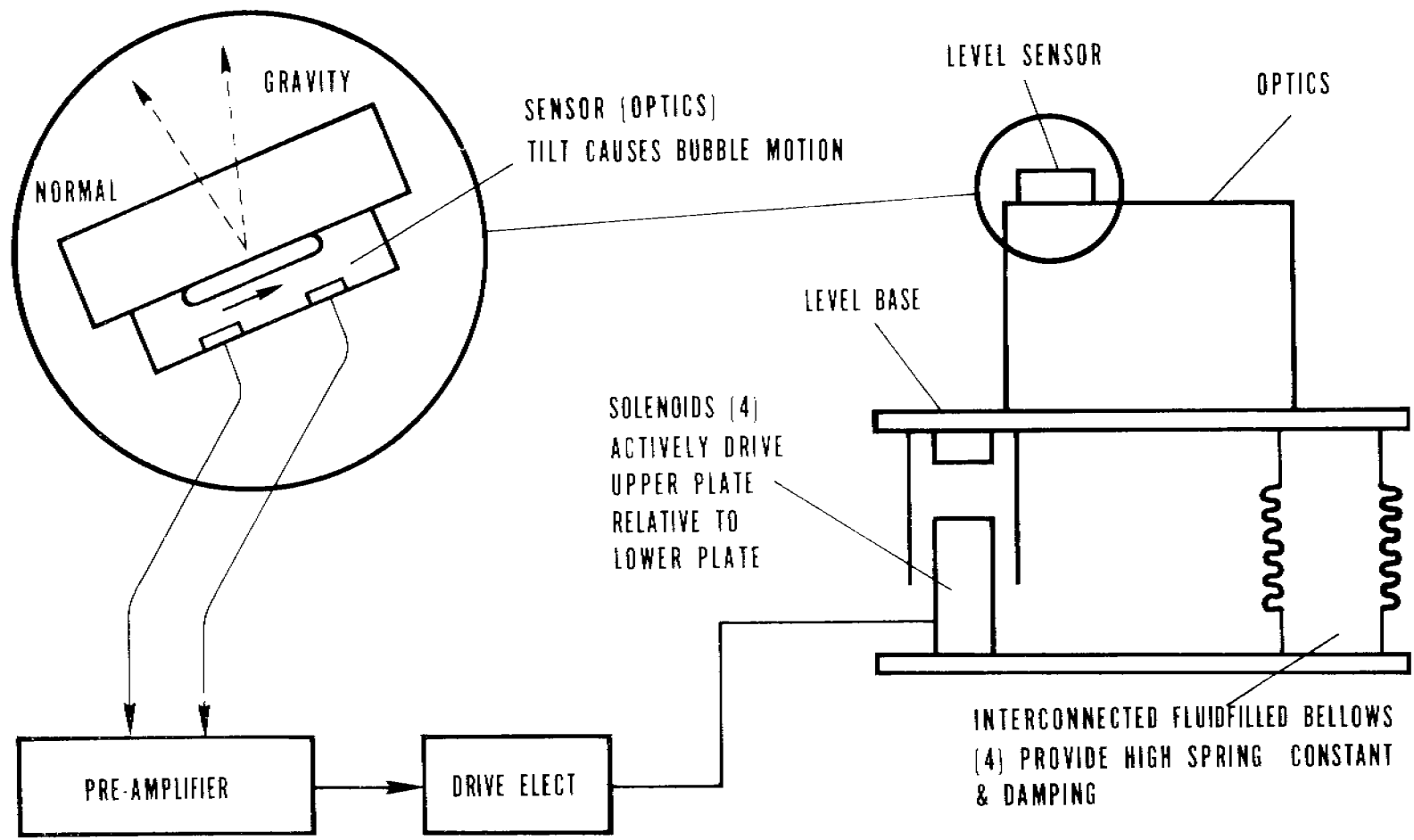


Figure 7



LEVEL SUBSYSTEM

Figure 8

located in the control unit. The level system will maintain the concentric mirror optical system within ± 0.1 arc sec of the vertical. Initially, the sensor head must be leveled by hand to within 50 arc sec to ensure proper operation of the level system in the automatic mode.

When a stellar image crosses a slit, a signal is generated by one of the photo-multiplier tubes. This analog signal is filtered, differentiated, and sent through a zero-crossing detector. The output of the zero-crossing detector is a logic level signal which is sent to the control unit and interrupts the computer. The computer then reads the clock to determine the time of transit. Computations then proceed as previously described.

Data are taken for one hour and then the sensor head is reversed and data are taken for another hour. The two positions are then combined into one position. The sequence is repeated and final position computed. The computer controls the system throughout the observing and computing period, requiring the operator only to monitor progress.

The control unit consists of the computer, timing equipment and electronics for the level system.

The computer selected for the AAPS is the Control Data 469 computer which weighs about 1 kilogram, occupies less than 47 cubic inches, and requires only 12 watts of power. It has an 8,192 word (16 bits), non-destruct readout.

A precision clock is also contained in the control unit and consists of a crystal oscillator and the necessary divider circuits to maintain time for the system.

The AAPS requires a self-contained precision time source traceable to any of the internationally adopted Universal Time Scales. The overall requirement is that star transits must be timed with an error not to exceed two milliseconds. This is based on the reasoning that time errors are systematic, that systematic errors are to be kept down to 0.03 arc second.

The clock is set initially and operates continuously from an external power source supplemented during periods of transport by its own internal battery pack. The counter portion is capable of containing 1×10^{11} milliseconds.

It is impractical and fraught with error to require a time correction applicable to each transit. Thus, we require that the frequency remain sufficiently stable so that a drift of not more than two milliseconds will occur during a two-hour site sequence. This represents a maximum allowable frequency offset attributable to environment (especially temperature) and aging effects.

To remain within this amount of offset over a period of one hundred days requires a maximum allowable frequency offset of 2.8×10^{-7} per two hours or 3.4×10^{-6} per day.

The aging rate will require frequency adjustments once every 600 days. Also, temperature, shock and vibration, and voltage variation all produce frequency shifts that are an order of magnitude below that needed.

Oscillator outputs are counted directly in the BCD-coded hexa-decimal system. Setting is accomplished by disabling the normal count sequence and manually stepping seconds, minutes, hours, and days separately to their desired values. The normal sequence is then initiated when the set time is as near as possible to the same instant as received via a standard time service broadcast, which can be manually executed to about 0.1 second with relative ease.

Final synchronization is accomplished by the well-known method of displaying the received time service, one PPS "tick", on a portable oscilloscope, whose sweep is triggered by the one PPS clock output. The clock is advanced or retarded in one millisecond steps until the "tick" is occurring just a few milliseconds after sweep start. This delay can then easily be noted to a fraction of a millisecond. Frequency adjustment will be accomplished with an indicating knob (10 turn pot) which has been coarsely calibrated.

To avoid interpolating time corrections to the site time, the oscillator frequency should always be maintained within one part in 10^8 . (This implies a 24-hour drift of less than one millisecond.) This is accomplished by recording the displayed delays on the scope on a regular basis. The mean slope drawn through about one week's data gives the frequency offset and averages through propagation delay variations. If the frequency is correspondingly adjusted, no difficulty should be experienced in maintaining the clock always within one or two milliseconds of the received time.

It is very important that the clock be powered at all times and that switching transients do not introduce count errors.

The current AAPS prototypes have two types of power source, lead acid batteries and Nicad batteries. The voltage, wattage and ampere hour requirements are shown here. (Fig. 9)

RESULTS

Now, let's discuss test results achieved with the AAPS to date. A limited amount of contractor test data was divided into five first order positions spanning seven nights during July 1973. A first order position consists of four sets, two in the

VOLTAGE	24V - 32V DC (Single Input)
WATTAGE	30 WATTS
AMPERE-HOURS	15 AMP-HRS

Figure 9. AAPS Power Requirements

direct orientation and two in the reverse orientation. The results shown should be used with caution due to experimental techniques used by the contractor. As shown in Table 1, we have the AAPS derived astronomic latitude and longitude differences from a standard position established by conventional Wild T-4 observations.

We show the horizontal displacement of each of the five first order positions from the standard position. (Fig. 10) Estimated standard errors of an AAPS first order position in latitude and longitude are ± 34.3 meters and ± 5.5 meters, as depicted with the dashed interval. The hashed area is contract goal.

Table 1

AAPS First Order Astronomic Results at Station Faribault

FO NR	DATE	LATITUDE DIFFERENCE(N)		LONGITUDE DIFFERENCE (W)		DEGREES OF FREEDOM
		ARC SECONDS	METERS	ARC SECONDS	METERS	
1	JULY 4, 1973	+1.06	+32.7	-0.04	-0.9	073
2	JULY 5, 6, 1973	+0.39	+12.0	+0.32	+7.1	080
3	JULY 6, 7, 1973	-0.35	-10.8	-0.10	-2.2	126
4	JULY 7, 1973	-1.40	-43.2	+0.23	+5.1	101
5	JULY 10, 1973	+0.78	+24.1	-0.19	-4.2	095

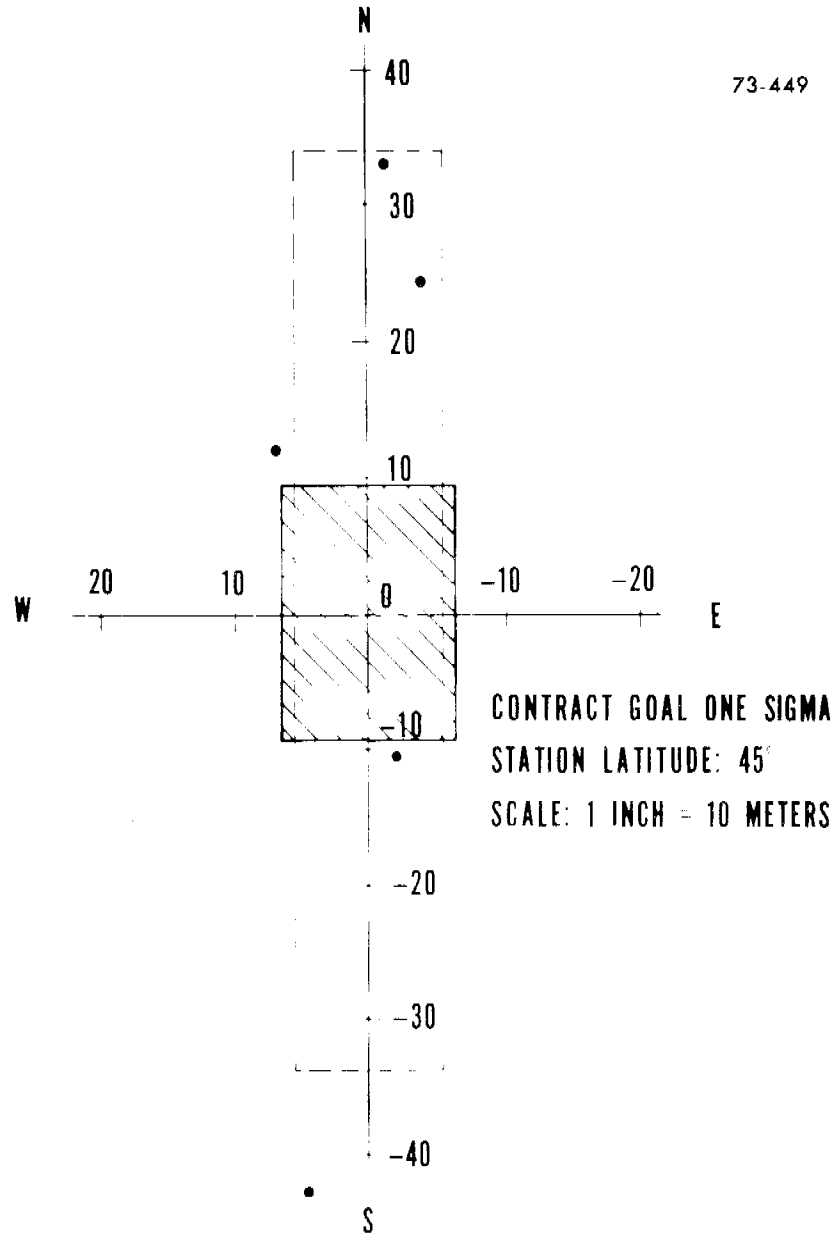


Figure 10. AAPS First Order Position Difference

The latitude displacement from the standard as a function of observation time is found in Figure 11 where the relationship between number of sets to time is one per half an hour. The longitude displacement is also covered in the same manner. (Fig. 12)

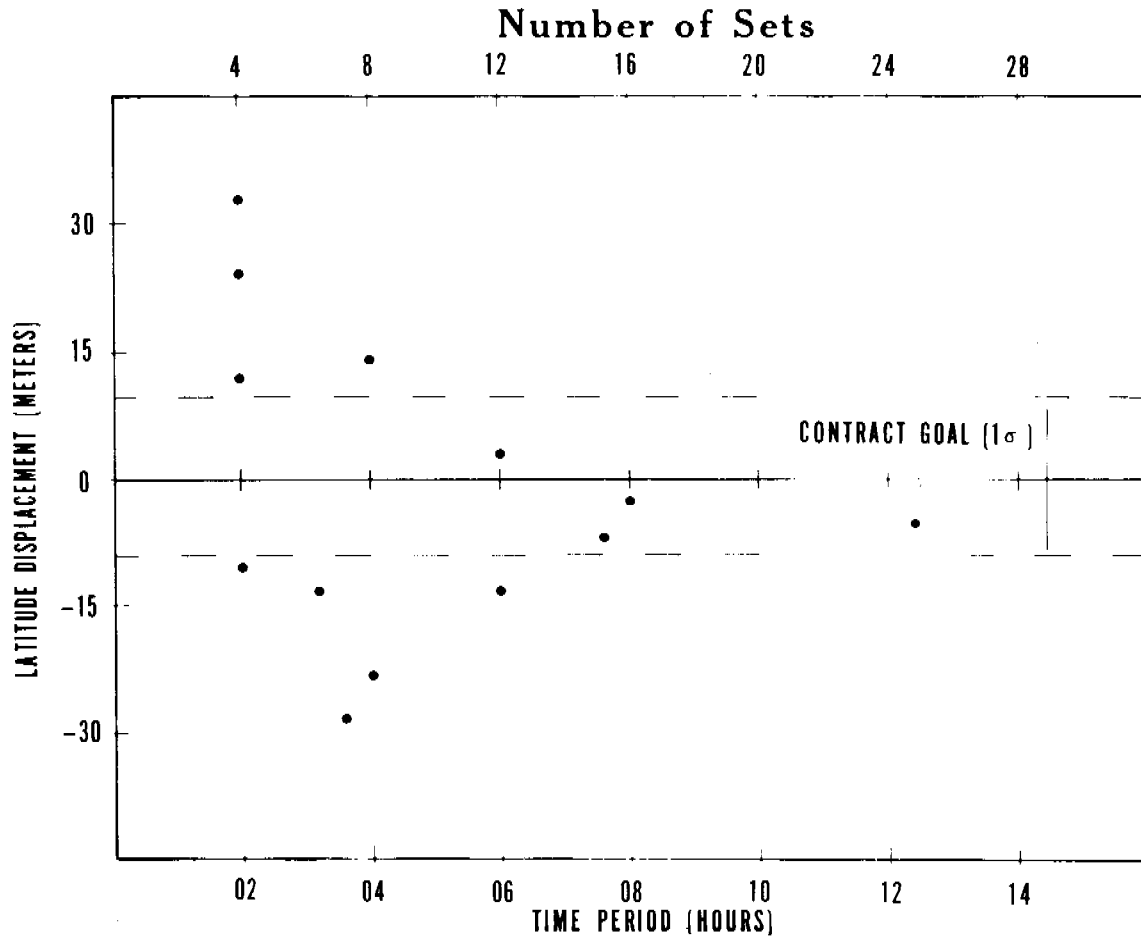


Figure 11. AAPS Accuracy Relative to a Standard

Some of the problems encountered in the AAPS R&D effort surfaced late in the program during environmental testing. Level sensors failed at high temperature (130°C) and fluid leaked through the optics onto the reticle and destroyed it. New sensors were obtained and again the failure occurred. Investigation revealed that temperature shock (rapid rise or fall) caused stress to build up due to non-uniform expansion characteristics of the quartz glass vial and the cup. Addition of a passive thermal blanket around the level sensor eliminated the problem. Environmental testing also revealed that some of the photomultiplier tubes were saturating the amplifiers by dark current rise with temperature cutting off at about 100°C. Since most of the photomultiplier tubes continued to operate up to the required 120°C, the problem can be solved by purchase of selected photomultiplier tubes to replace those that saturate at lower temperatures. The fact that the 120° temperatures will seldom be encountered in field operations indicates

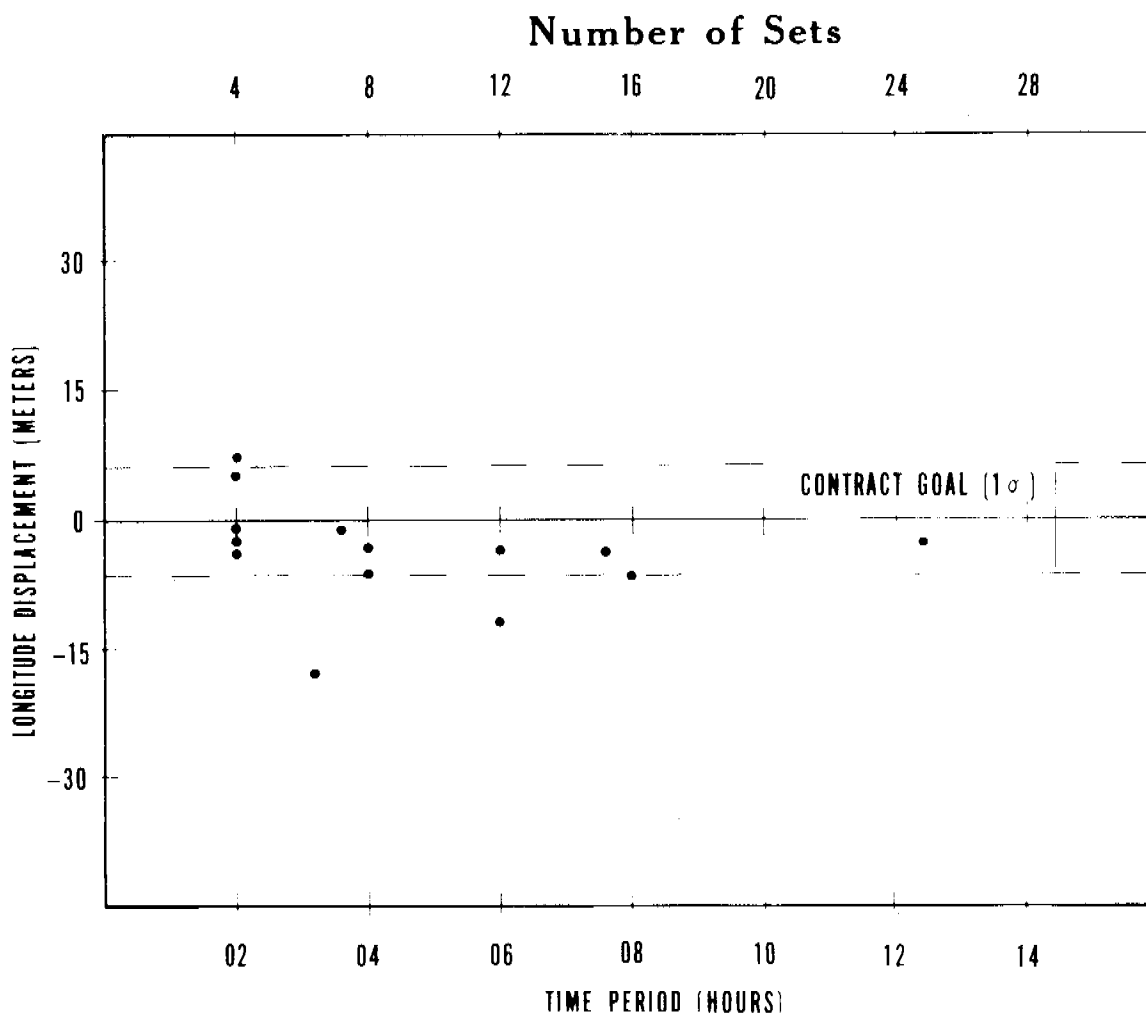


Figure 12. AAPS Accuracy Relative to a Standard

that the severity of the problem is low. Preconditioning the sensor head to the operational environment prior to operation will be made a part of the field operational procedure when unusually high temperatures are expected. A problem was encountered in fabricating the slit reticle to specifications for angular displacement and offset from the center. This was solved by computing slit azimuth and offset from field observations data and using the calibration data in the data reduction program as correction information.

OPERATIONAL TEST AND EVALUATION

The operational test and evaluation program for the AAPS calls for the two AAPS prototypes to be deployed on operational test sites to evaluate the field performance of the systems under operational conditions by field survey personnel.

Pre-acceptance tests have just begun at F. E. Warren AFB, Wyoming, where several high order conventional astro position stations are available. AAPS observations will continue at these stations between deployments to the "other" operational test sites, and after the operational test is concluded.

The data shown here (Table 2) are recent samples of test data collected at F. E. Warren AFB during November 1973. The corrected mean astronomic coordinates differ only 0'20 in longitude and 0'04 in latitude from conventional coordinates. This vividly demonstrates the potential of automated astronomic positioning.

We will deploy the prototypes for operational tests to Eielson AFB, Alaska (64°N, Subzero), Richmond, Florida (25°N), and the Canal Zone (9°N). A combination operational test and demonstration will be accomplished at the Naval Observatory in Washington next spring. A Southern Hemisphere test station is still a possibility but no firm location has been defined.

Table 2

Recent Test Data—AAPS Prototypes
10-11 November—F. E. Warren AFB, Wyoming

SET No.	LONGITUDE (W)	LATITUDE (N)
1	104° 51' 57".33	41° 08' 05".82
2	57".05	04".98
3	58".70	05".76
4	57".86	05".20
MEAN	57".53	05".44
UT1-UTC CORRECTION	-2".25	0
SEA LEVEL CORRECTION	0	-".30
	55".28	05".14
CONVENTIONAL 1st ORDER POSITION	55".48	05".10

CONCLUSIONS AND FUTURE POSSIBILITIES

In summary, the desired AAPS accuracy and time requirement for the field observation (dependent on required accuracy) have not been achieved during contractor testing. The prototypes have recently demonstrated the potential for acquiring 0.3 arc sec astronomic position accuracy. The unit cost of the prototypes has been relatively high. This will be offset, however, by reduced training costs for the astro observing team and the rapid data collection rate of the sensor. One astro team should be able to accomplish at least one first order astro position observation on a clear night.

Possible future engineering modifications and applications of the AAPS are:

1. The AAPS can be modified to provide astro azimuth readout and transfer capability. AAPS generated azimuths could then be transferred to required lines by using an autocollimating theodolite.
2. Better star right ascension and declination data can be obtained by using AAPS observations at fixed locations. This would improve star catalog data and, ultimately, the accuracy of astronomic positions.
3. The AAPS could be used at current or new observatories for monitoring time and latitude.
4. The AAPS can be used for providing astronomic positions to improve and increase the information necessary for determining geoid heights or the difference in height between the geoid and the ellipsoid (a mathematical reference spheroid).
5. In the same manner, the AAPS will provide a more rapid means of accomplishing astro positions in conjunction with geodetic positions in determining astro geodetic deflections, or the angular difference between the plumb line and the normal to the reference spheroid.
6. The development of the AAPS should result in more available and less expensive astronomic position data in current or future geodetic networks. The astro positions will result in more deflection data for more rigorous adjustments in three dimensions.

There is no doubt this revolutionary approach to astronomic positioning will disclose applications not yet conceived as well as provide instrumentation capable of time dependent accuracies in the one-third arc sec region.

I gladly acknowledge the assistance of Mr. Charles Whelan of our Geodetic Survey Squadron, Mr. Donald Murray of our Aerospace Center, and Major Beers of our Headquarters in the formation of this paper. It is my hope that they will be able to participate in the next PTTI Planning Meeting and discuss specific results based on field operational experience of the AAPS.

QUESTION AND ANSWER PERIOD

MR. CHI:

Are there any questions?

(No response.)