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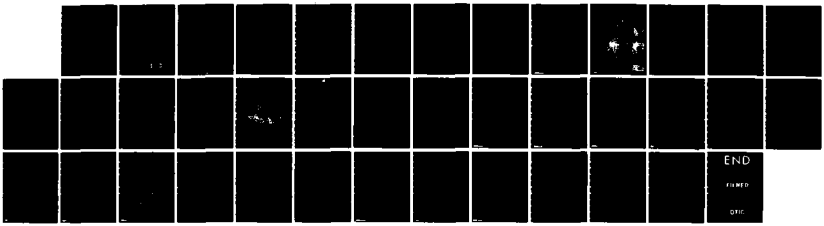

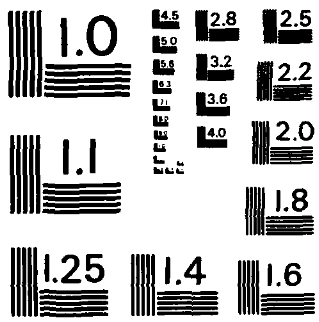
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RECENT DEVELOPMENT IN ASTRONOMIC POSITION DETERMINATIONS

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ABSTRACT

An advanced engineering model of an electro-optical star sensor system designed by Ball Aerospace Systems Division, incorporates a charge injection device (CID) detector having a 256 x 256 pixel array. The system is integrated with a Wild T-4 astronomic theodolite in the focal plane to replace the human eye. A star image is acquired and tracked across detector pixels to determine a time versus meridian angle intercept that is synchronized with a very accurate time. Zenith angle intercepts are also measured. Track position, interpolation, and data reduction algorithms are derived and incorporated into the system software to provide astronomic latitude and longitude to about ±0.1 arc second (1 sigma). This system is being built for the Defense Mapping Agency under an on-going technical development program to improve the accuracy of astronomic position determinations. The need for accuracy improvements, the limitations of conventional instruments, an analysis of major error sources, the results of previous developmental efforts, and the design and use of advanced production instruments are also presented.

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This paper describes the design and development of an advanced engineering model of an electro-optical star sensor system designed by Ball Aerospace Systems Division. This automated sensor, with associated electronics, incorporates a charge injection device (CID) detector having a 256 x 256 pixel array. The system is integrated with a Wild T-4 astronomic theodolite in the focal plane to replace the human eye. A star image is acquired and tracked across detector pixels to determine a time versus meridan angle intercept that is synchronized with a very accurate time. Zenith angle intercepts are also measured. Track position, interpolation, and data reduction algorithm have been derived and incorporated into the system software to provide astronomic latitude and longitude to about ±0.1 arc second (1 sigma). This system is being built for the Defense Mapping Agency under an ongoing technical development program to improve the accuracy of astronomic position determinations. The need for accuracy improvements the limitations of conventional instruments, an analysis of major error sources, the results of previous developmental efforts, and the design and use of advanced production instruments are presented.

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RECENT DEVELOPMENTS IN ASTRONOMIC POSITION DETERMINATIONS

BACKGROUND

During the mid 1970's, DMA recognized the need to improve survey capabilities for determining deflections of the vertical. Studies were made of astrogeodetic determinations, inertial positioning system (IPS) measurements, gravimetric determinations, and interpolation/prediction by least-squares collocation methods. The results of these studies, and other practical considerations, indicated that the most cost effective approach was to improve the accuracies of astronomic position determinations.

An in-house investigation of the primary error sources affecting astronomic observations was initiated. In order to provide a reference for future improvements and identification of error sources, an accuracy capability study was undertaken by DMA's Geodetic Survey Squadron (DMAHTC/GSS). The purpose was to determine the best attainable accuracy of conventional astronomic position observations using DMA-qualified astro observers, standard equipment, and current observing methodology. This study involved 14 observers using Wild T-4 astronomic theodolites at a station in Cheyenne, Wyoming. The meridian transit method was used for longitude, and the Sterneck method was used for latitude. The results were published in 1979 (Gilbert, 1979).

The means of 338 sets of latitude determinations (2662 FK4 stars) and 322 sets of longitude determinations (2649 FK4 stars) in the Cheyenne test were accepted as the true astronomic position of the standard station. It was assumed that the personal equation, instrument bias, and anomalous refraction would cancel over the extended period of time with different observers using different instruments. This assumption was proven substantially correct. The findings of this test concluded that the estimated accuracies of DMA astronomic stations are:

TABLE 1

	LATITUDE	LONGITUDE
First-Order (FO); 2 nights	±0".15	±0".25 sec ϕ
Modified First-Order (MFO) 1 night	±0".19	±0".28 sec ϕ

Where a MFO observation normally consists of four sets in one night, 6-8 stars each set; and a FO is twice as many sets over two nights.

Other findings included:

1. No significant observer's personal equation in the astronomic latitude data samples.

2. Thirteen of the 14 observers had significant personal equations in astronomic longitude data samples.

3. Personal equations of the observers ranged from +0.46 to -0.31 arc second.

Table 2 shows the combination of instruments, observers, and number of nights required to achieve improved astronomic position accuracies in latitude and longitude. The data indicate that almost double the effort is required to improve accuracy for longitude than is required for latitude. The main reason is the large contribution of the personal equation error in longitude, which is an insignificant factor in latitude. These findings indicated that future improvement efforts would have to be concentrated on longitude observations.

A technical development program was formulated based on the results of the Cheyenne capability study and review of the research and development efforts of other studies performed in the international geodetic community. The comparison of astronomic position determinations using the Danjon and the VUGTK astrolabes published by the German Geodetic Commission (Kaniuth, Wende, and Schlueter, 1979) was significant. These tests, conducted over 18 months, were made principally for polar motion studies. The results of these tests indicated that astrolabes were capable of precision and accuracy surpassing those obtainable with astronomic theodolites, even though some personal equation bias remained. The German Geodetic Commission report reinforced DMA thinking that, in addition to improved instrumentation, precise astronomic reference stations, linked to the U.S. Naval Observatory Danjon Station in Washington, D.C., were needed at strategic locations throughout the U.S.

In 1976, the technical development program initiated by the DMAHTC/GSS coincided with a decision by HQ DMA to fund a research program at the University of Maryland to develop a charge-coupled device (CCD) eyepiece for astronomic theodolites and a two-color refractometer. The CCD would eliminate a major source of error by replacing the human eye. The two-color refractometer would provide a correction for anomalous refraction.

The major emphasis of the DMA in-house accuracy improvement program focused on three main categories of error in longitude determination and alternative solutions to remedy these error sources (Table 3). Also, the magnitude of the error contributed by each category was estimated. As noted in Table 3, the largest error category is the personal equation. The remainder of this paper will address the developmental efforts toward eliminating the human eye with an automated star sensor eyepiece for the Wild T-4 astronomic theodolite.

PERSONAL EQUATION ERROR: The personal equation error is mainly a systematic error that cannot be determined accurately and usually does not remain constant. The variation in an observer's personal error can be minimized through experience, the gaining of confidence, concentration, and being in good physical and emotional condition. For an experienced and capable observer, the tendency is for personal error to remain nearly constant for a "short period" of time. Without any modifications to the astronomic theodolite, personal errors can be reduced by following certain procedures. These procedures involve determining longitudes at reference stations before and after observations are made at field stations. It is a costly method, but high accuracy and reliability of the field station longitude value is

TABLE 2

STATISTICS OF ENHANCEMENT WITH VARIOUS COMBINATIONS OF INSTRUMENTS, PERSONNEL, AND OBSERVATIONS[1]

Astronomic Latitude Accuracy Improvement

No. of Instruments	No. of Observers	No. of Nights	Avg. No. of Sets	Avg. No. of Stars	Accuracy Std. Error	No. of Determinations
1	1	1	4	32	±0".19(MFO)	78
1	1	2	9	68	±0".15(FO)	38
1	2	3	11	84	±0".13	29
2	2	3	11	84	±0".15	28
2	2	5 to 7	22	170	±0".09	13

Astronomic Longitude Accuracy Improvement

No. of Instruments	No. of Ovservers	No. Of Nights	Avg. No. of Sets	Avg. No. of Stars	Accuracy Std. Error	No. of Determinations
1	1	1	4	32	±0".28 sec ϕ (MFO)	78
1	1	2 to 4	8	69	±0".25 sec ϕ (FO)	37
1	2	3	11	86	±0".21 sec ϕ	25
1	3	3 to 4	11	91	±0".18 sec ϕ	26
2	2	2 to 3	8	66	±0".18 sec ϕ	34
2	2	5 to 6	18	151	±0".14 sec ϕ	13
1	1	2 to 4	8	69	±0".15 sec ϕ (FO)*	37

*After applying corrections for personal equations.

[1]Gilbert, 1979, p.51

TABLE 3

MAJOR ERRORS IN LONGITUDE OBSERVATIONS

CAUSES:		
INSTRUMENT BIAS	PERSONAL EQUATION (PE)	BETWEEN-NIGHT ERROR
1. Level Vial	1. Judgment Error	1. Refraction Variations
2. Width of Contact Strips	2. Magnitude of Stars	2. Temperature Gradients (in Levels & Instrument)
3. Wobble	3. Physical & Emotional	3. Variations in Wobble
4. Temperature Effects	4. Manipulation of Instrument	
5. Lost Motion	5. Eye Adaptability	
ERROR ±0".12	±0".20	±0".13
REMEDIES:		
Level Calibration (1)	Correction for PE (1,2)	Two-Color Refractometer (1)
Measure Wobble (3)	Use of CCD System (1-5)	Insulation (2)
Insulate Level Vials (1,4)	Multiple Observers (1-5)	Wind Protection (2)
Make & Break Timing Contacts (2)	Astrolabes (1,2,4,5)	Wobble Determination (3)
Multiple Instruments (1-5)	Motorized Micrometers (3,4)	New Observing Methods (1,3)
Reference Stations (2,5)		Multiple Night Observations (1,2,3)
Electronic Levels (1,4)		Astrolabes (2,3)
Mercury Levels (1,4)		
Astrolabes (1,2,3,5)		

achieved. Three additional reference stations have been established by a U.S. Naval Observatory team from their Danjon Station in Washington, D.C. The three new reference stations are at Cheyenne, Wyoming; Lompoc, California; and White Sands Missile Range, New Mexico. These three reference stations will be used in future testing and calibration of astronomic instrumentation as well as in the transfer of latitude and longitude data to new precise astronomic stations.

CHARGE-COUPLED DEVICE (CCD): The prototype charge-coupled device uses a 3 x 4 millimeter silicon chip (semiconductor) which is highly sensitive to visible light and near-visible infrared light. The incident light from a star enters the optics of the theodolite and is focused on the silicon chip creating an electron flow across 100 x 100 pixels in a rectangular grid. This flow of electrons, called charge coupling, can be moved to a point of detection, converted into an electronic signal that represents the star's position on the grid, and captured by the computer. The entire grid is scanned 40 times per second, but only a small portion of the data, up to a 10 x 10 pixel patch, is stored on a computer magnetic tape. The software analyzes the small pixel patch, column by column, to detect the position of the star on the grid. A multiparameter curve fit of the signal determines when the star image enters and exits a grid column. From these curve fits, the grid position and time correlation of the star is determined. The remainder of the data reduction process for the latitude and longitude determination is analogous to conventional astronomic position data reduction procedures.

CCD Hardware System. A schematic diagram of the first CCD system is shown in Figure 1.

- T-4 Astronomic Theodolite (Figure 2) - normal observing procedures are followed with the human eye replaced by the CCD eyepiece.

- CCD Eyepiece - detects the starlight which generates a signal that is input to the computer.

- Thermal Control Unit - maintains the CCD at a constant temperature.

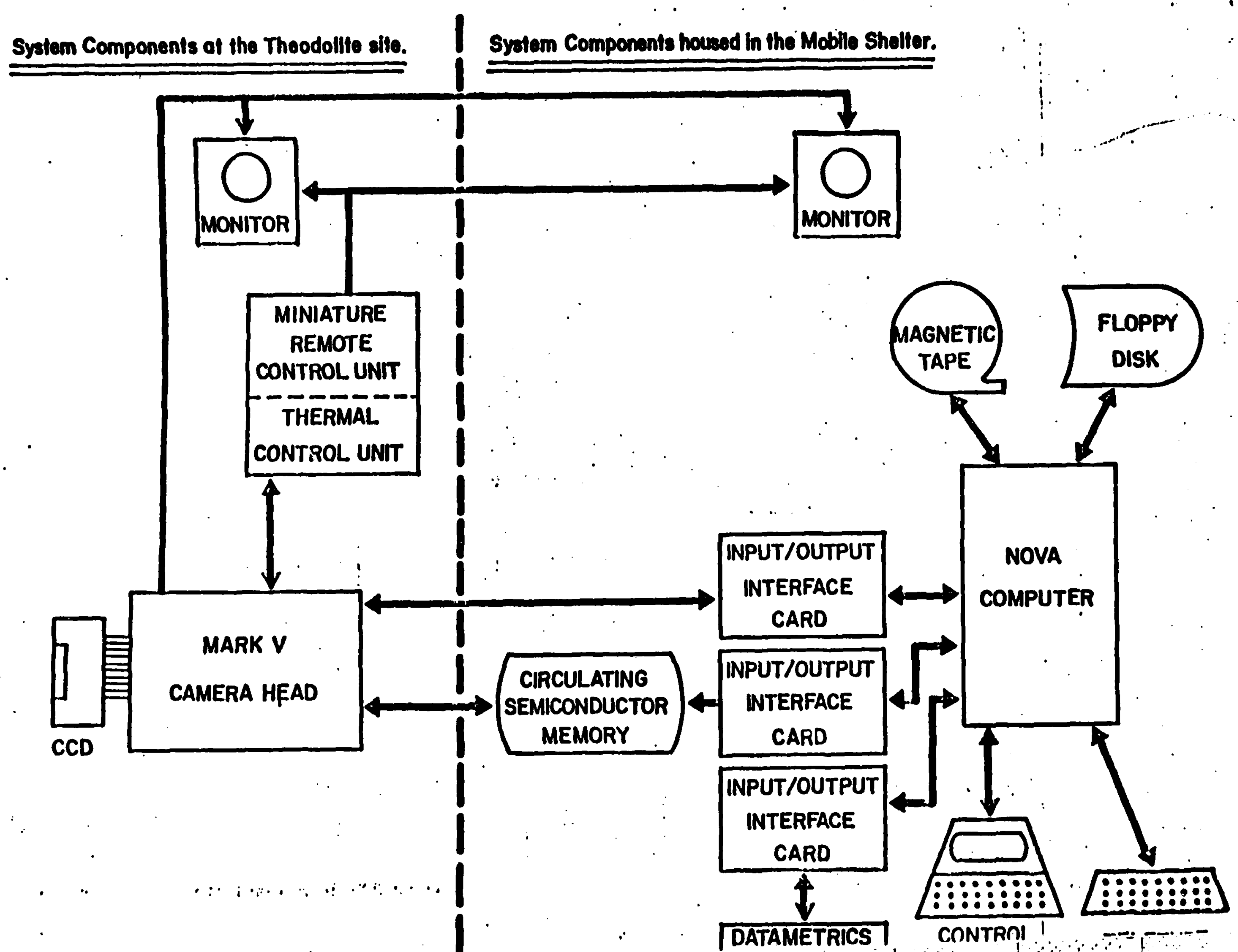
- Circulating Semiconductor Memory - stores the "dark current noise pattern" which is subsequently subtracted from the signal to produce an image free of background noise.

- Nova Computer - performs data processing and intelligent system operational control functions.

- Remote Control Unit - consists of a microprocessor which generates the scanning function and the selection of clock voltages and other operational modes.

- Video Amplifiers (monitors) - provides the observer and the remote system operator with a display of the star image as sensed by the CCD.

- Datametrics Timing System - provides the time for the astronomic events.



System Components at the Theodolite site.
System Components housed in the Mobile Shelter.
MONITOR
MONITOR
MINIATURE REMOTE CONTROL UNIT
THERMAL CONTROL UNIT
MAGNETIC TAPE
FLOPPY DISK
NOVA COMPUTER
INPUT/OUTPUT INTERFACE CARD
INPUT/OUTPUT INTERFACE CARD
INPUT/OUTPUT INTERFACE CARD
MARK V CAMERA HEAD
CCD
CIRCULATING SEMICONDUCTOR MEMORY
DATAMETRICS
CONTROL

- Magnetic Tape Drive - stores programs for input to the Nova computer and stores CCD data for final data reduction.

- Control Terminal - input/output device for operational control of the CCD system.

FEASIBILITY AND FIELD TESTING: The integration of the DMA prototype CCD system hardware was completed in November 1981. For the following six months, feasibility testing was performed at Beltsville, Maryland. Repeatability of a single night's observations was ±0".17 sec ϕ (1 sigma). In May 1982, the CCD system was installed in a mobile shelter and moved to the U.S. Naval Observatory (USNO) Danjon station in Washington, D.C. for operational testing and evaluation by DMA personnel. A summary of astronomic longitudes determined using the CCD appears in Table 4. The close agreement (-0".05) and the small standard error of a single night (±0".11 sec ϕ) were particularly gratifying.

In June 1982, the system was moved to Cheyenne, Wyoming, where it was tested. During this test period, there was one hardware failure in the power supply which was repaired. A second failure caused a delay of over two months. Several attempts were made to repair the system when in January 1983, the problem was determined to be in the Nova computer.

The mean of the CCD/T-4 system longitude results agreed with the standard station longitude at Cheyenne by +0".05. However, the standard error of a single night was ±0".29 sec ϕ, or three times that obtained at the USNO station in Washington, D.C. (Table 5).

The January 1983 CCD/T-4 observations (10 nights) at Cheyenne showed a large east bias, 0".41 in longitude and the standard error of a single night's observations was +0".36 sec ϕ. A reoccupation of the USNO Danjon station in March 1983 (7 nights) resulted in a west bias of 0".40, but with a standard error of ±0".16 sec ϕ for the mean of a single night.

These results from the prototype CCD/T-4 system provided DMA with the proof of concept necessary to continue to develop an automated star sensor system. In September 1983, DMA contracted with Ball Aerospace Division, in Boulder, Colorado, to build an advanced engineering model of a Precision Star Sensor using a charge injection device as the primary detector.

CHARGE INJECTION DEVICE DETECTORS: Development of a star tracker using charge transfer device (CTD) technology began at Marshall Space Flight Center and Ball Aerospace Division (BASD) in 1975. Early work used a CCD because of availability. Subsequent work indicated that the CID had advantages for star tracking. Studies by General Electric and later by Jet Propulsion Laboratory verified the potential advantages.

TABLE 4

CCD FINAL ASTRONOMIC LONGITUDE RESULTS
AT STATION DANJON ASTRO (USNO), WASHINGTON, D.C.

1982 LOCAL DATE	ASTRONOMIC LONGITUDE FOR NIGHT	RESIDUAL FROM STANDARD	NUMBER OF SETS
29 April	77°03'58".04	-0".19	2
3 May	58.12	-0.11	4
4 May	58.42	+0.19	4
5 May	58.10	-0.13	5
6 May	58.21	-0.02	5
10 May	58.32	+0.09	4
11 May	58.01	-0.22	3
13 May	58.39	+0.16	2
25 May	58.25	+0.02	4
26 May	58.25	+0.02	5
1 June	58.12	-0.11	5
2 June	58.13	-0.10	3
7 June	57.96	-0.27	3
8 June	58.12	-0.11	2
			51 SETS

WEIGHTED MEAN	58".18	±0".036	(350 STARS OBSERVED)
FIXED POSITION	58".23	±0".009	(OVER 50,000 STARS OBSERVED)
DIFFERENCE	-0".05		

STANDARD ERROR OF A SINGLE NIGHT ±0".11 sec ϕ

TABLE 5

CCD FINAL ASTRONOMIC LONGITUDE RESULTS
AT STATION WEEKS, F. E. WARREN AFB, WY

1982 LOCAL DATE	ASTRONOMIC LONGITUDE FOR NIGHT SECONDS	RESIDUAL FROM STANDARD SECONDS	NUMBER OF SETS	NO. OF STARS OBS	NO. OF STARS ACC
18 June	47"31	+0"06	2	19	12
23 June	47.92	+0.67	2	13	13
28 June	47.41	+0.16	4	30	28
02 July	47.19	-0.06	4	30	28
06 July	47.05	-0.20	4	31	25
07 July	46.58	-0.67	3	20	18
12 July	46.58	-0.57	4	32	31
19 July	47.00	-0.25	3	21	19
20 July	47.15	-0.10	4	33	30
21 July	47.14	-0.11	4	32	32
22 July	47.37	+0.12	3	20	20
23 July	47.37	+0.12	4	31	31
30 July	47.78	+0.53	4	23	22
03 August	47.62	+0.37	1	07	07
04 August	47.92	+0.67	4	27	27
05 August	47.36	+0.11	3	22	21
06 August	47.04	-0.21	4	07	06
12 August	47.52	+0.27	1	07	06
16 August	47.86	+0.61	5	32	30
TOTALS			63	461	425

WEIGHTED MEAN 47"30

FIXED POSITION 47"25

DIFFERENCE +0"05

STANDARD ERROR OF A SINGLE NIGHT ±0"29 sec ϕ

THE WEIGHT FOR EACH NIGHT IS THE NUMBER OF ACCEPTABLE STARS.

Marshall Space Flight Center (MSFC) entered into a contract with GE in 1977 to produce a 128 x 128 pixel chip and readout electronics with characteristics determined to be advantageous in these studies. From the test results of that contract, BASD produced a detailed analysis that formed the basis of a breadboard tracker which was built and tested. Unique acquisition and tracking concepts were developed by BASD and incorporated into the design. Also, GE produced an increased number of pixels (256 x 256). The results indicate that a star tracker capable of tracking to an accuracy of better than 0.01 pixel is feasible.

The CTD is an array of photosensitive picture elements, or pixels, that are formed on a semiconductor chip through the use of integrated circuit processing techniques. The pixels are small (on the order of 25 μm), so that a very large number can be deposited on a small chip. The device is unique in that the photon-generated electrons are integrated and stored at the respective pixels. Only after a command for a readout or recombination is given are the electrons removed.

Many variations of CTDs have been developed. However, they can typically be placed into two generic categories:

1. Charge Coupled Devices (CCD).

2. Charge Injection Devices (CID).

The basic difference between the two is in the method of readout and electron charge removal.

The CCD is read by sequential transfer of charge from pixel to pixel along the columns. The charge signals are detected at the end of the columns and can be related to the pixel clocking sequence. The charge is removed in the readout process.

The CID cannot transfer charges between pixels. Each pixel has a row-connected and a column-connected capacitor between which charges can be transferred. The displacement current, which is proportional to the charge, is detected for signal readout during the intra-pixel transfer. The charge is not destroyed in this mode, so that multiple readings can be taken while charge is integrating at the pixel.

The use of multiple nondestructive readouts (NDRO) allows readout at a sufficiently high frequency to eliminate interface (I/F) noise, and tends to reduce system noise by averaging. After the read cycle is complete, the charge is removed by injection into the substrate.

The random access and NDRO capabilities, combined with high uniformity of response and dark current, make CIDs attractive for tracking small light sources such as stars. Table 6 is a qualitative comparison for the star tracking application.

Table 6

NO.	TRADE ITEM	CID	CCD
1.	Defect Tolerance	Defect Confined to Pixel	Defect Propagates Down Columns
2.	Optical Overload Tolerance	Blooming Confined to Local Area	Blooming Propagates Down Column
3.	Charge Storage Capacity	10^6 Carriers Typical	10^6 Carriers Typical
4.	Dark Current Generation	1 nA per cm^2 Typical	5 nA per cm^2 Typical
5.	Quantum Efficiency	High (0.4 to 1 um)	High 0.4 to 1 um
6.	Response Uniformity	0.6% RMS Typical	1% RMS Typical
7.	Temporal Noise	*30 to 300 Carriers Typical	50 to 200 Carriers Typical
8.	Crosstalk Sensitivity	Confined to Adjac[illegible] Pixel	Occurs Over Several Pixels
9.	Data Address	Direct X-Y Access to Data Pixel	"Bucket Brigade" to Data Pixel
10.	Charge Transfer Efficiency	One Transfer	Full Array Transferred
11.	Operational Flexibility	Destructive or NDRO;On-Chip Processing	Destructive Full Frame Readout
12.	Power	Only Required Pixels are Read at Required Update Rate	Full Array is Read at Required Update Rate
13.	Radiation Effects	Efficiency of Only One Transfer is Affected	Effects on Transfer Efficiency Propagate Down Columns
14.	Yield	Three Masking Operations Involved in Fabrication	5 to 12 Masking Operations Involved in Fabrication
15.	Technical Maturity	Implemented in Tracker and Tested	Implemented in Tracker and Tested

*Noise is reduced to 30 carriers by multiple NDRO

The chart indicates a bias towards the CID. However, either device will meet performance requirements for most applications. Performance was downgraded on the list of selection criteria. The major selection criteria were:

1. Lower dark current (item 4) requires less cooling power.

2. Defect tolerance (item 1) and yield (item 14) indicate advantages in productibility.

3. Direct access (item 9) of only the data that are needed, which reduces processing.

4. Operational flexibility (item 11) reduces system processing requirements and enhances performance.

5. Lower power (item 12) reduces electrical and thermal design effects.

The CID was therefore selected for star tracking applications.

DESIGN OF THE SYSTEM

SYSTEM DESIGN CONSIDERATIONS: The first step in designing the DMA T-4 theodolite star sensor was parametric analysis of the electro-optical system and consideration of trade-offs. The following parameters were among those analyzed:

- Star magnitude and class.
- Star rate of motion.
- T-4 theodolite optical characteristics.

  Aperture size

  Field of view focal length
- Atmospheric effects.
- Signal and noise.
- Timing
- Accuracy

The sensor system was designed to match the optical characteristics of the Wild T-4 theodolite.

The photoelectron energy produced on the CID by a star's light depends on:

- The star's magnitude
- The star's spectral class
- Optical efficiency

- Atmospheric attenuation

Calculations were performed to ascertain the minimum detector flux. Depending upon the star's spectral characteristics, a star, 5.5 to 6.0 in magnitude (atmospheric transmission of 0.7; optical efficiency of 0.8, T-4 objective aperture of 70 mm), requires a minimum detector flux of 2 x 10^5 E/sec.

This requirement dictates the search, acquisition, and tracking logic. To ensure meeting the necessary signal to noise ratio, the star image is focused on approximately 1 1/2 pixels.

The specific device is the GE ST-256 CID. (Figure 3) A thermoelectric cooler is part of the detector assembly.

It appeared feasible to develop an electronic star tracker, because they are well suited for making accurate time determination and their internal functions are typically timed in milliseconds. The primary challenge was to develop algorithms which would accurately model the trace of the star across the focal plane and thus provide the accurate locations and associated times required. The contractor will produce a concept verification model, which will determine whether a solid state sensor can be utilized to determine local longitude and latitude.

SYSTEM DESCRIPTION

DMA T-4 THEODOLITE STAR SENSOR SYSTEM DESCRIPTION: The system is partitioned into three separable units (Figure 4). The van houses the processor system; the Time of Day receiver which receives its signal from the GOES satellite; and a generator which provides 115 VAC and 60Hz power. A 50-foot interface cable connects the pier (T-4 platform) and the van. The pier electronics provide the controls and displays required for instrument operation, and are mounted in a portable unit located adjacent to the pier.

The sensor is mounted on the T-4 theodolite trunnion axis. The CID detector is at the focal plane of the theodolite. The detector's electronics are in the sensor housing, and the signals are transmitted to the pier electronics.

AC power is transmitted directly to the pier electronics where it is converted and regulated by the power control logic, and provides illumination power, cooler power, and a power source for the sensor AC/DC converters in the pier electronics. A variable frequency signal is provided to the thermal electric cooler (TEC) control circuitry. Video and audio data are also routed through the interface cable between the van and pier electronics.

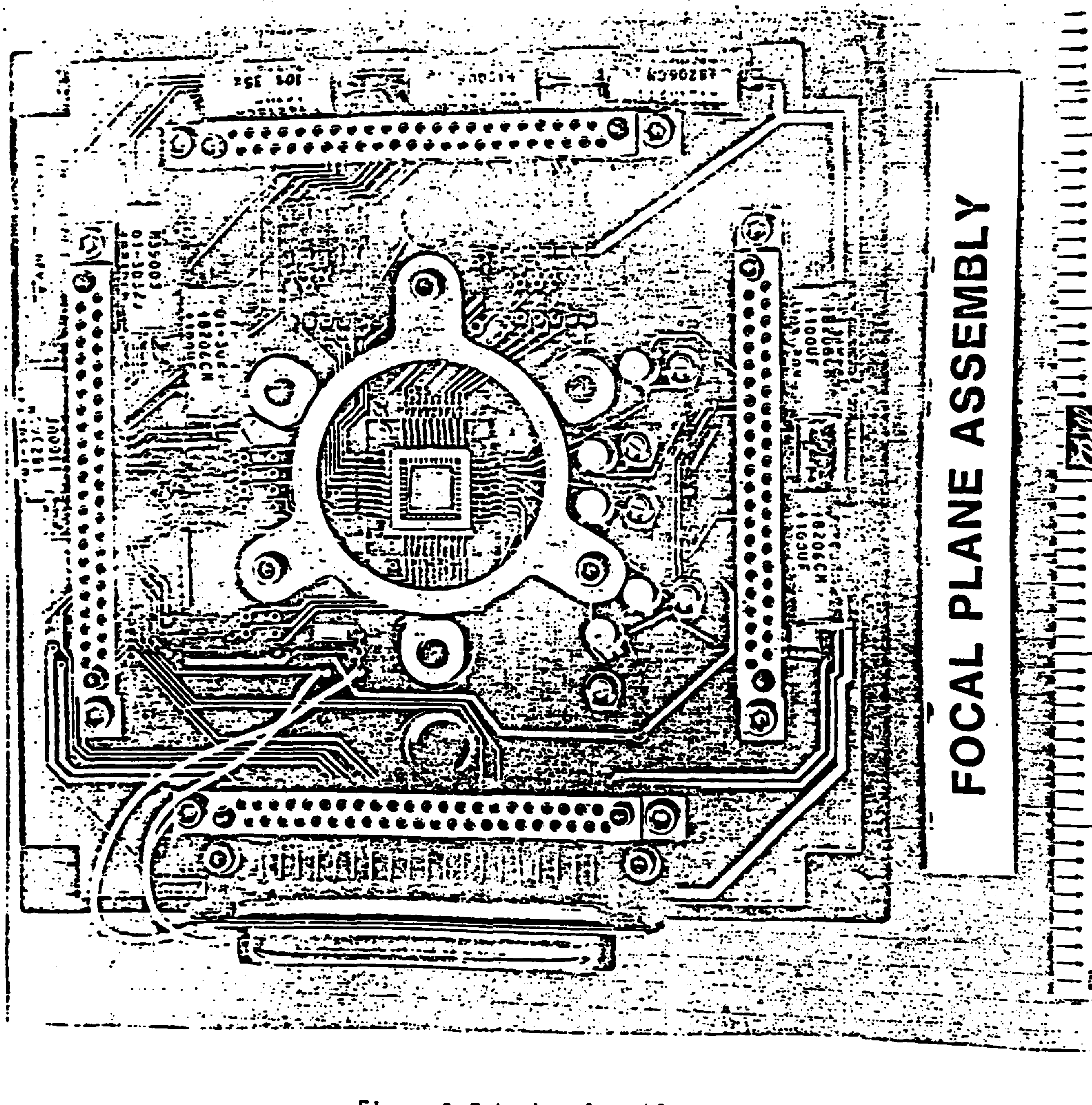


Figure 3 Detector Assembly

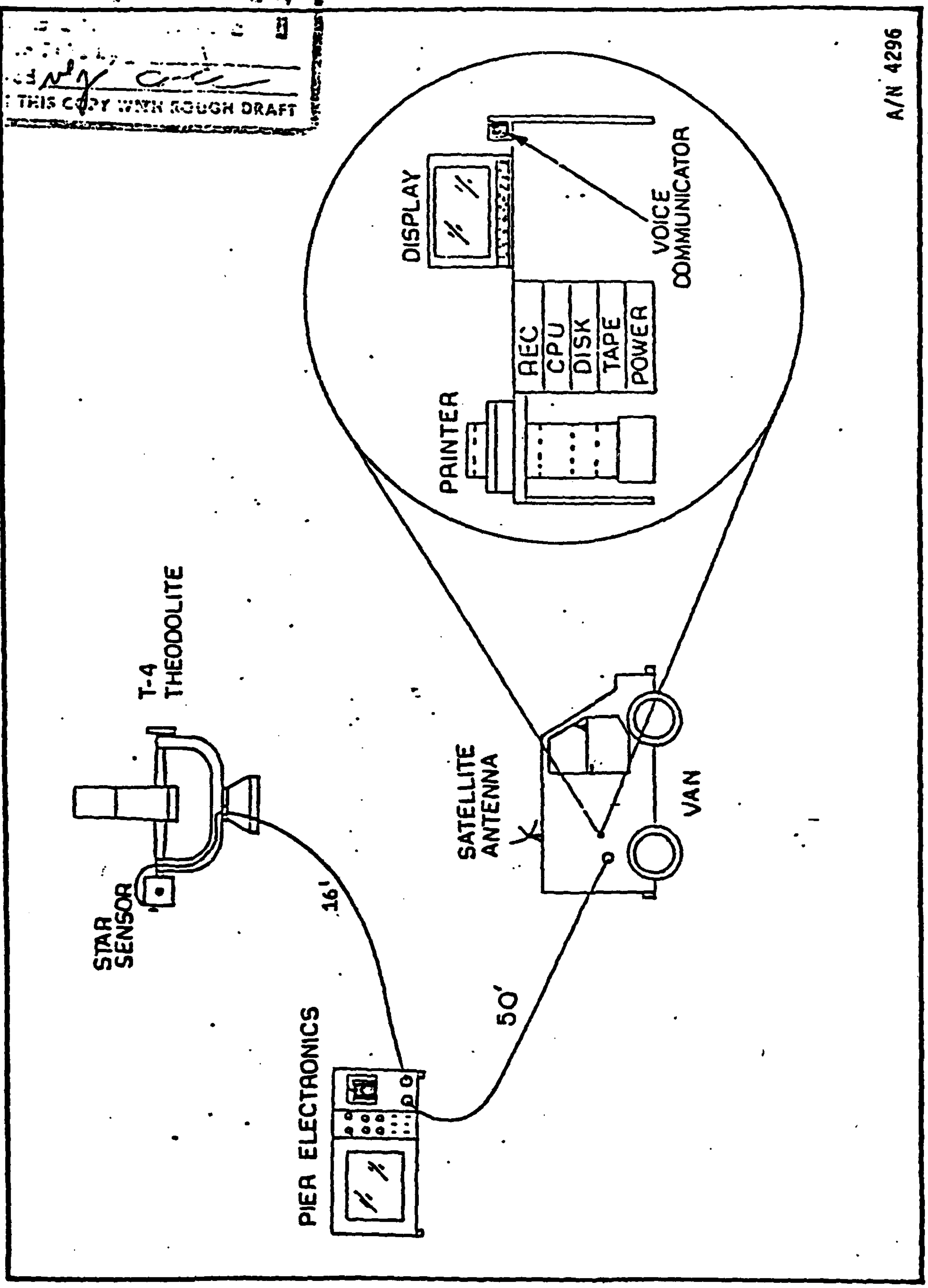


Figure [illegible] DMA Star Sensor Subsystem

SENSOR DESIGN REQUIREMENTS

GENERAL DESCRIPTION: The T-4 theodolite star sensor acquires and tracks a known star entering or in the field of view. Given an initial approximation of the instrument's position on the earth's surface, the sensor system will compute the astronomic position to an accuracy of ±10 feet by precisely determining the time at which a known star crosses the meridional plane through the T-4 theodolite.

A one-sigma accuracy of 3 meters (0."1 sec ϕ) results from data for a minimum of 6 north-south star pairs. This requires a single-star measure of longitude to an accuracy of 0."35 sec ϕ. Since the meridional plane is determined by the intersection of two track vectors referred to as the "in track" and the "out track", the single star longitude is affected by two separate system errors which we call the noise equivalent angle. The system resolution will be better than 0."25 sec ϕ.

The system is required to operate in a terrestrial environment in a temperature range of 0° C to 30° C. Table 7 summarizes the requirements.

TABLE 7
T-4 Star Sensor
Electro-Optic System Requirements

Stellar Magnitude	6.0 to 2.0
Stellar Rate	15 arc seconds/second = 2 Pixels/second (Maximum)
Star Class	0 to M
Single Night Longitude Determination (Mini-(mum of 6 N-S Pairs)	1 σ of 0."1 sec ϕ
Single-Star Longitude	0."35 sec ϕ (0."1 $\sqrt{12}$)
Determination of P (τ) System NEA	0."25 sec ϕ (0."3 $\sqrt{2}$)
Temperature Environment	0°C to 30°C
Operational Period	Sunset to Sunrise

The system needs to store data from about 30 star sightings per observational period and the FK4 star catalogue. The star catalogue is initialized to a precise time base and an approximate geographic location.

TRACKER SYSTEM OPERATION: The star tracker system requires two technicians for operation. A pier operator performs the mechanical adjustment and alignment of the T-4 theodolite, and a van operator controls the system modes with the computer to acquire and reduce data for each star sighting.

The star tracker system operates in four major modes for data acquisition and instrument alignment. The sequence of these modes is:

1. Polaris Alignment

2. Focus.

3. Placing in meridian.

4. Longitude and latitude determination.

This does not include the parameter set up and star list program functions, which initiate the star catalogue file and instrument adjustment. The operational flow diagram depicting both van and pier tasks for meridian transits is shown in Figure 5.

The sensor operates in either a search or track mode, both of which are subsets of the tracker system modes. Two methods of search are incorporated into the system's operation:

1. Edge or linear search (meridian, longitude and latitude)

2. Select area raster search (meridian alignment)

During the select area search, the sensor reads and integrates photon charge over a 16 x 16 pixel array in a raster fashion centered near the theodolite's optical axis. In a "select area search", a specific area near the optical center line is designated on the CID focal plane for a meridional star acquisition. In edge search, a 16 x 16 migrating pixel array is read along the top edge of the detector to detect and acquire stars entering the field of view. In the latitude and longitude determination, the T-4 theodolite is reversed to provide out-track data. As a result of this reversal, reacquisition must resume with a linear search across the central area of the detector.

The "track" mode of operation is entered automatically once star acquisition is completed. During "track" operation, a 4 x 4 pixel array is read and charge is integrated over an update period of 120 milliseconds (maximum). During this "track" update period, data are averaged at intervals called data sets, and consists of six or four non-destructive readouts (NDRO), depending on the star's magnitude. Processing NDRO data at this frequency reduces star scintillation effects.

The T-4 theodolite operational time line for the longitude and latitude star data aquisition appears in Figure 6. The intersection

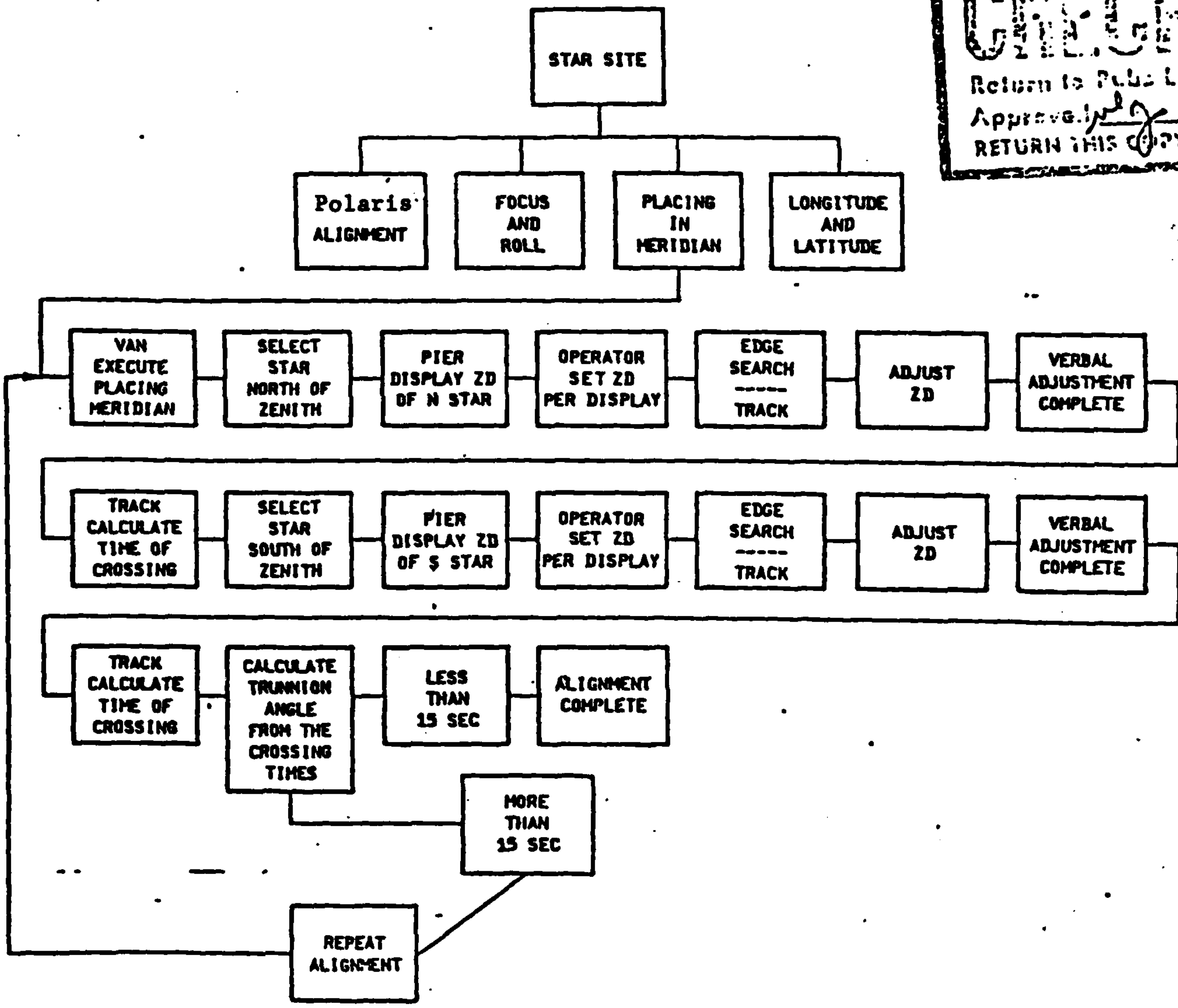
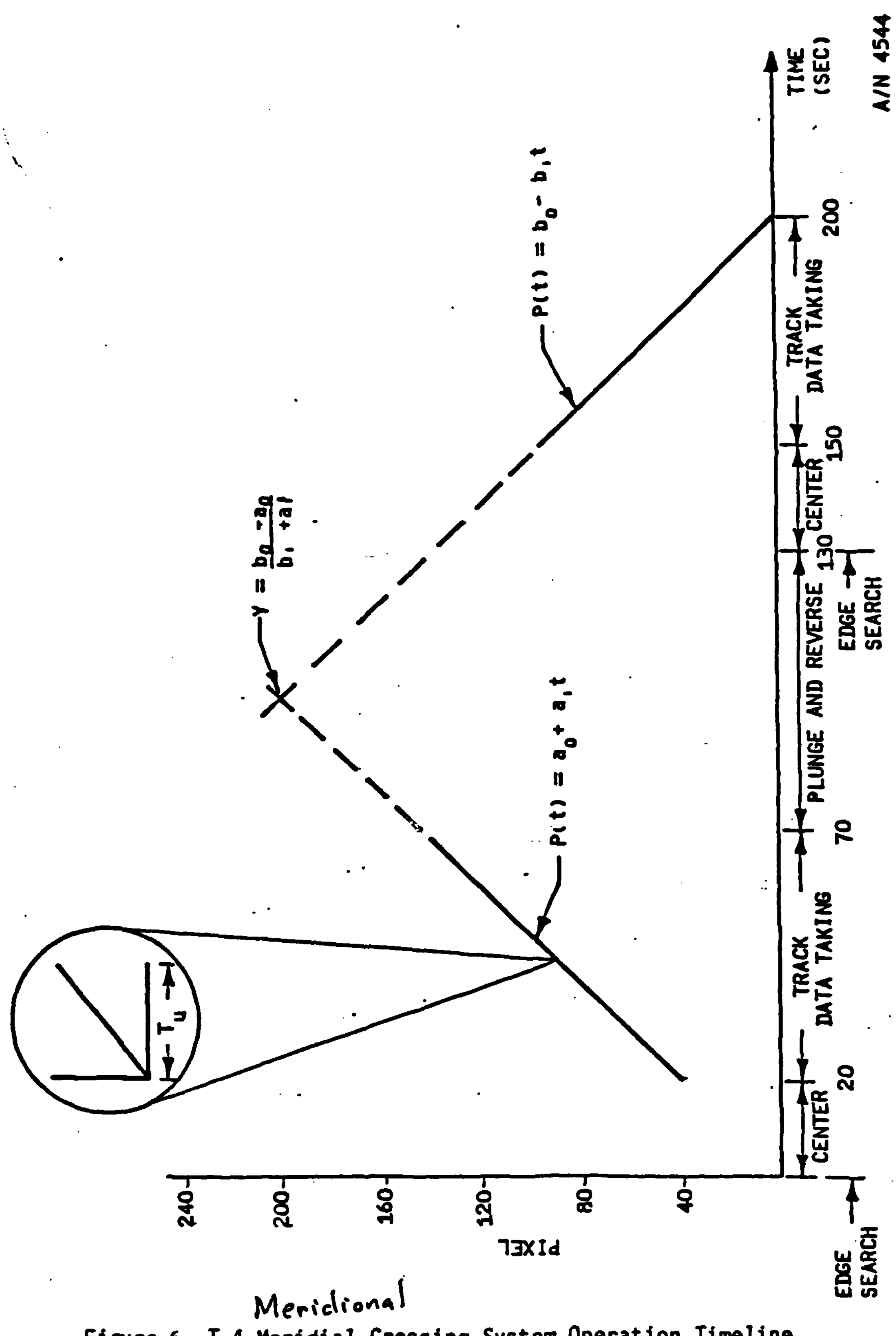
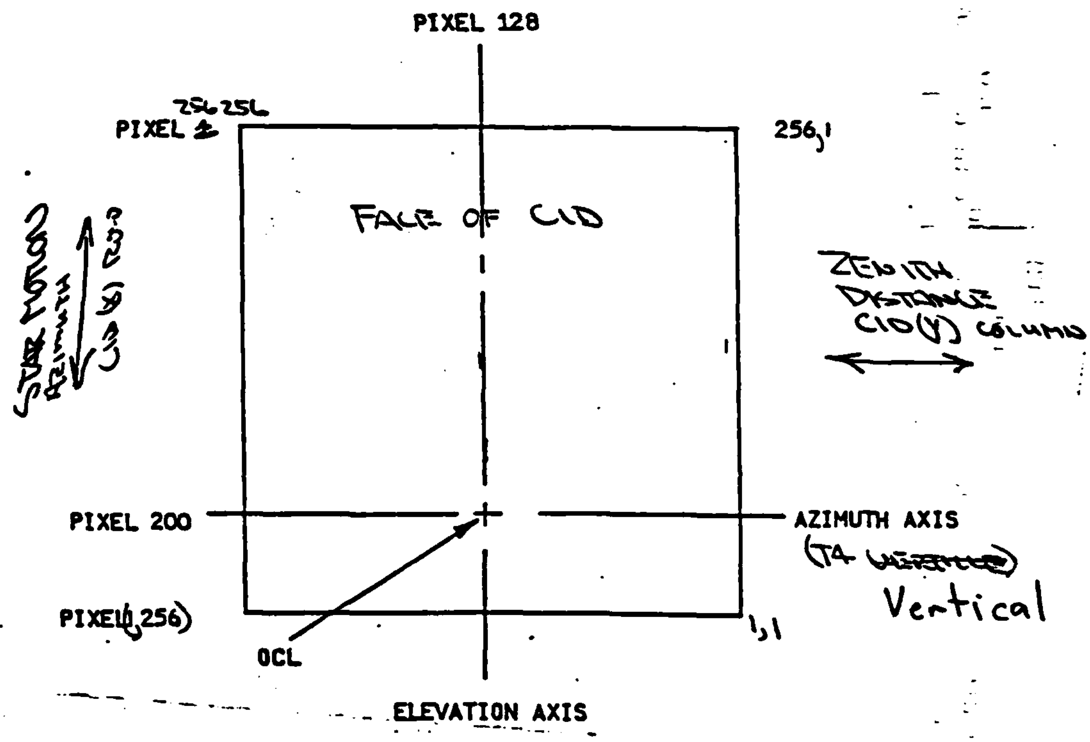


Figure 5 Meridian Crossing Operational Flow Diagram



Meridional
Figure 6 T-4 ~~Meridial~~ Crossing System Operation Timeline

DMA T-4 - DETECTOR FORMAT



$$\text{PIXEL SUBTENSE} = \tan^{-1} \frac{\text{PIXEL SIZE}}{\text{EFL}} = \tan^{-1} \frac{20 \times 10^{-6}}{530 \times 10^{-3}}$$

= 7.78 ARC SECONDS

TOTAL CID
ARRAY FORMAT = 33.2 ARC MINUTES = FIELD OF VIEW

Figure 7 DMA T4 Detector Format

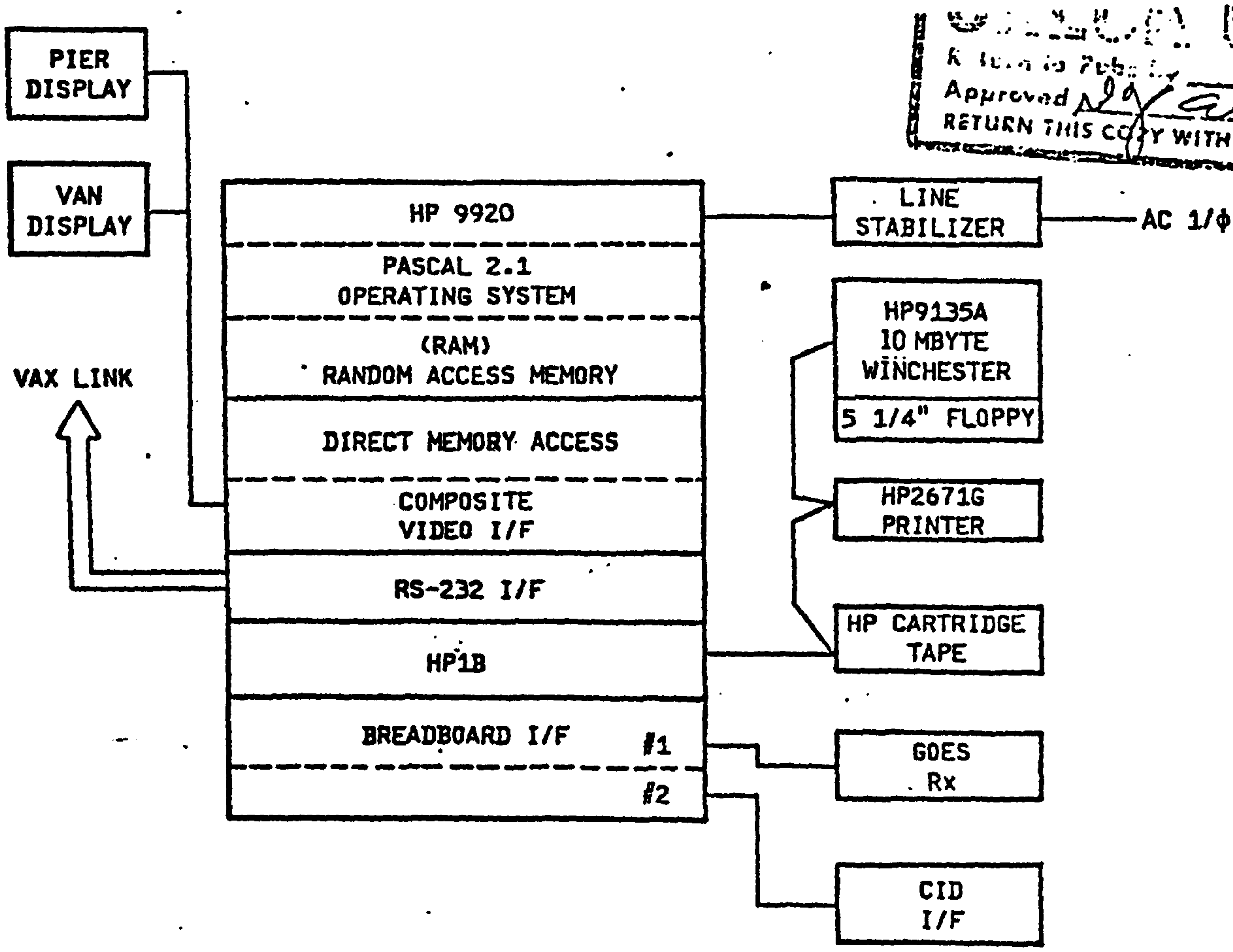


Figure 8 DMA T4 Star Sensor Computer System

point, Y, for in- and out-track sensor data, is the value used to determine actual position coordinates. The operational processes related to time are indicated along the abscissa.

<u>SENSOR COORDINATE AXIS:</u> Figure 7 illustrates the relationship between the T-4 optical axis and the CID pixel matrix. Star motion across the CID focal plane (azimuth) traverses the CID pixel rows (X). The zenith distance is measured by the CID pixel columns (Y). The optical center position on the CID is not used for latitude or longitude determination. The center position is used to determine zenith distance and to provide azimuth alignment of the T-4 theodolite. The optics of the T-4 theodolite are aligned to the mechanical center line. The sensor pixels (Y=128) are aligned approximately in elevation to the X=200 pixels. The actual boresight pixel reference is determined using a collimated artificial star.

Boresight is obtained when the pixel readout is exactly the same after a T-4 theodolite is transitted and in reverse position. These data are input to the operating system software. The roll reference of the CID chip axis to the T-4 axis is determined automatically by the software as part of the meridional tracking procedures. The roll angle of the tracking vector to the CID axis is calculated and then corrected for the pixel angular subtense (7.78 arc seconds). The total field of view is 33.2 arc minutes.

<u>SENSOR SYSTEM SOFTWARE:</u> There are three categories of software used in the system: System Control (SCS), Applications, and Sensor CID control. The applications programs call up the SCS, as required, and SCS software housekeeping functions. The sensor CID control software controls the read and timing functions of the detector (Figure 8).

The sensor computer system's hardware components housed in the van are:

- HP9920 CPU
- HP9920 keyboard
- HP9133B Winchester drive
- HP2671G printer
- HP9144 cartridge tape
- GOES receiver (satellite time base receiver)
- Van display monitor
- AC power conditioner

The CID and GOES interface (I/F) electronics are contained on cards that plug into the back of the HP9920 CPU. The disk drive, printer, and tape connect to the standard IEEE 488 bus (HPIB). The pier and van monitors are connected in parallel to the HP9920 video I/F. This system requires two megabytes of random access memory (RAM).

SENSOR DESIGN

FUNCTIONAL DESCRIPTION: The eyepiece and the vertical setting circle are removed from the T-4 theodolite in order to position the detector in the focal plane. The design of the sensor housing, its attachment, and the associated electronics had to satisfy the following considerations:

1. The total mass of the sensor assembly equals the mass of the items removed from the T-4 theodolite, so there were no changes in torques or stresses on the trunnion axis.

2. The thermal effects to the T-4 theodolite approximates the dissipation of the reading circle illuminator while maintaining the CID at $0^{o}C$.

3. The T-4 can rotate a minimum of 180 degrees about the vertical axis and 40 degrees about the trunnion axis.

The sensor electronics are housed in the assembly attached to the T-4 theodolite (Figure 9). The sensor detector is mounted to the baseplate and placed at the focal point of the T-4 telescope. The mother board assembly is mounted to the baseplate and connects the CID detector to the four circuit cards.

ELECTRONIC DESCRIPTION

PRINTED WIRE ASSEMBLY (PWA): The four PWAs contain the electronics necessary to control and monitor the detector performance. The functions of each is described below.

SERIAL I/O: The serial I/O card is an interface between the sensor and the van computer, providing electrical isolation necessary to eliminate common mode grounds. The selection and conversion of sensor analog voltages are accommodated as commanded by the computer. The -23 volt power input is post-regulated to -19 volts for detector control.

DECODE LOGIC: The decode logic card decodes the van computer control work and generates the address strobes necessary for command routing. It contains the command latches and level shifters necessary for detector mode and data acquisition sequences, and generates the -2 volt and -13 volt references for detector operations.

ADDRESS LOGIC: The address logic card generates the split phase clock signals necessary to drive the detector address shift registers, and

Figure

SENSOR ASSEMBLY ELECTRONICS BLOCK DIAGRAM

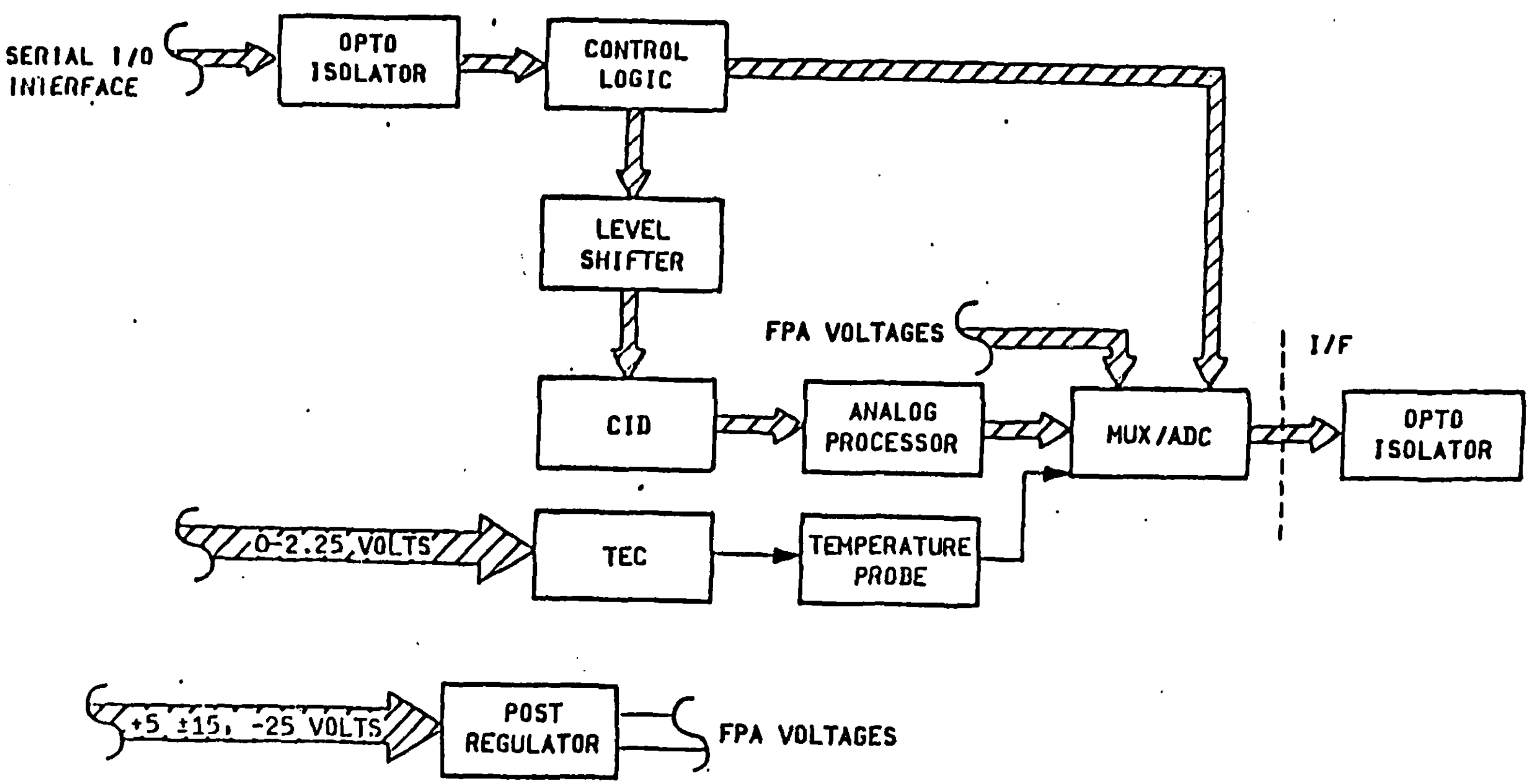


Figure 9 Sensor Electronics Block Diagram

A/N 4544

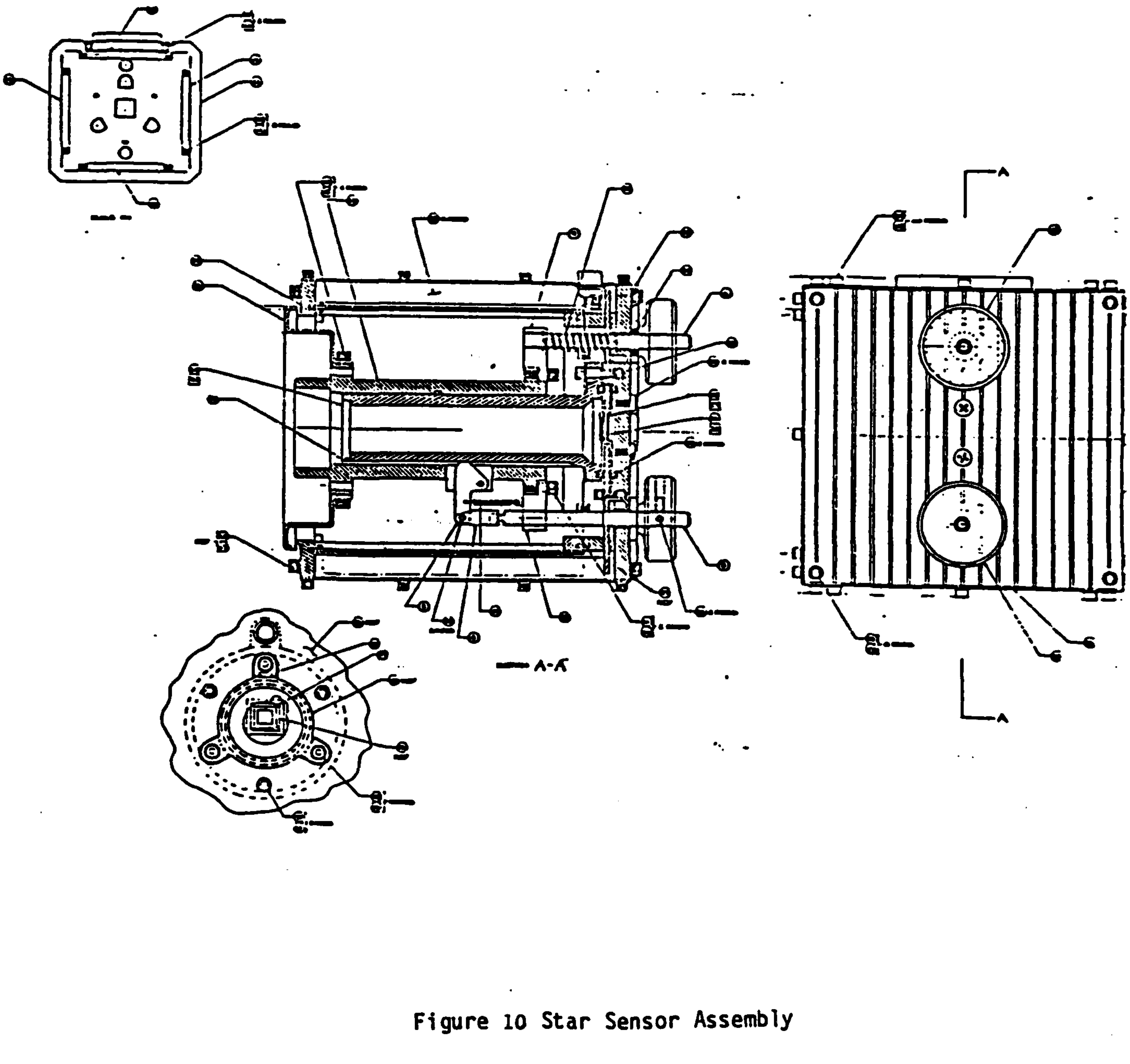


Figure 10 Star Sensor Assembly

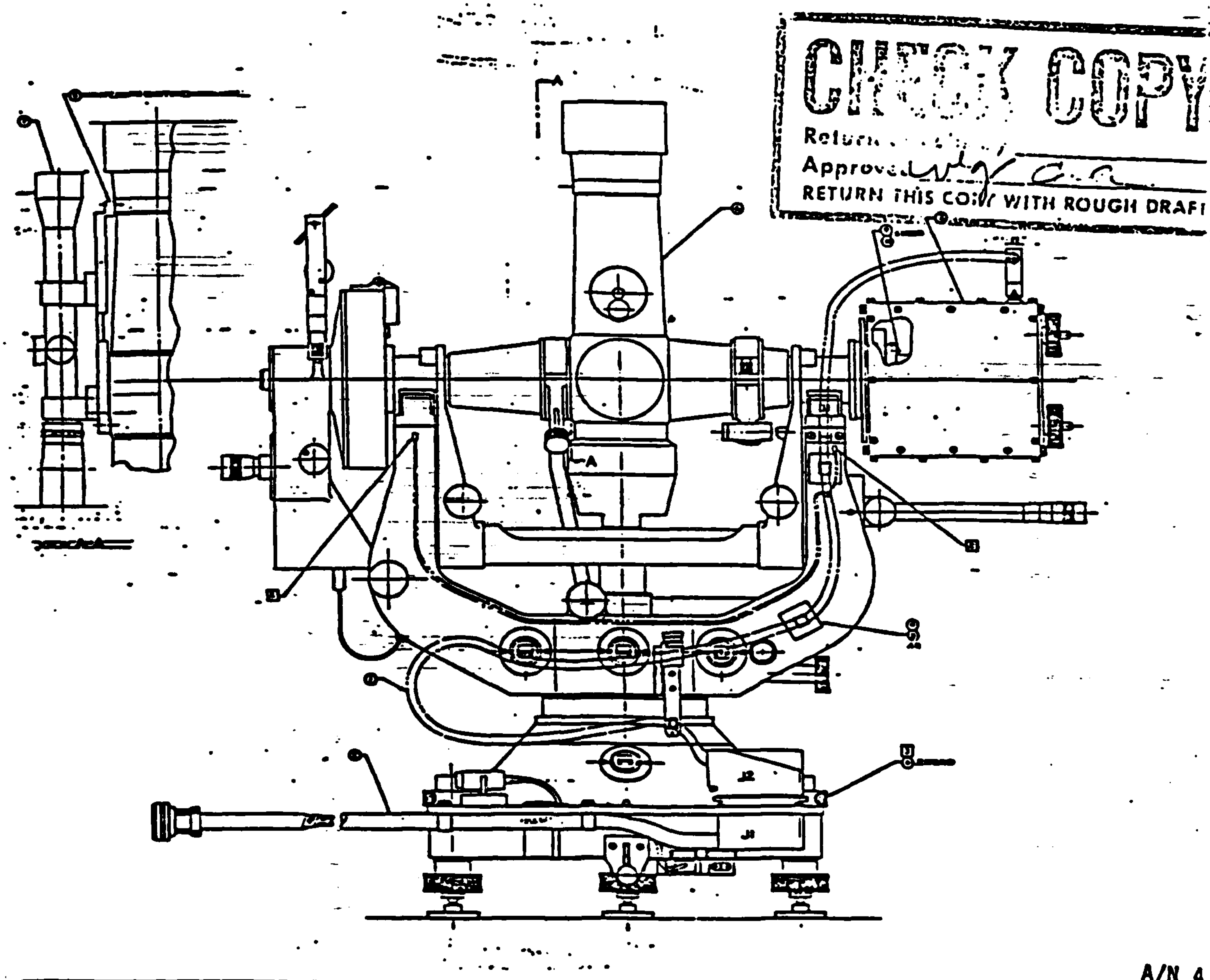


Figure 11 Star Sensor and Theodolite Configuration

generates the -8 volt and -16 volt references for detector operation.

ANALOG PROCESSOR: The analog processor card amplifies the low level readout voltages, then restores the DC baseline of the processing chain and the sample/hold of these voltages while the conversion is made.

SIGNAL FLOW: The van computer data are received by the sensor opto-isolators and level shifted for distribution in the sensor electronics. The clock line is used to enter the data into the shift registers. Each command transmission is supplied to the shift registers in parallel.

Strobe signals control data transfer from the internal shift register to the output latch. Output of the latches, indicated by the signal flow through level shifters or ancillary control logic to the CID, controls the CID. The outputs of the CID are routed to the analog processor where they are selected and converted to a digital word for transmission to the van computer.

STAR SENSOR PHYSICAL DESCRIPTION

The CID star sensor (Figure 10) mounts to the T-4 theodolite in place of the vertical setting circle assembly. (Figure 11)

SENSOR OPTICAL/MECHANICAL DESIGN: The CID detector and thermoelectric cooler (TEC) are bonded to the Kovar baseplate using ceramic-filled epoxy. Kovar was chosen because the coefficient of thermal expansion is nearly the same as that of the aluminum ceramic housing of the CID detector and the TEC.

Three pads on the baseplate and three pads on the sensor support are lapped to 0.000044 inch and are parallel to the baseplate to assure proper alignment of the CID detector to the bore of the theodolite. The sensor support and sensor interface is 6AL-4V titanium which was chosen for its strength and light weight.

The baseplate and sensor support are bolted together with the mother board to form the baseplate assembly which is purged with dry nitrogen. The dry nitrogen purge in the sensor support assures a frost-free CID in a cold environment and a moisture-free CID in a warm environment. The seal of the sandwiched parts is maintained by two Viton O-rings placed on each side of the motherboards.

The four PWAs are held in place by screws at the baseplate and by retaining slots in the front plate. The baseplate and front plate are held together by four aluminum rails, and the star sensor is enclosed by two 0.040-inch thick aluminum covers.

Located at the front and attached to the sensor interface is an electromagnetic interference (EMI) shield, which forms a labyrinth seal with the front plate to protect the PWAs. All aluminum parts are black anodized. The steel parts are passivated, the titanium is left natural and the Kovar is painted black.

The dimensions of the star sensor are 6.75 x 5.6 x 5.6 inches, and its weight is approximately 7.2 pounds.

FOCUS: The focus locking mechanism is located on the star sensor backplate. Focus is obtained by first unlocking the focus lock knob, and then rotating the focus knob while monitoring the X-Y display in the pier electronics. Each mark on the back of the focus adjust knob is equal to a travel distance of 0.001 inch. The preload of the compression spring on the focus adjust shaft eliminates slack. The focus is then relocked by tightening the focus lock knob to a finger-tight setting.

DETECTOR: The detector is a General Electric ST-256 charge injection device (CID). The spectral response is illustrated in Figure 12.

TABLE 8

Detector Characteristics

Characteristic	Parameter
Array Size	256 x 256 Pixels
Pixel Size	20 x 20 µm
Active Area	5.12 x 5.12 mm
Dark Current	10^4 E^-/ sec-pixel at 0^oC
Quantum Yield	0.4 (peak)
Dark Current Variation	0.4% (1 sigma)
Response Variation	1% (1 sigma)
Readout Noise	3.9 E^-/Hz 1/1
Response Point Spread	Trapezoidal

The thermoelectric cooler is mounted to the detector to provide cooling.

PIER ELECTRONICS UNIT

FUNCTIONAL DESCRIPTION: The major functions of the pier electronics unit (PEU) are CID voltage supply, TEC power control, CPU monitor, microphone/speaker amplifier, and the sensor processor I/O interconnect (Figure 13). An audio channel is provided for simultaneous two-way conversations. A video channel is provided to give the T-4 theodolite operator observational parameters and to prompt time critical sequences, and displays the van operator's computer display, so that both operators view the same data.

<u>MECHANICAL DESCRIPTION:</u> The pier electronics are mounted in a standard Tectronics chassis, and designed to contain the Tektronics Model 634 video unit. The video unit requires half of the available space on the chassis. The remaining space houses the electronic circuitry required for the pier functions. This chassis is shock mounted with a removable cover to protect the front panel components.

TABLE 9

Physical Characteristics

of the Pier Electronics Unit (PEU)

- Weight	90 pounds
- Dimensions	10.75 x 24 x 28.5 inches
- Requirements	250 volt-amps

An additional component is the isolation transformer that is mounted on the rear panel of the carrying case. At the pier, the T-4 operator can: (1) apply power to the sensor independent of the processor; (2) set the volume of the audio signal received from the van; and (3) set the T-4 theodolite illumination system brightness level.

The PEU is set up about three feet from the pier. It is placed where the T-4 operator can view the video from both the ocular east and ocular west positions.

VAN ELECTRONICS PROCESSING SYSTEM

<u>FUNCTIONAL DESCRIPTION:</u> The van processing and sensor control system is functionally depicted in Figure 14. The computer components are mounted in the van control console. The environmental characteristics are listed in Table 10.

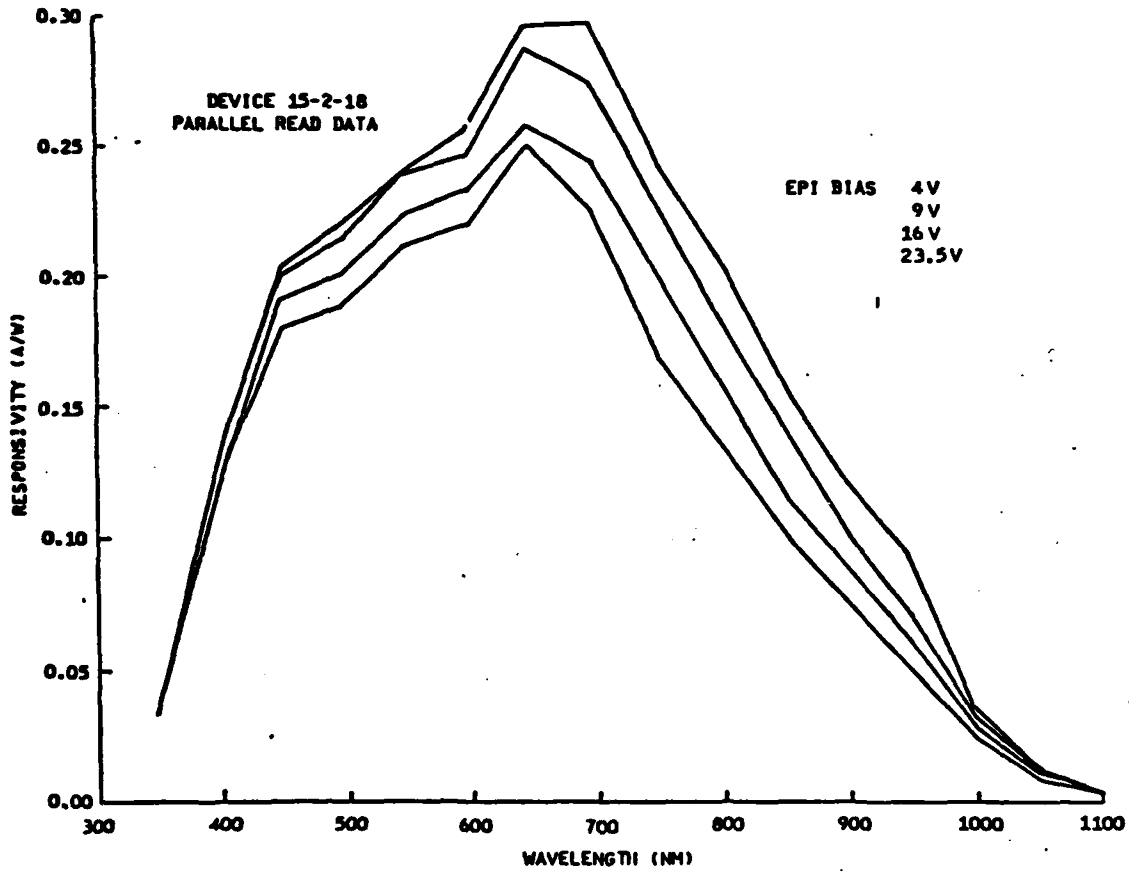


Figure 12 Detector Spectral Response

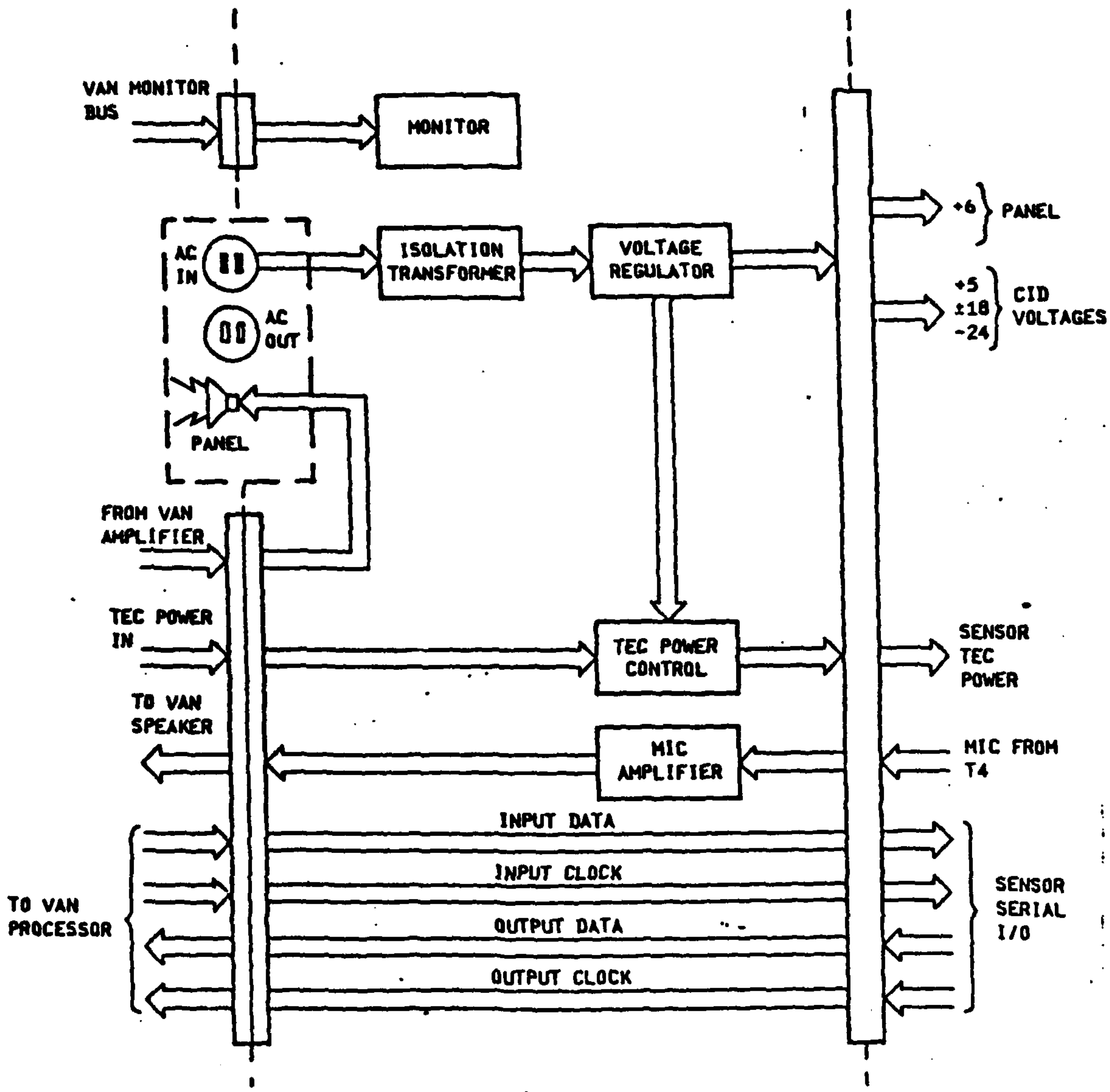


Figure 13. Pier Electronics Functional Diagram

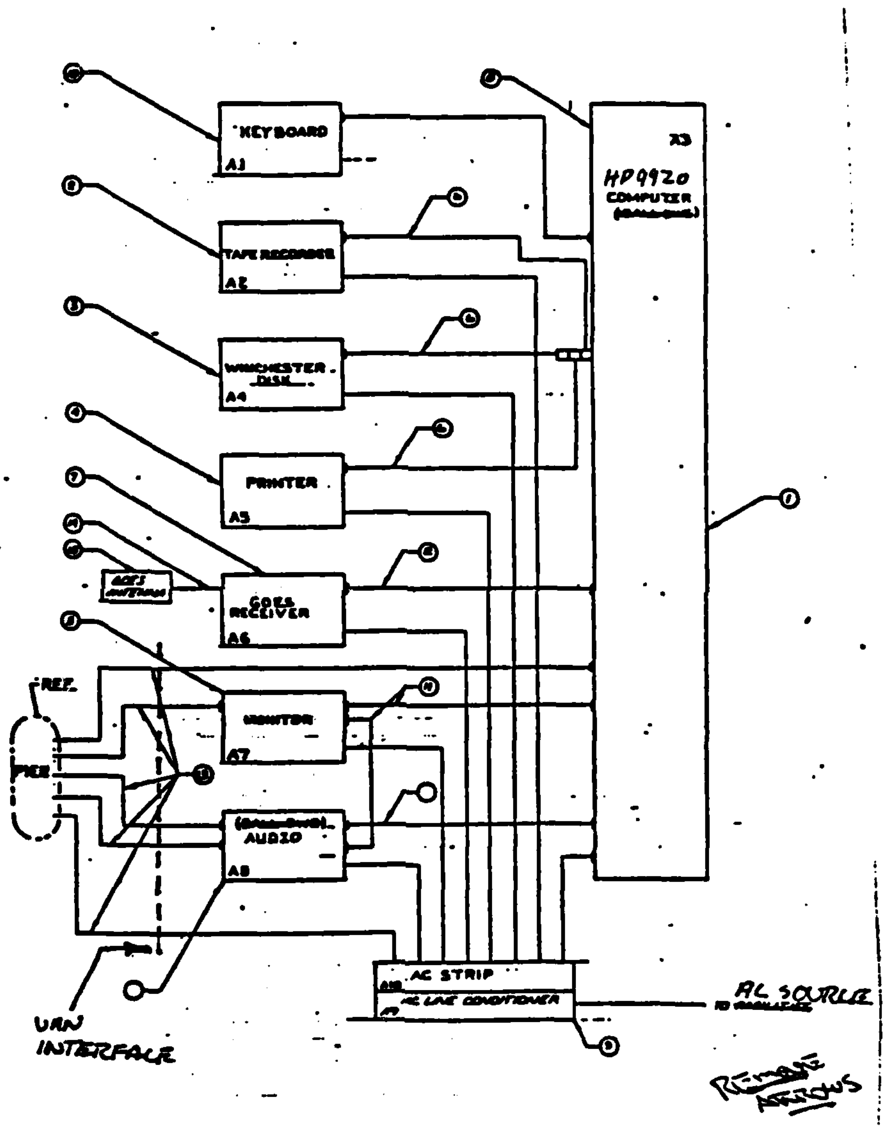


Figure 14 Van Computer System Block Diagram

TABLE 10

Van Environment Range

Criteria	Parameters
Operating Temperature	10°C to +40°C
Humidity	20% to 80% noncondensing
Maximum Wet-Bulb Temperature	+25.5°C
Storage Temperature	-40°C to +75°C
Maximum Altitude	4,572 m (15,000 ft)
EMI	Conducted and radiated interference meets VDE 0730, CISPR Publication II, and FCC Class B Standards
Line Transient Spike Immunity (1 nanosecond rise, 800 nanosecond duration)	1kV
Cleanliness	Class 100,000 Federal Specification 209-B (goal)

THEODOLITE MODIFICATIONS

T-4 THEODOLITE MODIFICATIONS: The major modification for the T-4 theodolite is the removal of the vertical setting circle, the installation of the sensor assembly, the installation of the wiring harness and the installation of the pointing telescope mounts.

T-4 THEODOLITE ELECTRICAL HARNESS: The harness (Figure 11) is permanently attached to the T-4 theodolite yoke, and provides service loops at both ends. The harness permits ±40 degrees of motion about the trunnion axis and 180 degrees of motion about the vertical axis. Also, the harness allows 360 degrees rotation about the vertical axis, when disconnected, to permit leveling of the theodolite. Two temperature probes monitor the T-4 theodolite yoke temperature gradient. The yoke temperatures can be monitored by the processor for system performance checks.

POLARIS SCOPE MOUNTING: The initial orientation of the system calls for the operator to image a star (in the northern hemisphere - Polaris) on the CID. After the star is acquired and tracked to the optical axis of the T-4/CID, the operator can zero the horizontal reading circle. The value used to zero the horizontal circle is taken from the star's right ascension at the time it is tracked to the center of the optical system. The time is taken from the universal time data received from the GOES satellite. To aid in placing the star in the field of view of the CID, a 4X rifle scope is mounted on the theodolite's telescope. The rifle scope can be mounted repeatedly to within ±2 arc minutes. After acquisition of the star and the alignment of the T-4 theodolite horizontal circle, the scope is removed to avoid its striking the hanging level during other operations.

T-4 THEODOLITE INTERFACE PLATE: An adapter plate is provided as an interface between the pier electronics cable and the T-4 theodolite, providing a point for connecting the T-4 harness. It provides a rigid structural member to support the interconnect cable, a mounting surface for the pier operator's microphone, and a LED monitor indicating the status of the pier power system. When this indicator is on, the pier AC/DC converters are powered, and the T-4 theodolite cable should not be connected or disconnected.

FUTURE DEVELOPMENTS

With the successful demonstration of the silicon chip technology using the T-4/CID star sensor eyepiece, there remains the urgent need to replace the base instrument with a precise astrolable designed for maximum optical efficiency with the CID eyepiece. An astrolabe with mercury leveling and an automated azimuth drive would be a totally automated astronomic positioning system which could be driven by a computer similiar to the HP9920 described previously.

The development of a totally automated system would eliminate the need for highly-trained, proficient astro observers presently required for precise astronomic position observations. It would provide the means of observing large numbers of highly accurate astro geodetic deflection stations at a reasonable cost using available manpower resources.

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