

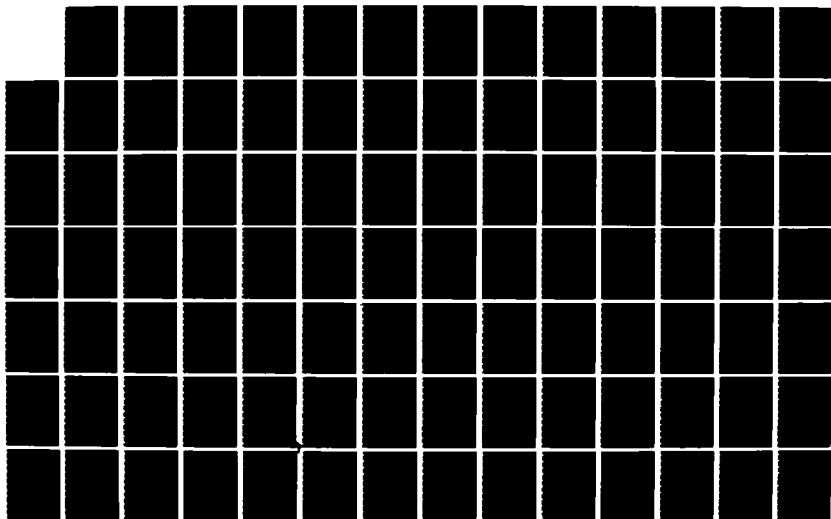
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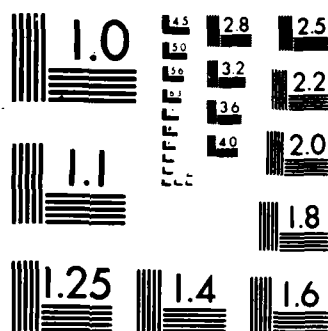
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On Two Color and CCD Methods for the
Determination of Astronomic Position

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14 March 1986

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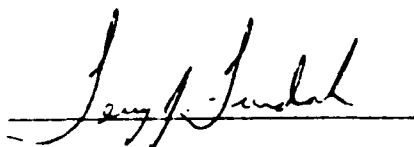
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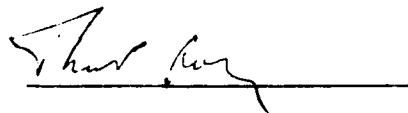
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ASTRO-POSITION AND THE TWO-COLOR REFRACTOMETER

by

Department of Physics and Astronomy
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22 December 1984

I. INTRODUCTION

The long-range objective of the investigations in the area of astroposition within the Amplitude Interferometry Program at the University of Maryland consists of the application of new electro-optical techniques to obtain increased precision, accuracy, and effectiveness in the field operation of an astroposition instrument. The topics which are discussed in this paper relate to a portion of this program, that is, the design, construction, and use of the Two-Color Refractometer (TCR). The purpose of this investigation of the TCR is to provide a series of corrections to the astroposition field measurements which would be made by a T-4 Theodolite or by an Astrolabe. These corrections address the errors caused by the refraction in the atmosphere. The corrections must be applied to the measured star coordinates in order to establish a more accurate value for the astronomic longitude and latitude.

A. Astroposition Objectives As Related to Two-Color Refractometry

The long term objectives consist of:

- (i) Demonstrating the feasibility of an instrument (the Two Color Refractometer), to evaluate the measurement of long-term atmospheric refraction, especially anomalous refraction, and of
- (ii) providing corrections to the measurements made by conventional astroposition instrumentation; for example, a T-4 Theodolite or a field Astrolabe.

The dual objectives of the current project consist of an outline of the design and operation of such an instrument, and a demonstration that such a procedure is feasible.

As shall be discussed later, the projected accuracy for the correction of the long-term anomalous refraction effects (i.e., the correction of the observations obtained during one night for the systematic effects of temperature

gradients) is approximately 0.10 arc seconds.

B. Results

The prototype Two-Color Refractometer #1, when operated on the 24-inch telescope at USNO, demonstrated the appropriate operation of the Two-Color Refractometer scheme when observing stars in the field. An analysis of the data demonstrated measurement accuracies that are relevant to improved astroposition measurements (evaluation of systematic refraction to an accuracy of 0.6 arc seconds.) However, it deviated significantly (by a factor of between 8 and 20, Wellnitz, 1982) from the theoretical performance which might be expected under ideal operating conditions.

An automated field instrument has been fabricated and tested in the field on stars. Up to this time, these observations have primarily yielded information which applies to the development of this instrument rather than a series of astroposition determinations. An additional observing program would be required to permit refinement of this instrument and to permit astroposition measurements to be performed in a regular program.

II. REFRACTION AND ASTROPOSITION

In this section we will consider a short history of the role of refraction in astroposition. Its purpose is to provide a pedagogical review of the origin of the design of the Two-Color Refractometer. This is not intended to be a proper history of the understanding and/or the measurement of anomalous refraction in the determination of astroposition.

A. A Review of the Definitions and Role of Refraction

The earth's atmosphere causes both refraction and dispersion during the passage of a star's light. The simplest form of the calculation of this effect can be made with the assumption that the earth is flat. Then the refraction may be computed directly (Smart, 1965, pp. 58-62) and may be expressed in the form:

$$R = 58.2 \tan z$$

where R is the angle of refraction in arc seconds and z is the zenith distance.

In the case of a spherical earth, the computation depends upon the vertical profile of temperature. The simplest approach is to assume a uniform temperature. In this case (for atmospheric pressure equivalent to 30 inches of mercury and a temperature of 50°F) we have (Smart, 1965, pp.62-68) an expression of the form:

$$R = 58.294 \tan z - 0.0668 \tan^3 z$$

where the units are the same as the previous expression. The case of an

analytic calculation for a simple family of temperature profiles is given by Garfinkel (1944, 1967).

Empirical results which represent the real temperature profiles appear in the Pulkovo Tables (1870) and the Greenwich Table (1898).

An alternate approach, which reduces the apparent requirement for the knowledge of the temperature profile, has been developed (Currie, 1985). The significance of the profile is difficult to separate from the general spherical forms in a conventional formulation. However, this reformulation permits a direct separation of these effects.

In general, the magnitude of the normal refraction is primarily determined by the local temperature, pressure and humidity. With small corrections for the effects of the profile, the normal refraction may be determined with sufficient accuracy when using data measured on the ground near the telescope.

To correct for the locally measured pressure and temperature, the ideal gas law may be used. The refraction is then given by

$$R' = \frac{16.989 P}{459.67 + T} R$$

where R' is the angle of refraction under the altered conditions, R is the angle refraction under standard conditions, P is the pressure in inches of mercury and T is the temperature in degrees Fahrenheit.

For higher accuracy, non-linear forms are required. The comparison of various equations is discussed by Owens (1967).

In the remaining discussion of this section, we will presume that, to first order, the atmosphere is statistically horizontal i.e., there are no changes in the horizontal direction. Then the primary influence of atmospheric composition will influence the angle of refraction only when it occurs in the immediate

vicinity of the telescope (Smart 1965, Currie 1985). In this region, water vapor is the only constituent of the atmosphere which has a significantly large variation which can affect these results. Thus, one must measure water vapor in the region of the telescope during the observation. The influence of other constituent variables are negligible. For example, high altitude ozone is a very small percentage of the atmospheric gases and is distributed approximately uniformly in a horizontal direction. Any effects must be due to horizontal variations and/or the role as it affects the spherical term (Currie 1985). Both of these are very small.

B. Definition of Anomalous Refraction

We define anomalous refraction as the deviation of the actual value of the refraction angle from the value of the refraction angle computed from Smart's equation, above, using locally measured pressure, temperature, and humidity. From a theoretical point of view, anomalous refraction contains the effects of:

- i) any horizontal gradients in the earth's atmosphere (due to pressure, temperature and other effects such as wind),
- ii) any local effects of temperature gradients within the observing structure, generally known as "room refraction", and
- iii) terms involving the combined effect of the upper atmospheric temperature profiles and the curvature of the earth.

As we have defined the anomalous refraction, it does not include the errors which occur in the instrument used for the measurement of star position, nor does it include the normal refraction. Both, of course, will lead to erroneous results for stellar position if they are incorrectly handled.

C. Current Procedures for Refraction Corrections

In this section, we wish to address the current procedures which are used in the field to correct the deviations in star position caused by refraction. The normal refraction is usually computed on the basis of zenith distance and local measurements of pressure, temperature and humidity. A more sophisticated version of the computations which are used for the astroposition reduction may be found in Hofkinson (1952).

An example of the standard procedure for computing refraction for use in field measurements may be found in Table 5 of the Purveying Computer Manual (1964). In this document, on page 413, a table gives the refraction for a specified pressure, temperature and humidity as a function of zenith distance. Corrections for variations in pressure and temperature are given in succeeding pages of the same table.

During normal field operations specific measurements are made to determine anomalous refraction in conjunction with a determination of field astroposition. The procedure used in conventional astroposition measurements to reduce the effects of anomalous refraction is to make observations on several successive nights. This has the implicit assumption that the effects of anomalous refraction will average out, i.e., that there will not be long-term correlation phenomena in the values of the refraction. However, this procedure effectively eliminates the possibility of making an astroposition observation in a single night without accepting the impact of the errors involving anomalous refraction.

The magnitudes of the anomalous refraction which one might observe are highly variable. They range from a small effect to a significant fraction of an arc second. The role of anomalous refraction on open plain observations

is less than 0.20 arc seconds in longitude and (table variate) and 0.12 arc seconds in latitude. These numbers refer to the variation of refraction averaged over one night. This term is the combination of the refraction and variable personal errors in certain other terms. We may make a projection as to the non-random part which would consist of 0.08 arc seconds in latitude and 18.8 arc seconds in longitude. However, for coastal sites we might expect a larger effect due to wind and temperature systems which are stably supported and asymmetric due to the water/land interface. This has an interesting connection with respect to some coastal measurements indicating refraction at the level of 0.4 arc seconds.

In the case of astrometric measurements made at a fixed observatory site, procedures using cycles of observations over a year (or so-called "chaining" of successive measurements) and repeating this procedure on successive nights, leads to the elimination of some of the components of anomalous refraction.

D. Spectral Analysis of Anomalous Refraction

One way to isolate various aspects of anomalous refraction is to consider a representation in which the magnitude of the angles of the anomalous refraction are expressed as a function of the time between successive measurements (either single measurements or average measurements). The Fourier transform of this data will yield the magnitude of the power of the anomalous refraction expressed as a function of the frequency of these observations.

Let us now consider the compilation of data on astrometric errors for various time delays which has been developed by Hog (1968). This data set consists of the information on astrometric errors for a variety of different astrometric instruments and for a variety of different time scales. This data

is combined in a heterogenous manner. When so combined, this data has the form shown in Figure II-1.

This data may be fit by an analytic curve, which may be expressed in the form:

$$\Delta\theta = 0.3(0.65 + t)^{-0.25}$$

where t represents the time interval between two successive measurements and w is the magnitude of the error in arc seconds. If we consider the power spectrum of the errors due to anomalous refraction, then we have a relation of the form shown in Figure II-2. This plot illustrates the generalized dependency of spectral power at different frequencies, showing that there are large amounts of power at low frequencies.

In the spectral representation of the data, the motion of the atmosphere which typically occurs across the aperture of the telescope is seen in the highest frequency portion of the curve. This phenomenon causes an increase in the size of the image. At slightly lower frequencies we see the effects of atmospheric structures which are larger than the aperture size and are carried by the wind. This produces the familiar normal image motion. Thus, the parts of the power spectrum which are contributed by the image motion are found in the high frequency region.

However, at lower frequencies (longer time intervals) the phenomena can be addressed in a different manner. Variations in the anomalous refraction which have time constants of several hours may be related to changes in the wind, pressure gradients within the atmosphere, or thermal phenomena in the atmosphere or in the instrument. Changes in the anomalous refraction with a period of 24 hours could be related to a resonant phenomenon such as the earth

rotation or atmospheric tides (Chapman, 1970). Lunar tides may also be detected in the atmosphere but will not affect astroposition measurements to any accuracy currently under consideration. Variations in the anomalous refraction with time constants that are longer than 24 hours may be the result of major weather systems. For still longer time constants variations occur because of seasonal changes in temperature and weather phenomena, or perhaps due to changes in CO₂ content due to vegetation change with the season (Physics Today, 1982, p.49).

For the normal procedures in the determination of astroposition, significant improvement can occur by combining many separate measurements over a relatively short interval of time. In general, the typical measurement for one night will consist of approximately 6 hours of observations. Frequent measurements which are relatively evenly spaced may occur during this time interval. This can assure that there are not significant aliasing problems at frequencies in the range of 10 minutes to 6 hours. In general, the aliasing problem is significant when there is a significant amount of power in the region which is not sampled. However, for the interval from 1 to 10 minutes, we see from Figure I-2 that there is not expected to be excessive power in this spectral band. Gathering data in the manner described in the previous paragraph, we reduce the influence of the high frequency terms (where this data is combined either by averaging or fitting a derived long-term variation of the refraction) and, with respect to the short period and purely statistical phenomena, obtain an improvement defined by the square root of the number of observations in this interval. As a result, the data is then influenced primarily by those frequency components which have periods which are greater than 6 hours.

We may compare these sets of observing procedures in the following

simplified form: A Modified First Order (MFO) determination of astroposition (AP) is based upon one night of observation, while a First Order (FO) determination of AP is based upon two nights of observation. Therefore, the difference between the determinations will be greatly influenced by the elimination of a class of frequency components. The data from a second night of observations will greatly reduce the influence of frequencies which roughly relate to intervals between 18 and 30 hours. Since data is not taken during the daytime, frequency components equivalent to intermediate intervals of time are not reduced. This will result in an aspect of the problem commonly termed aliasing occurring in the presumption of the improvement in the First Order determination of astroposition. The power rises for longer and longer periods (smaller frequencies). For this reason, the gain in the separated observations will, in general, dominate the aliasing problem. However, if one neglects aliasing, one may theoretically expect improvement in the astroposition determination by a factor of 1.6 (i.e. the fourth root of 5), in going from a Modified First Order to a First Order determination. This estimate is based upon the Hog data (1968, p. 313). Note that this data has primarily been obtained from astrometric observatories, which might alter this factor of 1.6.

The basis of the above arguments is in some sense a grand long-term average over all types of weather, sites, and instruments. There will clearly be large deviations in this data which are related to the personal equation of the observer, weather and wind conditions during an observation, and the existence of room and instrument refraction. Some of these effects are random in nature and will average out. Other of these effects may have longer temporal periods and thus produce systematic errors.

The procedures used by Hog and the observatories from which he obtained

the data will differ from the procedures used in the connection of astroposition data resolution for the elimination of "bad data". This might significantly alter the results in a systematic manner.

Intuitively these phenomena are separate from the expected decrease in the magnitude of the error which we may expect with an increase in the numbers of observations in the same time interval; in principle the accuracy would increase with the square root of the number of observations. Finally, a point will be reached where the accuracy of the result is limited by the systematic (i.e. correlated) effects, including the effect of some part of the anomalous refraction.

E. Impact on Observations

In this section we address the magnitude of the phenomena which might affect the measured refraction. In a simplified model which is vertically isothermal, a horizontal temperature gradient of several degrees per kilometer is sufficient to cause significant errors, i.e.:

$$\text{anomalous refraction angle} = (\text{thermal gradient in } ^\circ\text{C/km})/3.$$

where the refraction angle is in arc seconds. However, such a simple model of the atmosphere neglects the dynamic structure of the atmosphere. That is, while one degree per kilometer will cause an astroposition problem, this calculation does not take into account the equilibrating effects of the atmosphere. That is, it neglects the wind pattern which would be generated by the temperature gradient which, in turn, would reduce the horizontal temperature gradient. It also does not take into account the results of heat inputs into the atmosphere which will maintain these gradients. This illustrates the class of errors we might consider. In order to presume that we are using this as a correction, an empirical analysis of data would be

required.

F. Normal Methods to Reduce the Impact of Anomalous Refraction

The anomalous refraction is generally defined as the primary residual refraction errors which will apply to the measurement of the star position and thus in the determined astroposition. The normal procedure to reduce the impact of the anomalous refraction is to make repeated observations on successive nights. Such a series will average over the meteorological conditions and, subject to the discussion in the earlier section, produce improved values of the astroposition.

However it does not take into account low frequency, or "correlated" errors. For example, seasonal effects and stable topographical effects would have to be evaluated by very careful observational approaches (i.e. chain closing). These are not acceptable in astroposition and, in themselves, do not completely handle the problem.

G. University of Maryland Two-Color Refractometer

As discussed in the previous section the conventional procedure to minimize the impact of anomalous refraction consists of repeated observations to reduce both statistical errors and short term anomalous refraction phenomena. We now consider a new approach to the correction of anomalous refraction in astroposition measurements. This consists of making measurements with a Two-Color Refractometer and using the resulting refraction measurements to provide corrections to the measurements performed by an astrometric instrument, such as a T-4 Theodolite or an Astrolabe.

The University of Maryland Two-Color Refractometer attempts to determine the dispersion by observation of specific stars of appropriate spectral types

and magnitudes. The value measured for the dispersion is then used to compute the refraction and thus provide the input data for the correction of the measurement of astronomic position.

The Two-Color Refractometer consists (Photos, Appendix A) of a small telescope, a color separator and a position measurement device which together may be used to observe a select group of stars. Using the data which one then obtains from the Two-Color Refractometer measurements, one may determine the magnitude of the dispersion caused by the atmosphere acting upon the light from that star. This knowledge of the dispersion and a knowledge of the chemical composition of the earth's atmosphere permit the determination of the magnitude of the angle of refraction affecting the light of this star. The basic calculation and approach has been discussed by Currie (1978b).

III. THEORY OF OPERATION OF THE TWO-COLOR REFRACTOMETER

A. Principle of Operation

The normal mode of operation for the University of Maryland Two Color Refractometer, consists of an observation of an individual star by a specialized telescope and detector system. Within the instrument one determines the separation of the red and blue images of the star in the telescope focal plane. This information is then used to determine the magnitude of the dispersion angle in the star light, which is used in turn to determine the refraction angle. The relationship between refraction and dispersion is listed in Table X by Currie (1978b).

The basic operation of the Two-Color Refractometer has two critical requirements. The first is that determination of the refraction requires a highly accurate measurement of the centroids of both the red image and the blue image of the star as they appear within the Two-Color Refractometer. A discussion of the procedures for achieving this accuracy may be found in Currie, 1978b. The theoretical precision of measurements on a 24-inch telescope is on the order of 1 or 2 milliseconds of arc (Currie, 1978b; Wellnitz, 1982). The second is the requirement of a procedure for the measurement of the magnitude of the angular separation between the red image of the star and the blue image of the star.

B. Astroposition Application

There are two modes by which the Two-Color Refractometer may be used in an observing program or survey for the precise measurement of astroposition. In both cases, we consider a program in which the Two-Color Refractometer is used as a separate, stand-alone instrument. Thus it operates

in conjunction with a separate astrometric instrument such as the Wilde T-4 Theodolite or an astrolabe. The first mode of operation is:

1) Direct Observation Of An Astrometric Catalog star.

This mode of operation consists of the observation of the catalog* star which is simultaneously being observed by the astrometric instrument. The particular advantage to this approach is that one obtains a refraction measurement on the star which is being measured astrometrically. The difficulty with this procedure is that the Two-Color Refractometer operates most effectively on a limited range of spectral types. This is due to the requirements for significant intensity in both the red and the blue images. For this reason, more than half of the stars of the FK4 Catalog would not be acceptable for the Two-Color Refractometer.

While one might make use of a reduced version of the FK5 Catalog, for the present we presume a different approach which is discussed in the next section.

2) Global Characterization of Astro-physical Dispersion

For astro-position, we are primarily interested in the correction and elimination of any long-term errors. For this reason, we can perform a number of observations and combine this data to produce a correction which is applicable for the entire several hour span. We would limit the relevant interval to several hours in order to assure proper sampling of the different temperature regimes of twilight cooling and late-night thermal stabilization.

Most of these observations would be performed near the zenith since a higher precision will be obtained, due to the reduced magnitude of the normal

* By "catalog star", we refer to the star in the astroposition catalog. This is the star for which the angular coordinates will be measured. This may be a star in the FK-4 catalog, the FK-5 catalog, or a special catalog developed for this program.

dispersion. In general, we may expect a class of systematic errors to be proportional to the normal dispersion. The zenith observations reduce the effect of this class of systematic errors.

Implicit in the approach described in this section is the assumption that the average value of the anomalous dispersion does not change radically over different parts of the sky nor at different times during the night. The verification of this assumption will have to await the result of long-term observations.

IV. TECHNICAL DESCRIPTION - IMPLEMENTATION

This section describes the function of each of the important components of the Two-Color Refractometer and then provides a brief description of the hardware. The purpose of this description is to provide a base for an understanding of the operation. More detailed descriptions of these aspects are available in other documents (Currie, 1978a; Wellnitz, 1982).

A. Automatic Guider System

The Automatic Guider System (AGS) consists of an opto/electronic system which provides the data to permit a larger system to automatically center an image. It will also (with less accuracy) determine the position of the centroid of an image. The central unit of this system is a photomultiplier tube with four quadrants, each of which may be used as a photon counting subsystem. This Quadrant Photo Sensor (QPS) and the attendant special electronics permit the counting of photoelectrons in each of 4 pie shaped segments of approximately 90°. The data from these four channels are then used to drive the image to the center of the four diodes. Error signals are provided to correct the pointing of the telescope. A more detailed discussion of the AGS is available (Currie, 1978a).

B. The Prototype Two-Color Refractometer

A prototype Two-Color Refractometer was designed, fabricated, and tested by the University of Maryland. It was first installed for observational testing at the Goddard Optical Research Facility (GORF) 48-inch telescope near Greenbelt, Maryland. It was later moved to the U.S. Naval Observatory 24-inch telescope in Washington, D.C., for further testing and observations. The

important subsystems of this refractometer are presented in the following subsections. More detailed discussion may be found in the Ph.D. dissertation of Wellnitz (1982).

1) Image Centering

The function of the image centering subsystem may be described as providing a capability of centering the image on the face of the QPS. The hardware consists of two small servo-driven mirrors and the electronic system to drive them. The motor/electronic system has a response of about 50 Hertz.

2) Color Wheel

In order to determine the position of the red image and the blue image separately, a color wheel is used to transmit one color at a time. This color wheel interposes red and blue filters successively in the path of the beam. By synchronous detection of the light entering each of the four quadrants of the QPS, one may separately determine the centroids of the red and blue images or, more accurately, errors in the centroids of the red and the blue images.

3) Dispersion Nulling Wedges

The Quadrant Photo Sensor is extremely sensitive and accurate for determining that the image is centered or for determining the position of a nearly centered image. However, the Automatic Guider System is relatively inaccurate in the determination of the image position if the image is significantly displaced from the center. More precisely, the conversion from the information obtained for each channel in the Automatic Guider System to an image offset requires a knowledge of the image size and shape if the displacement is significant. For this reason, we operate the Automatic Guiding System in a manner which drives the image to the center, i.e., in a "nulling" mode.

To assure that both the red and the blue images are at the center of the

QPS, we must provide a technique within the Two-Color Refractometer to introduce dispersion which compensates for the dispersion of the atmosphere. To provide this dispersion, wedges are used to introduce a dispersion which combines with the atmospheric dispersion to produce a null. The dispersion-nulling wedges, which describes the function, are physical optical components which consist of compound glass wedges composed of different materials with properly defined angles. Figure IV-1 shows a cross sectional view of the dispersion wedges in a converging light beam. They are drawn in the position which gives maximum dispersion power. This indicates the separation of a red and blue image for non-dispersed input of white light.

In order to permit control as to the magnitude and direction of the dispersion, two wedges are needed. These are servo-driven in angle in order to introduce an arbitrary amount of dispersion in the light, within the limit defined by the maximum dispersion to be nulled.

In order to continuously correct for the dispersion introduced by the atmosphere, these wedges are motorized and driven with error signals generated within the microprocessor of the Two-Color Refractometer. To determine the position of these wedges which properly compensates for the atmosphere, 16-bit encoders are used to determine each wedge position, resolving the position to 0.01 degrees for each wedge.

4) Pulse Handling Electronics

Pulses produced by photoelectrons from the Quadrant Photo Sensor system must be amplified, discriminated, and sorted for use in fine pointing for color separation, and then used to drive each of these two wedge systems.

5) Image Centering Servo Structure

The errors in the positioning of the centroid of the image, as detected by the differential counts in the quadrants of the Automatic Guider System,

are averaged, and this data is used to drive the fine position mirrors such that the image will move toward the center of the QPS. The speed or time constant of this drive may be adjusted by various system parameters. The choice of these parameters depends upon the detailed applications and operating conditions of the system.

6) Dispersion Servo Loop

Within the TCR, the data from the four quadrants is procured in a synchronous manner in order to determine the centroids of the red and the blue images separately. This data is then used to provide the information for moving the wedges. The computation of the separations of the centroids must be followed by a calculation which incorporates information on the current wedge positions as well as the amount of residual dispersion which must be corrected. The output is the drive data to move to new wedge positions.

7) Data Recording

The most important aspects of the data recording are the angular positions of the dispersion nulling wedges recorded as a function of time. This information is the key data for determination of the amount of dispersion required to counteract the dispersion of the atmosphere.

Various types of secondary data are also recorded. For example, the photo counts give the apparent offsets of the image on the photomultiplier. Although the counts have not been extensively used to date, they may be used for a fine correction.

Other data recorded permit evaluation of the system operation and evaluation of required constants.

C. The Prototype Field Two-Color Refractometer

The prototype Field Two-Color Refractometer was developed to study the

problems of constructing and using a field-operable Two-Color Refractometer. A number of new requirements and improvements as well as our experience with the prototype Two-Color Refractometer directed the design of the new instrument. We considered the following points. The instrument should

1. be as self-contained as possible,
2. operate as automatically as feasible,
3. be easily transportable, therefore light in weight and small in size.

These considerations led to a completely redesigned refractometer package, including a telescope and all of the electronics needed for operation. All optical components which could be used unaltered were so used, but some required new mounts or differing electro-optical interfaces. The differences between the prototype Two-Color Refractometer and the prototype Field Two-Color Refractometer will be described in the following sections.

1) The Mounting Structure

The basic mounting structure consists of a 24 by 36 by 1 inch aluminum plate stiffened by a perpendicular longitudinal aluminum rib 1 inch thick and 11.5 inches high. A frame of light angle aluminum was erected to form a box 36 by 24 by 24 inches. The interior of the box was divided into 4 bays containing the telescope, the refractometry optics, the power supplies and the refractometry electronics. The box was designed to be supported from axles projecting from the centers of opposite sides of the aluminum plate. The exterior was partially covered with black material to exclude light from the optical areas while maintaining accesses to the electronics and controls. Doors were provided to achieve access to the optical components for adjustment and for operation. Cable connections were provided to allow remote control, supply of power, and data recording.

2) Telescope

To collect starlight and provide an image of the correct size at the photosensor, a custom-designed Kierken-Dall Cassegrain reflecting telescope was built. The main aperture is 8 inches, with the secondary mirror providing an f/20 beam at a location about 40 inches beyond the primary, to accommodate the refractometry optics.

Tests of the telescope in a well-collimated beam of white light showed it to provide a nearly diffraction-limited image, of about 0.5 arc seconds, when the primary and secondary were properly aligned. Due to the unusual requirements on the optical design of the telescope, the exact alignment of the secondary to the primary was found to be quite crucial to maintenance of image quality. Also, slight motions of the secondary cause large changes in image position, so vibration of the secondary mirror must be kept to a minimum.

To allow the large changes in focus of the telescope necessary for the testing of the refractometer, the secondary was made longitudinally moveable. At first, a threaded mount was used for the secondary, which allowed adjustment of telescope focus by rotation of the secondary. When it was found that the mirror could not easily be made sufficiently perpendicular to the axis of the threads, and that the total range of focus adjustment was inadequate for testing purposes, a lockable linear translation stage was added to move the entire secondary mount. This method of focus adjustment was found to be satisfactory and also provided a read-out of the focus setting by means of the adjustment micrometer screw.

3) Color Wheel

The color wheel of the prototype refractometer was driven by a synchronous 60-Hertz 120-VAC motor, locking the rotation of the color wheel to the frequency of the power line. Instead of synthesizing 60-Hertz alternating

current for the field refractometer, we replaced the AC motor with a 24-volt DC motor and used a precision electronic servo to control the speed of rotation of the color wheel. This resulted in much lower power used to maintain proper rotation of the color wheel and also eliminated 120 VAC from the instrument, resulting in greater safety for the operator.

4) Micro-Computer

A micro-computer was built directly into the electronics of the refractometer. The micro-computer was needed for calculation of the wedge positions needed to cancel the residual dispersion derived from the red and blue counts from the Quadrant Photo Sensor. It was also useful for reading out and formatting data and for increasing the automation of the refractometer. As a developmental testing tool it was extremely useful, since revision of the control programs could gather additional diagnostic data, allow testing of alternate control and servo algorithms, or sometimes solve unforeseen problems. However, the micro-computer used in the field refractometer had fewer capabilities than the mini-computer which had been used to operate the prototype refractometer, so some of the functions which had previously been performed by the computer were implemented in hardware for the field refractometer.

5) Pulse Handling Electronics

Extensive changes were made in the electronics which handle the electronic pulses which represent photons received by the Quadrant Photo Sensor. Some of these changes were directed towards reducing or eliminating radio-frequency interference (RFI), cross-talk between channels, and count-saturation, which had been identified as possible problems during the testing of the prototype refractometer. Other changes were made to allow operation of the internal guiding mirrors in a full integral-mode servo system, which was

hoped to reduce the requirements for fine pointing of the entire unit, identified as one of the major contributions to systematic errors in the refraction measurements of the prototype refractometer.

6) Data Recording

In addition to the refractometry data recording usually done, a data acquisition system was installed to allow collection and display of operating information concerning the refractometer. This data was used to remotely monitor the performance of the components of the field refractometer and aid in diagnosing problems during development and testing.

7) Mounting and Pointing of the Prototype Field Refractometer

At various stages in the development and testing of the prototype field refractometer, various mounts were used to hold and to point the refractometer towards a source. For alignment, transportation, and early testing a cart was used. This cart allowed manual adjustment of the pointing around the elevation axis, and crude adjustment of the azimuth by positioning of the cart. For testing requiring finer pointing of the refractometer, DC motors were added to a machine table, allowing pointing of the refractometer towards a source. To test fine servo-controlled acquisition and tracking of a source, the entire refractometer was mounted in a suspended balloon gondola with elevation and azimuth control to sub-arc second levels. For development and testing of the refractometry capability of the field refractometer, it was mounted on an optical table and a servo-controlled heliostat and bending mirror combination was used to direct starlight into the telescope.

V. ANALYSIS PROCEDURES AND RESULTS

This section addresses various aspects of the analysis procedures and discusses the successive stages in the analysis of Two-Color Refractometer observations. Observations were made with the prototype Two-Color Refractometer during the summer and fall of 1981. Some of these observations were extensively analyzed to evaluate the capabilities and potential of the Two-Color Refractometer in measurement of refraction and to identify the sources of random and systematic error and operational difficulties (Wellnitz, 1982). This analysis and its results will be summarized here to show the potential of the Two-Color Refractometer. Additional observations were made with the prototype Field Two-Color Refractometer during 1983 and 1984. The analysis of some of these observations will also be presented here, together with the conclusions which can be drawn.

A. Raw Real-Time Data

The basic observation cycle which has been used for the operation of the Two-Color Refractometer consists of the following steps.

- 1) Position the wedges.
- 2) Accumulate the red and blue counts from each quadrant for the preset integration time.
- 3) Record the time, total red and blue counts from each quadrant, and wedge positions.
- 4) Calculate the difference of the offsets of the red and blue images from the accumulated counts.
- 5) Calculate the magnitude and direction of the uncanceled dispersion and vectorially add it to the dispersion contributed by the wedges at

their current positions, to obtain the total dispersion.

6) Calculate the wedge positions which will cancel the total dispersion.

7) Go back to 1 and repeat.

The integration time used in the observation cycle has generally been about 10 seconds, as a compromise between reduction of photon noise and the need to move the wedges to cancel the dispersion of the slowly varying atmospheric refraction. Though the wedges at first may not cancel the atmospheric dispersion, each pass through the basic observation cycle should bring them a bit closer. Eventually the wedges cancel the atmospheric dispersion almost exactly and begin to track it. It would be possible to pre-calculate the wedge positions to pre-position them to nearly cancel the atmospheric dispersion. However, the various mounts used with the refractometers produce differing projections of the atmospheric dispersion, and its variation with time, in the frame of reference of the refractometer. A differing calculation would be required for each configuration. The effort to program for each case has not yet been justified. For a field refractometer with a given configuration, such a pre-positioning of the wedges would allow quicker positioning of the wedges to cancel the atmospheric dispersion, resulting in quicker measurement of the refraction.

Another improvement in the basic observing cycle would be to predict the amount and rate of change of the dispersion and slowly move the wedges to follow it during the integration. This should improve the accuracy of the measurements by allowing a reduction of the photon noise through increased integration time. However, the effort to prepare the differing programming has not yet been justified under the current work.

The recorded data consists of the integrated red and blue photon counts from each quadrant, the positions of the wedges, and the time, spaced at

intervals of one integration time. If the dispersion has been nulled, the positions of the wedges are directly related to the dispersion of the atmosphere and therefore to the refraction of the atmosphere. The position of each wedge is encoded with a precision of 0.01 degrees. If the position angles of the wedges are f and g and the dispersive powers at focus of the wedges are each equal to h , the magnitude of the dispersion of the wedges c will be given by

$$c = 2h \cos ((f-g)/2).$$

Notice that c is maximum when $f=g$ (wedges aligned), and zero when $f-g=180$ degrees (wedges crossed). This formula is exact only when the dispersive powers of the wedges at focus are exactly equal; however, the wedges are designed and positioned to closely approximate this situation. The dispersion of the wedge combination changes most rapidly when the wedges are nearly crossed. When the wedges are nearly crossed, a change of 0.01 degrees (the resolution of the wedge angle encoder) in one of the wedge angles changes c by $0.000746 h$. The usual wedges used in the refractometers allow nulling the dispersion caused by 80 arc seconds of refraction, corresponding to the refraction at a zenith distance of about 54 degrees. Therefore up to 80 arc seconds of refraction can be measured with a resolution limit of 0.007 arc seconds due to the encoding of the wedge positions. In general, other sources of error have come into play before this limit has been reached.

B. wedge Angle Determination

Since the refraction measurements are determined directly from the positions of the wedges as a function of time, knowledge of the actual angular position of the dispersion vector of each wedge is essential. As stated

above, the angular difference of the positions of the wedge dispersion vectors determines the magnitude of the dispersion produced by the wedge combination. The position angle of the dispersion produced by the wedge combination lies between the dispersion vectors of the two wedges, and is the mean of the position angles if the wedge dispersions at focus are equal.

After the wedges were mounted in the rotary tables, a laser beam was used to determine the relative positions of the dispersion vectors to within about 0.05 degrees. The relative position of the dispersions of the wedges is the crucial parameter for determination of the magnitude of the refraction. At the same time, the position of each dispersion vector was determined with respect to the mounting baseplate within about 0.05 degrees. However, the angle of the projection of the dispersion vector in the sky is less well determined due to the mounting of the refractometer on a support for tracking of the stars. For the refractometer used at the U.S. Naval Observatory 24-inch telescope, the angle of projection on the sky was known only to about 1 degree.

Better determinations of the actual projected dispersion vector produced by the wedge combination can be made by special observations together with data analysis techniques which allow the exact position angle of each wedge to be a free parameter which is determined by the overall data. Since the functional dependence of the dispersion vector is so unlike the variation of the dispersion of the atmospheric refraction, there should be little interdependence, allowing a unique solution for the exact positions of the wedge angles. It is also expected that the dispersive powers of the wedges at focus will differ slightly. Therefore the dispersive power of each wedge should be allowed as a free parameter to be determined. To date, due to the ongoing development of the refractometer, the configuration has not been

maintained stable for a sufficient time to gather the amount of data necessary for this determination.

C. Results from the Prototype Two-Color Refractometer

The prototype Two-Color Refractometer was operated at the U.S. Naval Observatory 24-inch telescope in a development mode from the summer of 1980 through the fall of 1981. During this time a number of operational problems were characterized and resolved. From the spring through the fall of 1981, refraction measurements of increasing reliability were made, culminating in a series of observations made on the night of 25/26 November 1981. These observations were extensively analyzed and have been presented by Wellnitz (1982). These observations will be briefly presented here to demonstrate the type of observations the refractometer is expected to make and to show the accuracy obtained at that time.

During the early part of the night, a number of observations were made of Beta Cygni A and B. Beta Cygni A is a close double star whose components are separated by about 0.4 arc seconds. Beta Cygni B served as a nearby star for refraction calibration. The refractometer responds to the color difference and separation of a close double star in a way which can be characterized fairly exactly. These observations were intended to demonstrate the capability of the refractometer to detect close double stars, to measure the position angle of a close double star, and to determine the separation of a close double star. In these goals we were successful, with results approaching those of speckle interferometry. The importance of these observations in the current refractometry work is that the refractometer measures the offset of the red and blue photocenters of a double star as a component of the dispersion signal, so double stars contribute a constant

offset to the measured dispersion and refraction of the atmosphere.

Furthermore, the refractometer can be sensitive to separations of double star components as small as 1 millisecond of arc, so special care must be taken to identify double stars among the stars observed for refractometry analysis.

During the later part of the night, two to three observations were made of four stars: Alpha AND, Epsilon CAS, Eta TAU, and Eta AUR. Attempts were made to observe each star before, during, and after transit, but scheduling and operational difficulties made this impossible. A major problem at the time was contamination of observational data sets by radio frequency interference (RFI), which had been identified as coming from television Channel 4. A check was made after each observation for the presence of the noise associated with this RFI. If it was found to be present, the data set was marked as questionable and operational procedures were used to reduce or eliminate the noise for the next observation. The results of the analysis of this data will now be presented.

Figure V-1. shows the X component (declination) and Y component (right ascension) of the residual color derived from the red and blue photon counts as a function of Greenwich Mean Time (GMT). The breaks in the data reflect the time taken to switch between stars. Proper operation of the refractometer should result in the driving of the wedges to null the residual color. From inspection of these graphs it is seen that the residual color has a mean of about zero. This data was also averaged for the segments which were chosen for refraction analysis and found to average to zero within the usual rms limits.

Figure V-2 presents the right ascension and declination components of the dispersion (here labelled color) introduced by the wedges. The units are an arbitrary unit designated wedge color units. One wedge color unit corresponds

to approximately four arc seconds of refraction; the conversion factor is determined more accurately in the data analysis which follows. The general trend in refraction due to the motion of the stars is especially noticeable in the right ascension component: the observations of the four stars fall onto four nearly straight lines. The last observation is of Eta AUR through transit. This star transits nearly through the zenith at U.S. Naval Observatory. Since the refraction approaches zero at the zenith, the magnitude of the dispersion to be provided by the wedges approaches zero, and the wedge angles become highly variable and then indeterminate. The wedge servo system could not handle this variation and become unstable even though the gain of the servo was varied over a large range. Therefore this last observation was not used in the analysis which follows.

To reduce the random noise and better show the trend of the data, a boxcar averaging technique was used. Figure V.3 shows the result. Each data point has been replaced by the average of itself with the preceding 16 and following 16 points. The nearly vertical features at the beginning and end of the observation of each star are caused by the averaging together of data from two different stars, and the slight ripples seen at the beginning of some of the observations are due to the delay before exact cancellation of the residual color was accomplished by the wedges. The averaged observations show some irregularities but are in general remarkably free of unexplained variation, especially compared to earlier observations.

Using these graphs as a guide, 100 continuous ten-second data points were taken from the center of each observation run, except the last one, and used to evaluate the local refraction. For each point, the expected refraction was calculated using the coordinates of the star, the coordinates of the observatory, the time of the observation, and the local temperature and

pressure at the time of observation. Then both data and predictions were averaged in the same way to produce a 1000 second observational data points and associated predictions for right ascension and declination. A grid search program was used to fit the data to the refraction, with three free parameters: the conversion between mean refraction and wedge color, the RA offset, and the declination offset. The results of this fitting procedure are shown graphically in Figure V.4. The vertical scale is in wedge color units, while the horizontal scale is in arc seconds of refraction.

Since the fit is fairly good, it is instructive to see the residuals, shown in Figure V.5. Once again the vertical scale is in wedge color units. From this fit, we have the following results:

- 1) one wedge color unit is 4.177 ± 0.037 arc seconds of refraction,
- 2) the right ascension offset is 1.076 ± 0.315 arc seconds, and
- 3) the declination offset is 0.722 ± 0.321 arc seconds.

The conversion of wedge color units to refraction is consistent with that predicted from the designed wedge strength. The right ascension and declination offsets are consistent with the amounts expected from instrumental effects, which should be characterizable with more observations and special observing procedures, such as rotation of the instrument. The errors are approximately a factor of three larger in size than predicted by photon noise theory, indicating a possibility of systematic effects which have not been taken into account. Due to count saturation effects, the count rates were limited to lower rates than would generally be used, raising the photon noise significantly.

Later correlation studies showed a very high correlation of the wedge position errors with telescope pointing errors. It appears that the telescope pointing was not sufficiently accurate, leading to major problems in the

measurement of refraction. Improvement in the telescope pointing could be expected to reduce the noise by a factor of as much as three, which would greatly improve the refraction measurements.

Though these results are encouraging, they do not reach the limits expected of the refractometer. However, it appears that the operational problems which remain are soluble, and that the refractometer could approach its predicted theoretical accuracy in the measurement of refraction.

D. Results from the Prototype Field Two-Color Refractometer

The prototype Field Two-Color Refractometer was designed and constructed at the University of Maryland. Extensive testing and debugging of various subsystems was performed at the University of Maryland, Goddard Space Flight Center, and Holloman Air Force Base. For development of the wedge driving software and measurements of the atmospheric refraction, the refractometer was installed in our facilities at the Goddard Optical Research Facility. A heliostat and bending mirror combination was used to feed the starlight to the telescope of the refractometer, allowing the instrument to be solidly mounted on an optical table for relatively easy access during the development phase.

After discovering and dealing with various problems, the wedge drive loop was successfully closed in June of 1984. As soon as data recording capabilities were added to the system, refraction observations were begun. Due to various problems, not every night of observation produced useful recorded data. The following table summarizes the data which was recorded.

Star	Date	Times, GMT	Records	Comments
Arcturus	22 Jun 84	02:06:10-03:03:10	259	Lost in middle of run.
Vega	22 Jun 84	03:40:40-04:34:10	286	Relaxation oscillation.
Altair	22 Jun 84	05:03:10-05:45:50	226	OK.
Vega	22 Jun 84	06:13:20-06:59:20	234	Relaxation oscillation.
Altair	22 Jun 84	07:25:00-07:55:00	160	Relaxation oscillation.
Arcturus	27 Jun 84	03:48:20-04:40:00	280	OK.
Vega	27 Jun 84	05:17:00-05:54:40	205	Lost 05:24-05:28 bad block.
Altair	27 Jun 84	06:25:10-07:05:00	216	OK.
Deneb	27 Jun 84	07:49:20-08:29:30	218	OK.
Deneb	16 Aug 84	05:24:30-06:06:30	228	Bad nulling.
Altair	16 Aug 84	06:31:20-07:13:00	217	Bad nulling first half.
Vega	17 Aug 84	01:50:50-02:54:40	346	Thru transit, small osc.
Deneb	17 Aug 84	03:18:20-04:47:40	484	Thru transit, small osc, bad blk.
Altair	17 Aug 84	05:08:20-05:51:50	236	OK.
Ph'metry	21 Aug 84	00:55:50-02:55:40	638	02:30-02:35 bad block.
Markab	21 Aug 84	03:22:00-04:06:20	240	Slow to null.
Deneb	25 Aug 84	02:53:00-03:17:30	133	Star lost at 03:04:40.
Deneb	25 Aug 84	03:48:10-04:28:10	211	OK.
Deneb	20 Sep 84	02:47:40-03:23:20	133	Lost star.

Vega	21 Sep 84	00:58:20-01:44:00	247	Nearly nulled.
Deneb	21 Sep 84	02:03:30-02:43:20	216	Nulled.
Altair	21 Sep 84	03:05:30-03:45:40	218	Nulled.
Vega	27 Sep 84	00:18:10-00:52:30	227	X wedge encoder lost position.
Deneb	27 Sep 84	01:16:00-02:01:50	246	X wedge encoder lost position.
Altair	27 Sep 84	02:29:10	241	X wedge encoder lost position.
Markab	27 Sep 84	03:49:50-04:05:20	84	X wedge encoder lost position.

The first column gives the name of the star which was used as a source. The second and third columns give the Greenwich Mean Time (GMT) date and times of the observation. The fourth column gives the number of records recorded, each record resulting from 10 seconds of integration time. The last column gives comments about the run.

The data from June 22 showed a relaxation oscillation in three of the five observation sets. This was traced to an improper conversion of wedge encoder readings when either wedge angle was between 320 and 360 degrees. This error in the TCR Operating System was repaired. The large break between 27 June and 16 August was due, first, to writing of the data analysis programs, and then, second, due to the poor weather in late July and early August. The break between 25 August and 20 September was due to waiting for the arrival of the re-figured bending mirror, which we hoped would improve the observations.

The data analysis done so far is illustrated in an Appendix entitled "Data Analysis Results: The Prototype Field Two-Color Refractometer."

Reviewing all of the processed data, we found that the measured

dispersion is not very well related to the predicted refraction. It appears that the major reason for this may be the grossly distorted image we have at focus in the refractometer. We can view the image only in red and white light; the image may be even worse in the ultraviolet. Also, the large size of the image leads to the possibility of distortion of the measured dispersion signal due to the curvature of the interface between adjacent diodes in the Quadrant Photo Sensor used. This would be only a small problem if the image were a couple of arc-seconds in diameter, but grows in magnitude rapidly as the image size approaches the size of the diodes.

It was thought that the distortion in the image had been traced to the outside bending mirror. When this mirror was re-figured, we expected a great improvement in image quality, but did not find much improvement.

VI. CURRENT PROBLEMS AND PROJECTED EQUIPMENT MODIFICATIONS

This section will address the major problems which have been identified within the research program conducted at the University of Maryland. We also suggest future modifications to the existing equipment and the fabrication of some new equipment in order to reduce the impact of these problems.

A. Optical Element Occultation

For a period early in the program, the Two-Color Refractometer was operated on the computer-controlled 48-inch telescope at the Goddard Optical Research Facility. The Two-Color Refractometer was integrated with the telescope's pointing and guiding control system to provide fine corrections and precise pointing. However, the focal length of that telescope at the appropriate mounting position for the Two-Color Refractometer is very long, resulting in an oversized image. This required a re-imaging system within the Two-Color Refractometer to provide appropriate correction in the image size. This re-imager was a reflective multi-element optical system with a secondary mirror. The secondary mirror in the re-imaging system and the secondary mirror in the primary telescope approximately overlapped but their relative shadowing depended upon fine details in pointing offsets. For this reason, some of the intrinsic symmetry of the operation of the refractometer was lost. The Two-Color Refractometer depends heavily upon a number of symmetries balancing well in order to reduce systematic errors. The observations on the 48-inch telescope indicated significant problems in dispersion offsets, so this work was terminated in order to proceed with the observations on the 24-inch telescope at the U. S. Naval Observatory.

B. Size of Stellar Image

The precision and accuracy of the field results which have been obtained at this time have been significantly worse than the results which had originally been theoretically projected. A major reason for this has been the fact that the stellar image has been significantly larger than one would expect for this type of optical system. For the night during which the data discussed in the previous section was obtained, it is estimated that the optical system had astigmatic errors between 6 and 8 arc seconds. The seeing was estimated to be between 3 and 4 arc seconds. This is to be compared with a nominal assumption in the original estimates of a two arc seconds image. Therefore, the observational results are not greatly different from the results which were theoretically projected if one re-calculates the theoretical projections in terms of the enlarged stellar image.

In general, the operation of the TCR causes the precision and accuracy of the dispersion measurements to scale with the size of the stellar image at the photodetector. In particular, the operation of the Two Color Refractometer is affected in the following ways:

1) Reduced Precision

The larger image means that the noise, expressed in arc seconds rather than as a fraction of image size, is greater. Therefore the r.m.s. error expressed in arc seconds does not have as high a precision, within a fixed observation interval, as had been projected for an image diameter which would have been smaller. This has the form:

$$\text{rms error} = (\text{constant}) * \text{r.m.s. image size}$$

2) Equipment Design Parameters

Certain aspects of the equipment have been designed based upon the projected value for the size of the image. Thus, the optical magnification in placing the image on the diode structure may be affected by the seeing. While this has not been a problem with the Two-Color Refractometer on the 24-inch telescope, it has been a significant problem on the field version of the Two-Color Refractometer. In the latter case, the magnitude of the image on the diode structure with the current size is significantly larger. This therefore has resulted in image overflow and some systematic problems during the measurements.

For the prototype field TCR, the problems were initially thought to be due to optical problems in our TCR setup. However, after these problems were corrected and the figure errors in two of the feed mirrors were corrected, the image was still much larger than expected. The current residual distortion of the image appears to be due to temperature anomalies within the telescope or optical feed path.

C. Saturation

Any electronic system used in photon counting is vulnerable to saturation at high count rates. The operation of the TCR is highly sensitive to saturations which are different in the different channels. For example, if we wish to find the position to 1% of the center of the image and we operate the photomultipliers at a rate such that their count rate is reduced by 10% due to the phenomena of saturation, then a 10% difference in the point of saturation or the degree of saturation output count rate = 0.9 input count rate between two channels in the photomultiplier will result in a 1% error in the computed position of the centroid of the image. This will cause a systematic error in

the measurement of the dispersion.

This type of problem required that the Two-Color Refractometer operated on the 24-inch telescope at the U.S. Naval Observatory be operated at significantly reduced counting rates. At the reduced counting rates, the random noise is a larger fraction of the signal, thus leading to a reduced signal-to-noise ratio for a given observation interval.

D. Wedge Angle Errors

Both the real time operation of the Two-Color Refractometer and the reduction of the data for the Two-Color Refractometer require a knowledge of the orientation of the wedges with respect to the encoder reference and a knowledge of dispersive strength of the wedges. Thus, an incorrect value of the position of the wedges with respect to the encoders will clearly cause a problem. In addition we have had difficulties due to apparent changes in the wedge position after the wedges have been mounted. If the error is large, the field operation is significantly degraded. However, if the error is small, one may use the observational data to provide a better estimate of this angle and thus re-compute the value of this offset from the observational data.

E. Radio Frequency Interference

The preamplifiers, which detect a signal from the individual photoelectrons, must have a very low input noise in order to work with the low gain in the quadrant photomultiplier. Thus, these preamplifiers are required to have a noise level of less than 300 electrons. This very high sensitivity makes these preamplifiers highly vulnerable to external interference. We had great difficulty with noise both in operations at Goddard Optical Research Facility and with operations at the U.S. Naval Observatory. This was

gradually narrowed down to the expectation that the difficulty was caused by television Channel 4, at least for the interval during which the Two-Color Refractometer was operating at the USNO. In conjunction with the U. S. Naval Observatory and the Federal Communication Commission, Channel 4 was turned off for one second to validate that this was the source of the problem. The noise stopped, indicating that Channel 4 radiation was causing the difficulty.

We have instituted new design procedures in order to reduce this problem. Using shorter high voltage leads and microwave absorbing foam and establishing a better grounding contact have eliminated the problem on the prototype field Two-Color Refractometer. These improvements have not yet been propagated to the 24-inch Two-Color Refractometer.

F. Computer Improvements

The computations required in the wedge servo-loop are sufficiently involved that a mini or micro-computer is required in the system. In addition, the formatting and recording of the data requires some type of computer system. For the system on the 48-inch telescope at Goddard Optical Research Facility and the system on the 24-inch telescope at the U. S. Naval Observatory a Data General NOVA 3 mini-computer was used for these and other functions. In order to make the system more compact and less expensive, a built-in micro-computer system was designed and fabricated for the prototype field Two-Color Refractometer. This system has been tested and has been used for the field observations with the prototype field TCR.

G. Mount

The 24-inch telescope at USNO had a full equatorial mount. However at our present field site, we are currently using a rather primitive heliostat to

point the telescope at stars.

A specially designed mount would be required in order to properly evaluate the field operation.

H. Field Ability

Various aspects must be improved in order to have reliable field operation. This will include a fair amount of automation.

VII. NEW DESIGN FOR FIELD TWO-COLOR REFRACTOMETER

This section, addresses the modifications in the design of the test and prototype field refractometry system which are suggested by our studies.

A. Assumptions for Operation

Several assumptions will be made in this chapter for the operation of the instrument. These bear heavily upon the optimal design and the feasibility of obtaining a particular level of accuracy.

- i) We presume that the instrument is to be transported by a van and lifted from the van either in a motorized manner or by two people.
- ii) The instrument would be mounted on a pier for observations.
- iii) The desirable mode of operation would be to operate the TCR and a T-4 at one site for at least one-half a night.

B. Nominal Design

An example of a field mount is illustrated in Figure VII-1. The mount as shown is currently used as a test mount. However, it illustrates the altitude-azimuth motion which we would expect to use. This system would also have gyroscope control. In that mode, we have measured a suspended version that is capable of pointing with a precision of better than 0.5 arc seconds.

C. Results

The device, which was designed as a balloon gondola was suspended rather than mounted on the ground. It provided a pointing accuracy of 0.5 arc seconds in azimuth and 0.3 arc seconds in elevation. This performance would be entirely satisfactory for the TCR field mount. (This system was developed

for another program.) However, for the astroposition application, this suspension mode may not be particularly feasible due to the portion of the sky which would be blocked and the larger physical size of the mount.

There are several difficulties in making a direct comparison of the expected accuracy of the pointing and tracking. The bearing for the field mount would have a larger diameter. This has the advantage of smoother motion but it also the requirement of higher drive power and larger problems with stiction. Several ideas for a ground mount (pier) have been discussed but no complete design has been made. However, these ideas seem entirely feasible and await further funding to be tested.

VIII. PROJECTED RESULTS

Considering the accuracy which might be achieved by the overall system in field astroposition measurements, we will divide the discussion into two portions. The first area is the accuracy of the TCR instrument, and the second area is the overall astrometric observational accuracy.

A. General Limitations - Instrumental Limitations in Accuracy

The Two Color Refractometer for an observation period of one evening should be able to achieve a precision of 0.03 arc seconds in the determination of the anomalous refraction. This assumes that the value for the anomalous refraction remains constant over this period. The data could be divided into two portions: one set for the early evening and one set taken some time later. Field observational data regarding the stability of the anomalous refraction is not yet available. However, such data will be required to determine whether one desires more frequent determinations of lower precision. Some information concerning these questions is available from various T-4 and Astrolabe observation programs conducted by GSS and USNO. (Ref) Appendix NN

B. Auxiliary System Requirements

The auxiliary system will require pointing accuracy to 0.5 arc seconds, which has been discussed earlier, and will be an alt-az instrument as discussed earlier.

C. The Role of the Two-Color Refractometer

The analysis of the data which would be obtained from the Two Color Refractometer and the astrometric instrument to measure the star position (with respect to hardware operation and with respect to theoretical projections) may be used to study the eventual performance of the Two-Color Refractometer as a field instrument. The following review will consider image motion that may be as large as one or two arc seconds. In this case the Two Color Refractometer will produce a significant improvement. However, the full advantage of the TCR cannot be obtained when one has separate instruments consisting of a Two-Color Refractometer and a T-4 or Astrolabe. For the separate operation one could expect to achieve accuracy of 0.1 to 0.2 arc seconds.

D. Long Term/Short Term Averaging

In order to evaluate in an independent matter the projected accuracy, we return to the results of Hog. We also presume that his measurements are primarily atmospheric in nature rather than instrumental. Then we may expect errors, which are related to the change of dispersion as a function of time, of about 0.03 arc seconds. This result presumes that long term effects, i.e., refraction, and company, are negligible.

E. Conclusions

In conclusion, it appears feasible and interesting to provide a separate aperture Two-Color Refractometer. This program appears to have relatively low technical risk compared to developing a new instrument which operates from a single aperture.

The expected accuracy would be 0.1 arc seconds, which would be a significant improvement, particularly for areas where atmospheric gradients produce systematic errors (i.e., in coastal or mountainous areas). This advantage may be smaller in open plane areas (i.e. for observations in Central U.S.).

The analysis of the dispersion as a function of time as the star moves over significant portions of the sky permits an improved determination of the wedge angle offset. This procedure has been performed and will not be considered further at this time.

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DEPENDENCE OF ASTROMETRIC ANGULAR DEVIATION
ON TIME BETWEEN SUCCESSIVE OBSERVATIONS

$$\Delta\theta = \frac{0.3}{(0.65 + T)^{-1/4}}$$

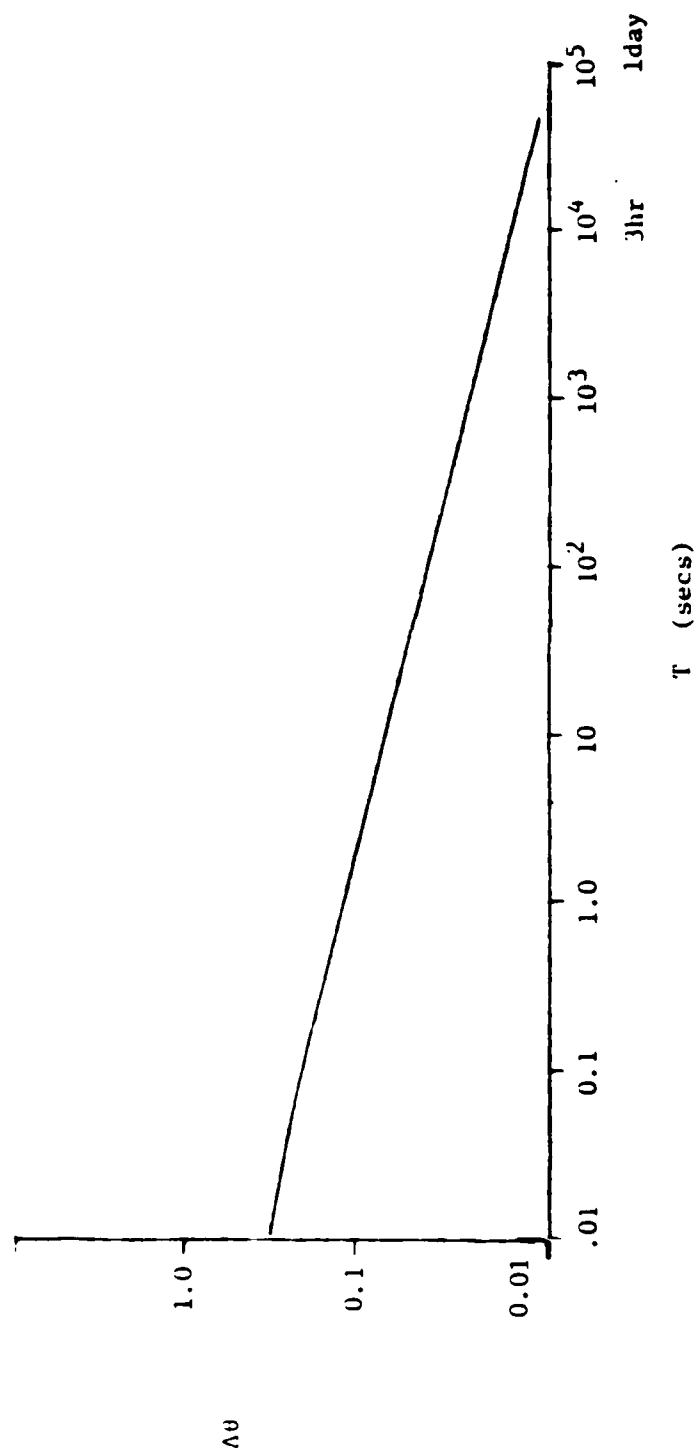
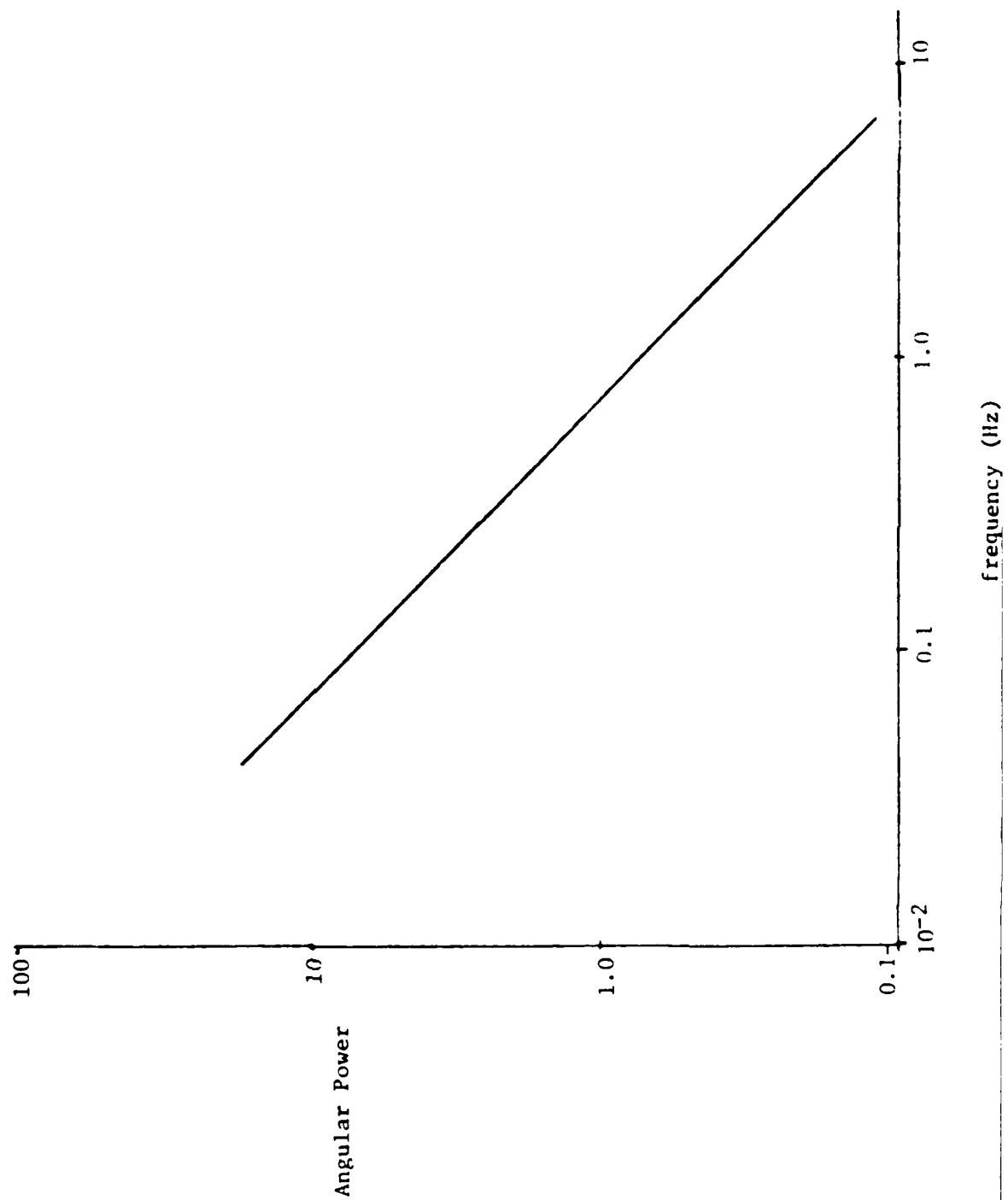


Figure 1-1

Figure 1-2
SPECTRAL POWER OF THE ASTROMETRIC ANGULAR
DEVIATION



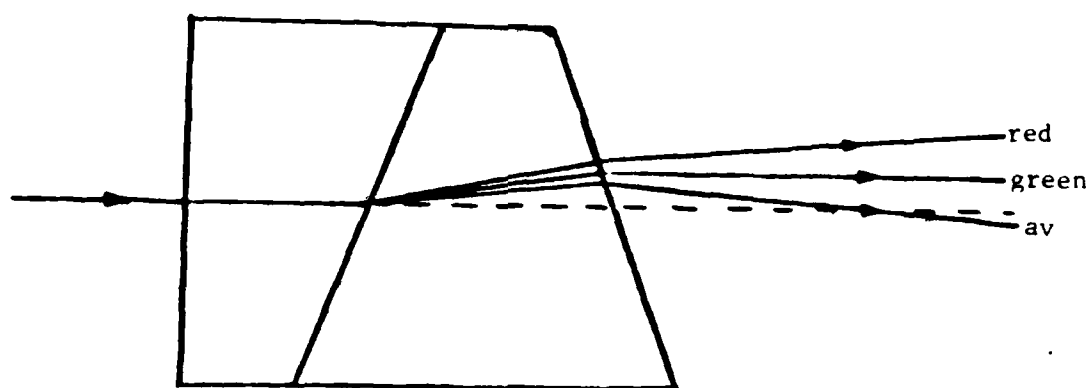


Figure IV-1. A compound wedge can disperse light without introducing an overall bending of the light.

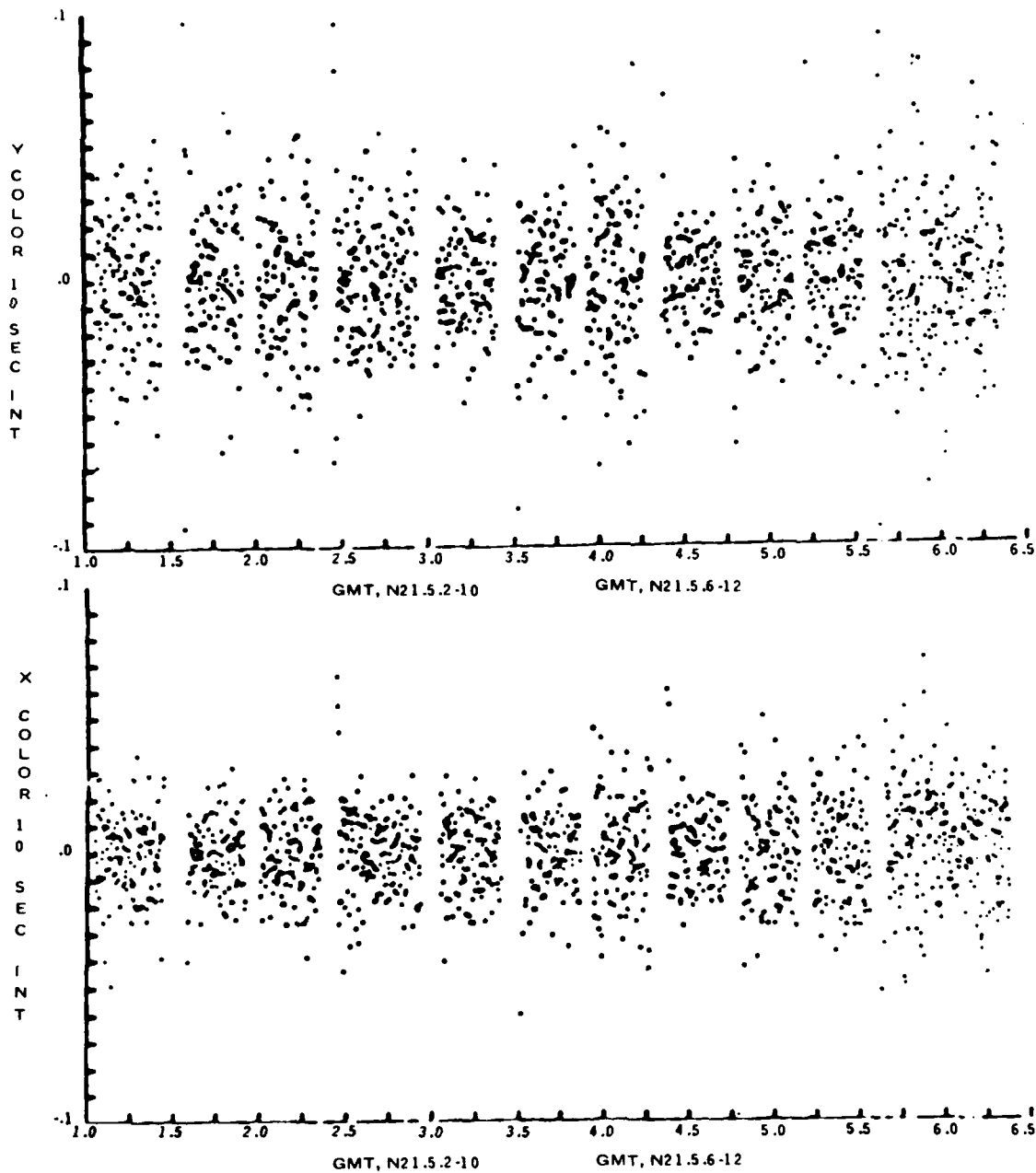


Figure V.1. The Y (RA) and X (dec) components of the residual color as a function of time. An integration time of ten seconds was used. The data is from USNO TCR Data Tape 21, file 5, Runid's 2-12 (N21.5.2-12).

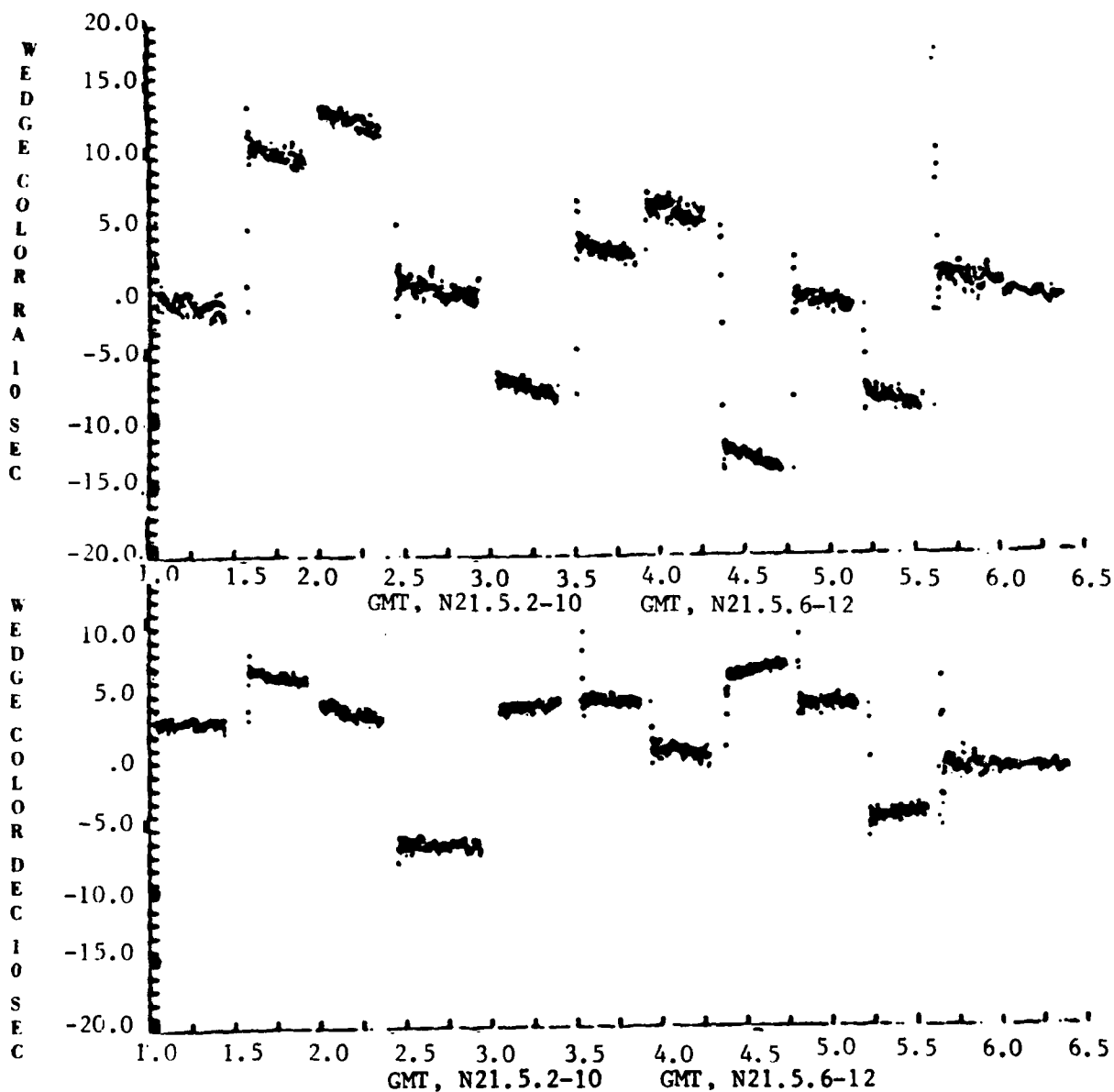


Figure V.2. Right ascension and declination components of the color introduced by the wedges. An integration time of ten seconds was used. The data is from USNO TCR Data Tape 21, file 5, Runid's 2-12 (N21.5.2-12).

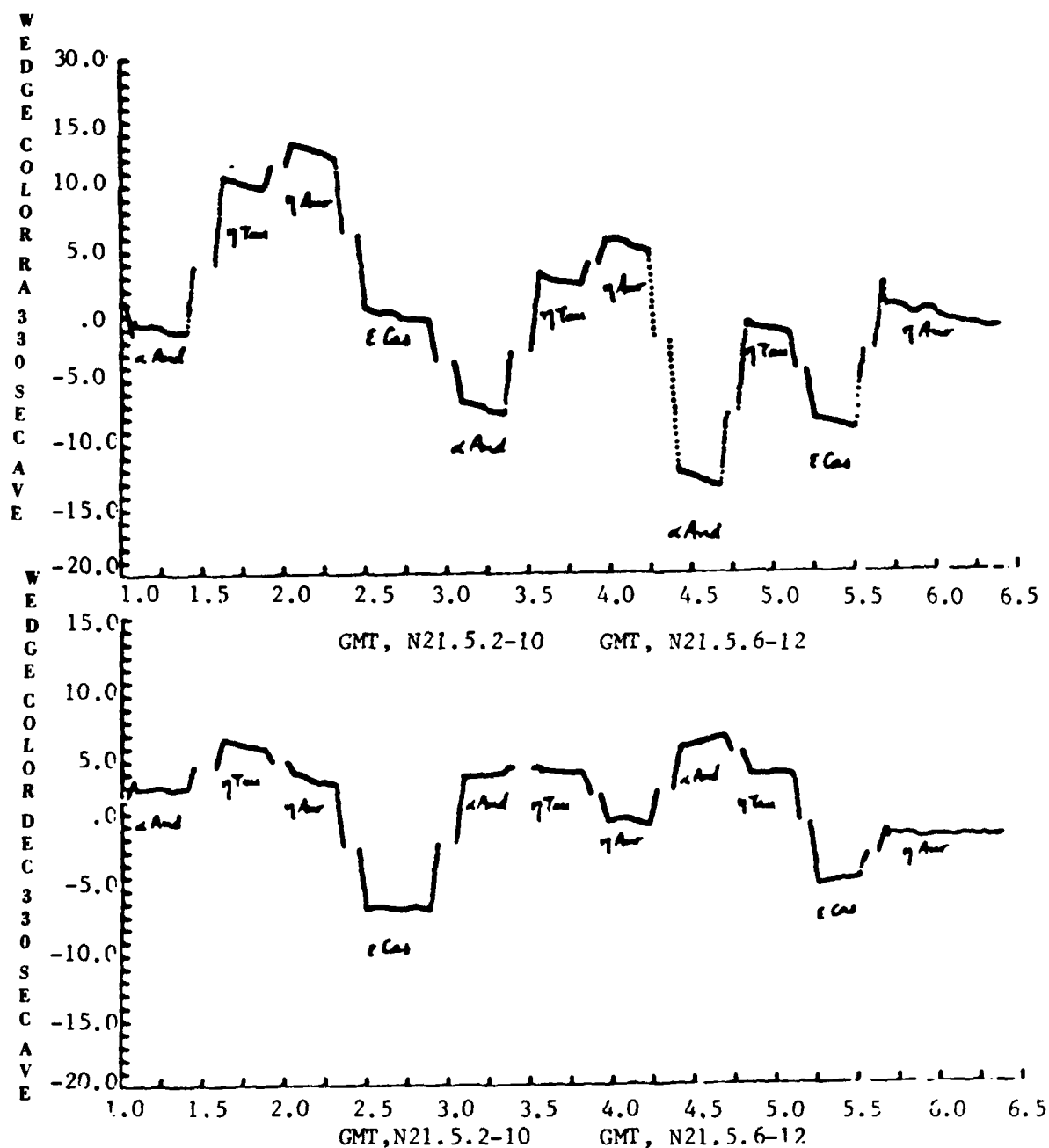


Figure V.3. A 330 second boxcar average of the right ascension and declination components of the color introduced by the wedges.

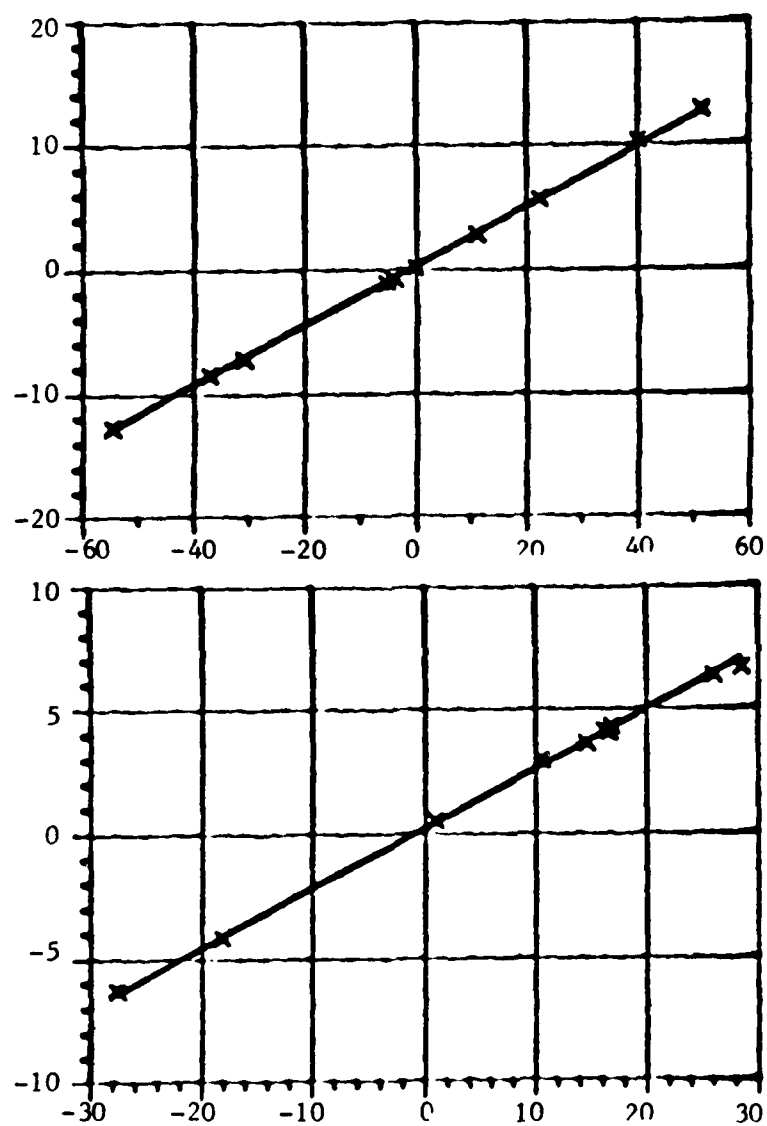


Figure V.4. Best fit for right ascension and declination components of wedge color to mean refraction in arc seconds.

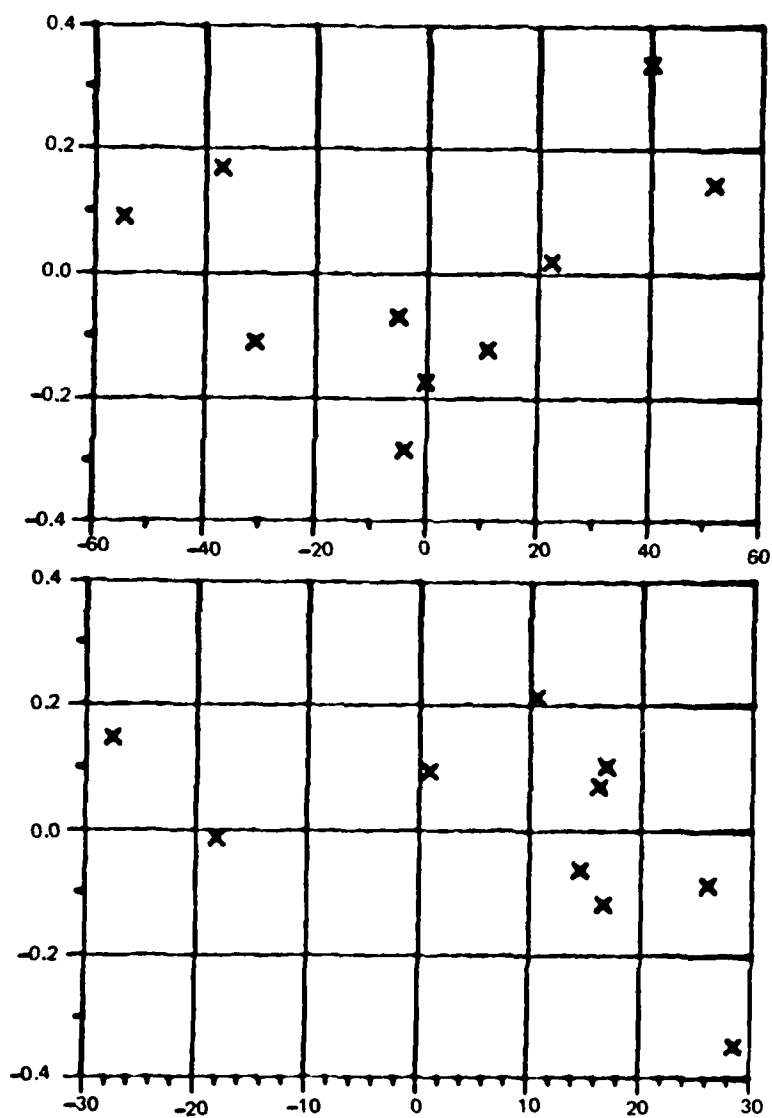
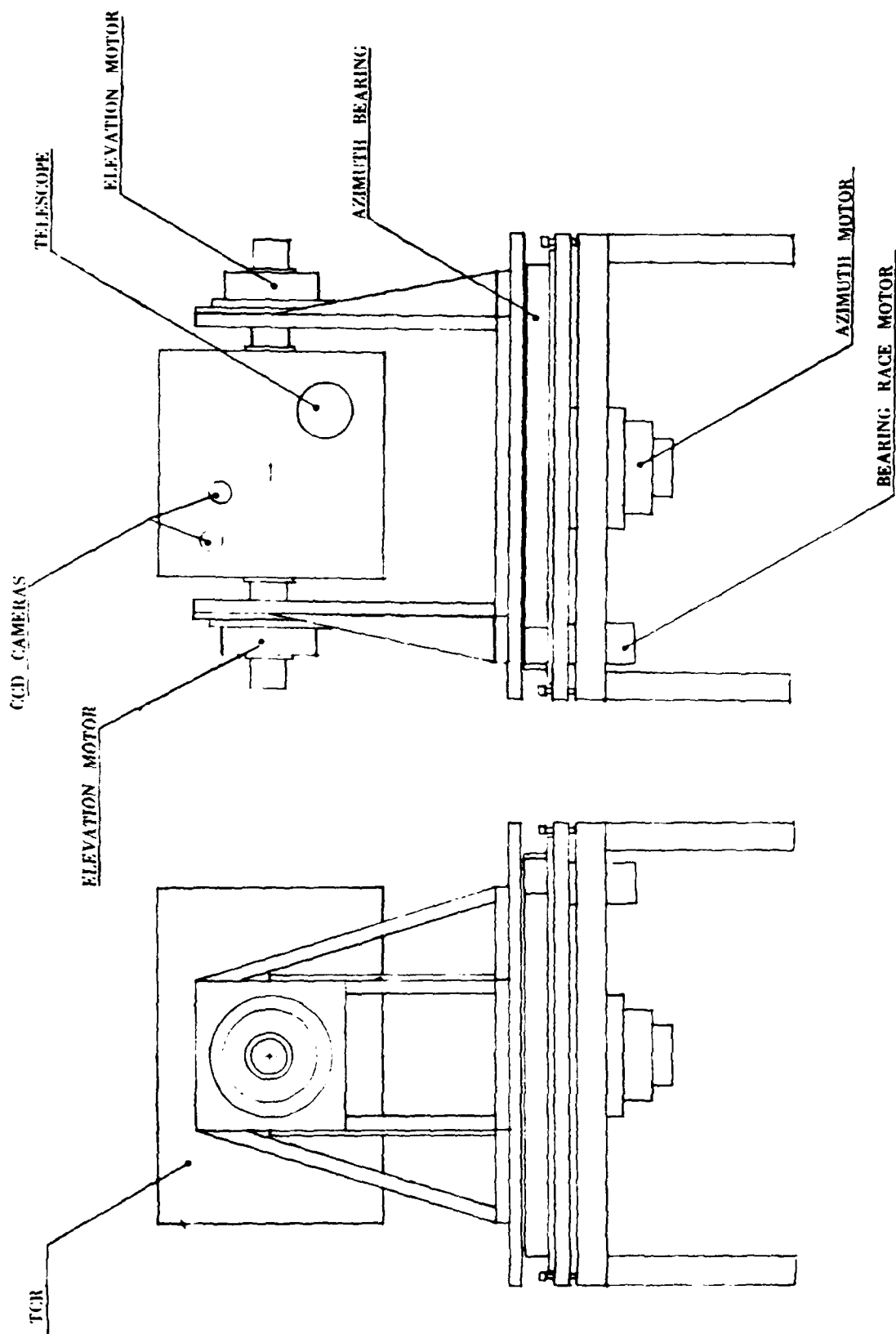


Figure V.5. Residuals from fits of right ascension and declination components.



A FIELD TEST MOUNT

Figure VI-1

ON A NEW ASTROMETRIC INSTRUMENT

THE GEOLABE

by

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22 October 1984

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SUMMARY

The general concept of a new astrometric instrument for the improvement of stellar positions, for the determination of improved observations of astroposition, and for the improved determination on earth rotation parameters will be developed. This instrument would consist of an astrolabe capable of providing corrections for anomalous atmospheric refraction as well as for normal atmospheric refraction. The nominal design of this instrument, as presented in this document, is based upon existing principles of the Danjon astrolabe and the Type II astrolabe made by the Nanjing Astronomical Instrument Factory. The procedures and instrumentation for the correction of refraction is based upon equipment which has been fabricated and field tested by the University of Maryland for correction of refraction in other measurements.

CHAPTER I

HISTORY

This section will provide a brief history to illustrate the various design choices that have been made in the GEOLABE and problems which the GEOLABE addresses.

The following history is intended to illustrate technology direction. It has no intention of properly acknowledging the history of the subject, nor presenting proper acknowledgement of the contributions of the various workers in this field. Other articles which have been written with this in mind are much more apropos. (Debarbat 1983).

The history will address only those elements which have influenced the development of the GEOLABE, as an instrument for the determination of astroposition.

A. WILDE T-4 THEODOLITE

We will first describe the operation of the T-4 Theodolite as it applies to our development of the GEOLABE. Consideration will also be given to those aspects which are related to the work done at the University of Maryland which incorporates a charged coupled device eyepiece in the operation of the T-4 Theolite.

1. Operation

This section describes the general principle of operation and some of the operational procedures.

a) Fixed Telescope

The device consists of a telescope with an aperture of 60 mm and a focal length of 540 mm. This optical system images the star on the cross-hairs in the normal eyepiece. The basic outline of this configuration of the Wilde T-4 Theodolite is shown in Figure I-1.

b) Definition of the Time of Meridian Crossing

The actual measurement for hour angle or for longitude is made by observing the time at which the star crosses the fiducial cross hairs. For the present, we will concentrate on this measurement since this is the primary set of measurements that have been made with the CCD in place.

c) Spirit Level for Direction of Gravity

In order to make appropriate measurements of astroposition, the properties of the star motion must be correlated with information on the direction of the gravitational vector. In the Wilde T-4 Theodolite, gravity is sensed with a spirit level. Thus measurements are, in essence, made on the star with respect to a plane which is established by means of gravity.

Neglecting collimation questions, this plane is established by comparing stars which are north and south of the equator. Thus, one establishes the plane which is defined by confining the local gravity vector and the direction to the north pole (i.e. the spin axis of the earth).

We may also naively consider this in terms of a zenith star. Thus, we are determining the time at which a zenith star passes through a direction perpendicular to the local gravity vector. The local horizontal plane is perpendicular to the local gravity vector.

The procedures for actually establishing this coordinate system are rather sophisticated due to the existence of multiple errors that are linked together.

d) Tracking Wires

In order to determine the instant that the star passes through this plane, a procedure is used which is far more sophisticated than the procedure that would be used to measure the time at which the star passes through a single point in the sky. The star is tracked with a fiducial wire. This is moved in a manner to assure that it overlays the image of the star. An electrical readout indicates the position of the wire as a function of time and this data is recorded. It is by analysis of this electrical readout of the contracts on a rotating drum that one determines the time of meridian crossing and then the zenith.e) Telescope Bearings

Since the telescope has a relatively small field of view (one-half a degree) it must be pointed toward the proper portion of the meridian. This is done with a bearing structure. This bearing structure is highly sensitive and the position measurements are also highly sensitive to the proper operation of this bearing. Procedures have been developed in order to minimize these problems. These procedures are used by various groups using T-4 observations for the regular determination of astroposition.

f) Latitude

Angles of this bearing axis are read with a setting circle. These angles are used in order to determine the elevation of the star and thus the latitude of the site.

2. Problems

This section will address some of the dominant problems in the the determination of the astromonic position of a site using the T-4 observations. In general, the magnitude and relationships among these problems have not been well separated and quantified in the literature.

a) Errors in the Bubble Level

The bubble level, or spirit level, presents a significant problem as it relates to obtaining the reference with respect to gravity (highly accurate in any case). This can be due to differential motion due to temperature gradients caused by wind, differential motion of the bubble caused by temperature gradients, or stickiness of the bubble.

b) Personal Equation

For the moving star, the overlap with the fiducial wire may not be precise. In particular, each individual tends to have a leading or lagging motion which in turn will depend upon temperature, image motion, etc. The usual practice is to assume that an individual's variations are small compared to the variations from one individual to another and thus to calibrate in a single number the idiosyncracies of the human eye.

c) Long-Term Atmosphere-Refraction Effects

Anomalous refraction with periods of minutes can lead to erroneous observations, particularly at some sites, where these effects seem to produce significant offsets.

3. CCD Observations

We have used Charge Coupled Devices built by the University of Maryland to replace the human eye. This work resulted in an improvement, by approximately a factor of two during a test series conducted at the U.S. Naval Observatory. The USNO tests were conducted at one site and during a single season of the year. A broader testing program of the CCD eyepiece system is required at various latitudes and temperature ranges.

An illustration of the internal agreement of the measurements of longitude conducted at USNO is illustrated in the document "Study of CCD Eyepiece on T-4 Theodolite" (Currie 1982). The standard error of a single night was 0.147 arc seconds with one set of equipment and 0.0121 arc seconds with a modified set of equipment. As a comparison, a determination by more conventional means (a human observer) results in a standard error of a single night of approximately 0.28 arc seconds (Salvermoser 1981).

4. Summary

The Wilde T-4 Theodolite gives highly accurate results when properly used. We will discuss the astrolabe as an improved instrument in performing the function of the T-4 Theodolite.

B. ASTROLABE

1. Definition

The Astrolabe will be described in general, but the primary focus will be on the Danjon Astrolabe as an example and as the specific device on which tests are being conducted at the University of Maryland. The general concept of the optical configuration of the astrolabe is indicated in Figures I-3. A more detailed description of the optical configuration for the Danjon Astrolabe may be found in the article by Danjon (1960). More specifically, this includes the description of the Wollaston Prism.

2. Primary Elements and Operation

The Danjon Astrolabe incorporates design features in several respects in a manner to provide significant improvement in the precision and accuracy, when compared to the performance of the T-4 Theodolite.

a) Mercury Surface for Gravity Determination

In the Danjon Astrolabe, we observe the reflected image of the star from the surface of a mercury pool (I-4). This image is received on the same detector that is used to observe the direct image of the star under observation (I-4). The detector may either be a human eye, a charge coupled device or a photomultiplier. This procedure assures a greater accuracy in establishing the local vertical as compared to the spirit level which is mechanically attached to the telescope tube and is not directly related to the star image.

b) Use Of Time As The "Angle Encoder"

Basically, the Danjon Astrolabe uses ticks of a clock as the encoder rather than a mechanical angular device. In the T-4 Theodolite, the angles are measured by comparisons using mechanical circles. The accuracy of these mechanical circles depend upon the accuracy of the markings on the circles and upon the accuracy of the bearings. Within the Danjan astrolabe, the use of a clock and its subdivisions in time eliminates most of the dependence upon mechanical precision and accuracy of internal parts of the astroposition instrument. Thus this procedure of using the divisibility of time as distinct from the divisibility of mechanical markings greatly relaxes some of the mechanical requirements within the Danjon Astrolabe as compared to the requirements of the T-4 Theodolite system.

c) Wollaston Prism

The Wollaston Prism Figure I-4 acts on the converging beams of light and creates the two additional stellar images in addition to the direct and reflected images. Thus we have two images which move together for visual comparison. This permits the operator to observe in a manner to eliminate one aspect of the personal equation. In particular, the two images observed by the operator, have a wire placed such that they both move in the same direction with respect to the wire and misplacement of the wire, to first order, does not create a systematic error. This is not true in the T-4 Theodolite.

3. Remaining Problems With Danjon Astrolabe

a) Anomalous Refraction Effects in the Atmosphere

The Danjon Astrolabe and the T-4 Theodolite are both sensitive to large scale gradients of temperature and/or pressure in the earth's atmosphere. These gradients or atmospheric wedges may be due to temperature gradients, pressure gradients or a combination of both of these effects. These gradients will cause all stars to appear to be shifted in a relatively uniform manner, thus causing an error in the determination of the star position for any astrometric instrument which would operate at one point on the earth's surface and which did not employ atmospheric correction procedures.

b) Local Temperature Gradients

Local temperature gradients in the vicinity of the astrometric instrument may also cause errors in the apparent direction to the star due to atmospheric refraction. Local temperature gradients may also influence the refraction of light in the prism of the astrolabe, effectively changing the angle of the prism which must be calibrated for each night of observation. The effects of thermal variations in the atmosphere near the instrument has been discussed by Hu (1984) and effects of temperature gradients within the instrument have been discussed by Hog (1968).

4. Areas of Improvement to Conventional Astrolabe Operation

With the previous information in mind we can now address several areas of improvement in the operation of the conventional astrolabe or similar instrument.

a) Larger Aperture

A larger aperture would permit the observation of fainter stars and brighter images.

b) Individual Personal Equation

The effect of the personal equation may still be important for the conventional astrolabe when operated by a human observer looking through a conventional eyepiece. This problem is not as large as the problem for the Wilde T-4 Theodolite.

CHAPTER II

TWO-COLOR REFRACTOMETER

This chapter describes the past and current work in Two-Color Refractometry at the University of Maryland. This work addresses both the feasibility of using a Two-Color Refractometer in the field for the measurement of astroposition and a nominal design for the GEOLABE as a system for the determination of astroposition. The Two-Color Refractometer is discussed as a concept and as a separate stand-alone instrument. The incorporation of the elements of the Two-Color Refractometer into the GEOLABE will be addressed in a later chapter.

A. OBJECTIVES

This section addresses the objectives of the independent Two-Color Refractometer project for the use of a separate telescope aperture as the light collector of the Two-Color Refractometer.

1. Long-Term Reference

The primary objective of the Two-Color Refractometer is to provide measurements which may be used to remove the influences of "long-term" anomalous refraction. By "long-term", we mean the components with periods of several hours to days or weeks. The objective is to eliminate the requirement to use a convention astroposition system to perform many samples during the many different conditions of the atmosphere. Data from the literature obtained using the T-4 Theodolite and the Danjon astrolabe indicate that, at least at some sites, there is a significant amount of anomalous refraction (0.4 arc seconds) which lasts for long periods (more than one week). This

means that the results obtained by measurements taken during a short occupation of a site may have a significant error. By the use of the two color refractometer, we wish to provide an observational procedure by which the long-term accuracy may be brought within the same domain of accuracy as the short term precision of the measurements.

2. Independent Field Operation

A secondary objective is to provide an instrument which may be operated in the field, away from a fixed, established telescope.

3. The Relation Between Anomalous Refraction and Conventional Refraction

The Two-Color Refractometer will measure the total refraction, the conventional (flat atmosphere), the spherical corrections and the anomalous refraction. Thus, it gives the total correction that is necessary to adjust the observation performed by the astrometric instrument.

As will be discussed in the later portions of this paper, the method by which the GEOLABE will operate will be to separate out these different components of refraction in order to permit the GEOLABE to operate in a manner which is independent of the conventional refraction. The GEOLABE will make proper correction for the anomalous refraction.

B. HISTORY

This section briefly describes the history of the Two-Color Refractometer. A more complete discussion of this instrument appears in a document entitled "Two-Color Refractometer for Astroposition Applications." (Currie 1985)

1. Basic Concept of the Two-Color Refractometer

The basic concept of the Two-Color Refractometer as it applies to astroposition measurements and the development of stellar catalogs was described in a paper presented at the IAU Symposium on Astronomical Refraction held in Uppsala, Sweden in 1978 as stated above. (Currie 1978) At the presentation of this meeting, a detailed discussion of the hardware which could realize this system was presented, as well as the theory which was addressed in the published paper.

The Two-Color Refractometer was invented and developed at the University of Maryland. The basic concept is to measure, on a very short time scale, the relative positions of the red and the blue images of a star. This is performed with sufficient accuracy to determine the angle of refraction from a knowledge of the dispersion of the atmosphere (Currie 1978).

A more complete description of the details of the instrument may be found in the doctoral thesis of D. Wellnitz (Wellnitz 1982) A description of the results is attached to this document. It describes the details of this technical approach.

2. Similar Work

Instruments to measure the dispersion for horizontal observations have been pursued by E. Tengstrom in Sweden (Tengstrom 1978) and by D. C. Williams in England (Williams, D. C. 1978). Their work was concerned with horizontal observations for surveying permitted the use of lasers as light sources. These instruments did not achieve the angular accuracies which have been demonstrated in the Maryland system.

The concept of observing the position of a star in two different color bands has been considered in the past. The U.S. Naval Observatory has considered using this approach for observations using band filters for an eyepiece on their Transit Circle. (Hughes 1978)

C. PRINCIPLE OF OPERATION

This section provides an extremely brief description of the principle of operation of the Two-Color Refractometer. (Currie, Wellnitz 1982)

1. Measurement of the Angular Distance Between Red and Blue Images

The Two-Color Refractometer measures the apparent angular distance between the red and the blue image of the star. An automatic servo system assures that the light of the red and blue image (the "white" image) is centered, so that it lies on center of a quadrant photomultiplier detector. A set of motor driven mirrors achieves the internal change of position of the image.

An optical-mechanical nulling system introduces counter-dispersion into the beams of light before they strike the quadrant photomultiplier system. This permits a precise measurement of the dispersion by the use of "null" observation. One then reads the encoder to

A rotating filter wheel is used to sequentially present separate red and blue images to the photodetector. This filter wheel has successive wedge-shaped elements of red and blue glass. In this manner, we may measure the positions of the centroid of the red and blue image separately.

The optical system to collect and focus the starlight may be a small aperture telescope which is an integral part of the Two-Color Refractometer or the Two-Color Refractometer may be attached to an existing telescope.

2. Supporting Electronic Subsystems

The system operates by an analog circuit centering the image on a Quadrant photosensor. The offset in an image position is interpreted and sent as a drive signal to small image moving mirrors.

A separate electronics system counts individual photoelectrons in each of the photosensor quadrants. The centroid of the red and blue images are computed and the processed signal is used to drive the dispersion nulling system.

A separate system records the data on magnetic tape or disk.

D. RESULTS OF STAND-ALONE SYSTEM

We now consider the current results of the measurements which have been with a stand-alone Two-Color Refractometer. That is, these are results which illustrate the performance as a separate instrument, rather than in a shared operation mode which would be used with the GEOLABE.

1. Results obtained on the 24-inch Telescope

The Two-Color Refractometer was operated on the 24-inch telescope at the U.S. Naval Observatory in Washington, D.C. The system was tested and debugged on the 48-inch telescope and GSFL and the 24-inch telescope. Rick's frequency in between was a control problem. During the few nights the instrument was operating well and the vach's frequency interference (as detrimental after the run) was not destruction. An observing run was performed on a sequence of stars. During this run, of about six hours each star was revisited several

times. Then, other stars were observed interspersed with the observation of the initial single star groups.

Since we had no independent measurement of the anomalous refraction through the night, we will interpret this data in terms of the precision of the remeasurements of the stars.

Addressing the repeatability from star to star, which consists of:

<u>Star</u>		<u>Mean</u>	<u>Number of</u>	<u>Standard</u>	<u>Standard</u>
		<u>Residual</u>		<u>Deviation</u>	<u>Deviation</u>
		<u>arc seconds</u>	<u>Observations</u>	<u>from the Mean</u>	<u>of the Mean</u>
				<u>in arc seconds</u>	<u>in arc seconds</u>
Alpha AND	RA	-0.42	3	0.71	0.50
	Lec	-0.35	3	1.59	1.13
Eta TAU	RA	0.21	3	1.28	0.91
	Dec	0.12	3	0.21	0.15
Eta AUR	RA	0.34	2	0.10	0.10
	Dec	0.06	2	0.15	0.15
Epsilon CAS	RA	-0.01	2	0.73	0.73
	Dec	0.28	2	0.16	0.16

Table I

The conclusion one may derive from this table of observational results is that the standard deviation of the measured refraction, as an internal measurement for successive measurements of the same star, lie in the subarc second region. This is indicated by the last column. One may also note that the actual residuals (the column labeled Mean Residual) are not dissimilar

from the standard deviation of the mean expected from the repeated measurements. This indicates that we are not dominated by systematic errors at this level. However this is not a full determination of the accuracy since some of the parameters were internally determined within this data set.

By considering the standard deviation of each measurement and using the ten measurements obtained during this five hour interval, we have a standard deviation for one observation in right ascension of 0.87 arc seconds. The standard deviation of the mean over this interval of observations is 0.29. The equivalent results for declination are a standard deviation of 0.81 and a standard deviation of the mean of 0.27. In a fundamental sense, we expect the instrument to have the same precision in both axes, so the agreement of the measurements in right ascension and declination is rather comforting.

Axis	Standard deviation from mean	Standard deviation one seconds	Range in degrees
Right Ascension	0.87	0.29	75
Declination	0.81	0.28	39.5

Table II

In this method of analysis the actual value of the anomalous refractions is included in the 0.29 and the 0.28 are second figures. Thus the error per observation is low. However, since we have no independent determinations, we assume that all of this is error.

Thus we see that the instrument, as operated during this evening, produced results which would determine, in one half of a night, a determination of the offset to a level which is better than 0.3 arc seconds. This value has some, but not great, interest for astroposition. However, for reasons discussed elsewhere (Currie 85a, Currie 85b, Wellnitz 82) the instrument was operated at a level which was significantly below projections. Thus this number may be used to illustrate reasonable operation and to project to better observations following the correction of known problems.

By comparison, we see that this is better than some of the worst effects of anomalous refraction which have been observed (Wellnitz 1982). However, this instrument as it stands is too large, not portable, and not of sufficient accuracy as defined by theoretical predictions.

The operating accuracy of the instrument was almost a factor of ten less than was predicted by prior analysis (Currie 1978 and Wellnitz 1982).

2. System Problems

In this section, we address some of the system problems.

a) Image size

One of the major problems that caused a reduction in the angular precision was star image which was larger than the nominal 2 arc seconds to imperfect optics. The angular provision in the determination of dispersion angle is partly due to atmospheric turbulence, but mostly due to this image size. (Wellnitz 1982)

b) Differential PMT Saturation

The QPM showed some saturation at higher count rates. Saturation coefficients which were different in different channels led to difficulties in centroiding the image.c) Telescope Tracking

We entered the telescope pointing errors into the paddle input. To prevent telescope damage, the rate of input had to be kept low. This caused a systematic error.d) Ratio Frequency Interference

Finally, poor telescope drive added to the problem as well as radio frequency interference which caused bad results on many nights.

3. New System

A new system was designed which used knowledge gained from the above defined tests. Attempts to solve these various problems and to produce a fully-automated system which was, in principle, portable was then undertaken. Effort with this instrument has proceeded well but it is not yet at an observing stage. This instrument is described in more detail in the Two-Color Refractometer paper (Currie 1985).

E. GENERAL CONCEPT

The field operation configuration is shown in Figure IV-1.

This instrument makes independent measurements from its two apertures. We might expect from theoretical considerations that this approach would be valid to the order of 0.1 arc-seconds.

However, for higher accuracy we have difficulty when dealing with short term anomalous refraction or image motion occurring in the two telescopes independently. For this reason, the independent motion must be averaged. In principle, one might situate the two instruments along the axis of the wind and therefore reduce this averaging problem. In a practical sense, however,

such a mode of operation would greatly constrain the observation procedurd, and not be practical due to the changing direction of the wind. This configuration would not address the so called "room refraction" or the effect of the local environment. Parts of the "room refraction" would affect each of the instruments separately.

The ideal procedure would be to bring the light to a single aperture and then distribute it to the two separate instruments, that is, one beam to the system to measure the position, and one beam to the system to measure the refraction (or the anomolous refraction).

CHAPTER III

ARRAY LIGHT SENSOR FOR GEOLABE

A. OBJECTIVES OF ARRAY SENSOR

This section addresses the use of an array light sensor for the detection of the star light. At the University of Maryland, we have applied such a sensor to T-4 observations.

The program objectives, which are related to the use of the Charge-Coupled Device Sensor System, consist of providing a high degree of impersonality, an accurate reproducibility of positional information and an increased accuracy.

In the future, we may wish to obtain enhanced sensitivity that will permit the observation of very faint objects with acceptable receiving apertures. We may then consider the use of one or more stages of image intensification prior to the use of the charge coupled device and/or a time delay integration technique. Such systems have been used at the University of Maryland in the past and will be discussed in the next section. However the use of such procedures will not be considered in the GEOLABE description within this document.

B. HISTORY OF ARRAY SENSOR IMPLEMENTATION

The University of Maryland has operated Charge Coupled Devices and Intensified Charge Coupled Devices since 1974. These have included:

1. Direct observations of the Pleiades using an ICCD on a 2-inch system (1974).

2. Spectrophotometric observations of a quasar using an ICCD on the 200-inch Palomar Telescope in (1977).
3. Development of an Eyepiece for the T-4 Theodolite (1979).
4. Astrometric observations on T-4 Theodolites (1977-1982).

C. DESCRIPTION

The CCD is used as a method to time the entrance and the exit of the star image in each photo sensitive element of the CCD. This is described in (Currie 1982)

CHAPTER IV

TWO APERTURE CONFIGURATION

A. A DESCRIPTION OF TWO APERTURE CONFIGURATION

In this chapter, we shall consider the use of the Two-Color Refractometer to provide a correction to the determination of astroposition carried out by the more or less conventional astrometric instrument, i.e., a T4 Theodolite or a Danjon Astrolabe. In order to distinguish this mode of operation from the different mode of operation to be discussed in the next chapter, we shall denote this mode of operation as the "Two-Aperture Configuration".

In this discussion, we will assume that room refraction will not introduce a significant amount of error in the mean refraction as seen from the two instruments. This assumption may or may not, in order to determine the importance of this differential room refraction, one would have to conduct astroposition observations in an optional configuration.

The use of two independent field instruments (i.e. a Two-Color Refractometer and an Astrolabe with two separate apertures will be refer to as the Two-Aperture Configuration. For the highest accuracy, we must assume that the high frequency motion is uncorrelated between the two apertures. This configuration is illustrated in Figure W-6.

This configuration consists of a Two-Color Refractometer operating on an independent mount and an astrometric instrument (T-4 theodolite or astrolabe) operating on its separate mount.

In this discussion, we will assume that room refraction be an appropriate assumption. to determine the magnitude of this effect.

In the Two-Aperture Configuration, one has a Two-Color Refractometer set up in one place and the T-4 in another place. The high frequency image motion may have an r.m.s. value of the order of 0.4 arc-seconds. (Currie 1982) This motion involves an averaging time, which is related to the transit time of an atmospheric cell across the system. As a concrete example, if we have a wind with a velocity of 3 meters/sec and a 1 meter cell size the characteristic time is of the order of 0.3 seconds.

Note that if one of the instruments is exactly down-wind of the other instrument, we have a much improved situation. However, we cannot rely on such a configuration. Thus, for the simplified concrete example discussed in the previous paragraph.

B. EVALUATION OF TWO APERTURE CONFIGURATION PARAMETERS

In this brief analysis we have discussed sample values of certain parameters. We have also implicitly presumed that most of the turbulence is in the lower atmosphere (Bufton 1970). In order provide a theoretical prediction of use for accuracy of this, one would need a detailed model of the turbulence, wind, and temperature profile of the atmosphere. In addition, one would need a good model for the wind flow and temperature structure around the enclosure. The data necessary to support the proper analysis should be collected in the field.

An ideal way to collect this data would be to operate a pair of Two-Color Refractometers. One would then determine the correlation between them.

On the other hand, one could operate two independent T-4 Theodolites equipped with CCD eyepieces. Both of these methods will isolate the various astrometric parameters which determine the relation between precision and averaging time.

Note that there is an implicit presumption in both of these methods that they are to be used in an open field without enclosures. This is to assure that there would be no room refraction.

CHAPTER V

OBJECTIVE'S OF THE TCR/CCD ASTROLABE

This chapter addresses the advantages of an astrometric instrument using both Two-Color Refractometer and an array detector. The Two-Color Refractometer performs the determination of dispersion. The astrometric determination of star position is performed using the star light which has entered through the same aperture and is detected by the CCD. Such an instrument results in a major increase in the complexity of the instrument as compared to two separate instruments. However, as we will discuss, the gains in the determination of astroposition are significant. We would expect to achieve significant increases in star position accuracy and a reduction in the required observation time to obtain the equivalent of a first order astrometric position.

A. UNCORRELATED ATMOSPHERIC NOISE

The primary reason for considering observations using a single aperture to collect the light for the position measurement and for the refraction measurement is to reduce the influence of uncorrelated atmospheric tilts.

Thus, if one uses light from a single aperture, the tilt which influences the TCR measurement and the tilt which influences the CCD determination of astrometric position are identical. Therefore the correction for refraction is directly (rather than statistically) related to the position determination. This means that one can observe for a shorter time in order to obtain a sufficient signal-to-noise ratio.

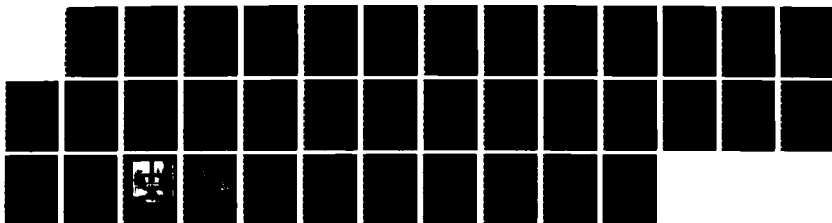
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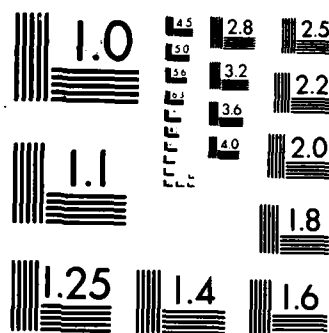
ON TWO COLOR AND CCD METHODS FOR THE DETERMINATION OF
ASTRONOMIC POSITION(U) MARYLAND UNIV COLLEGE PARK DEPT
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For a two aperture configuration one must average for a sufficiently long time in order to reduce the decorrelated aspects of the tilts of the wavefronts in the two apertures. The time required may be the limiting requirement for observational time. Thus our primary objective is to reduce the amount of time for a single star and/or the amount of time for a first order astroposition determination.

It follows that, for the highest precision, we would use the same aperture for both measurements. In a simple form, we might construct an instrument as shown in Figure V-1.

The dispersion nulling wedges shown in this figure are somewhat different than the dispersion nulling wedges which have been previously discussed for the Two-Color Refractometer. These wedges which we shall denote as refraction/dispersion nulling wedges or R/D nulling wedges may, idealistically, be considered as simple wedges of a single glass which has the same dispersion curve, or same index as a function of wavelength, as the air would. Thus, if they are to be made compound wedges, it is not to cancel out the refraction (as was the case for the wedges in the Two-Color Refractometer) but to make the index as a function of wavelength a better match to the index refraction/dispersion nulling

The wedges now eliminate the dispersion in the light before the beam splitter and, in doing so, eliminate the refraction of the light falling on the CCD. More explicitly, since the wedges are adjusted to eliminate the dispersion by the use of the Two-Color Refractometer, since they have the same index as a function of wavelength of the air, we have also eliminated the angular refraction. With the angular refraction eliminated, the beam falling on the CCD is falling in the position it would have if there had been no refraction by the atmosphere. Note that these are Dispersion/Refraction

Wedges as distinct from the type conventionally used in the Two-Color Refractometer. These wedges are not compound in the cancelling sense of the Two-Color Refractometer. In this idealistic form, one measures values of star position (an almucantor crossing) that are, on average, uncorrupted by refraction.

B. COMPARATIVE OPERATIONAL PROCEDURES

We may now consider the operational complexity of the GEOLABE as compared to the Two-Aperture Configuration discussed in the previous chapter. In many ways, the GEOLABE is simpler to operate and easier to automate. This is partly due to the difference between a single instrument and two instruments, and a reduced requirement for pointing precision in the case of the GEOLABE. In the data reduction, procedures to correlate the short term variations in the scene between the two separate apertures will be eliminated in the case of the GEOLABE. However, the GEOLABE will be a significantly more complex instrument to fabricate.

C. REDUCTION IN SYSTEMATIC ERRORS

The primary gain of the Single Aperture design is the reduction of the influence of systematic errors. Various examples of the errors will be discussed in a more general treatment under the evolution of the GEOLABE design, in a later chapter.

D. STELLAR CATALOG FOR THE GEOLABE

The Two-Color Refractometer measurement is only effective on stars which have a spectral type which yields similar a number of counts in the red and the blue channels. This means that we can use only a fraction of the FK4 or FK5. The star members of the FK5 catalog must be further reduced in order to eliminate those stars which are close binary systems. This new subcatalog of useful stars consists of only a portion of the FK4 catalog and may have only 40% or less of the full FK4 catalog. The actual number of stars depends upon details in the selection of the photomultiplier response, and the degree of correction which one obtains from the Refraction/Dispersion Nulling Wedges. Thus the rate of observation will be somewhat reduced with respect to the stars normally observed with the T-4 theodolite, or with a conventional astrolabe. The actual number of stars available may also be influenced by the aperture which is selected for the instrument.

A rough estimate indicates that it will take approximately three to four hours to obtain the group of sixty-four stars which would be necessary for the astroposition determination. This presumes the use of the stars which are in the reduced FK4 catalog.

From a longer term point of view, there are stars which are sufficiently bright for use in an extended GEOLABE catalog. These have been eliminated from the FK4 due to distribution or other reasons. One could gradually build up an extended GEOLABE catalog which would have a significantly larger number of stars with significantly greater brightness.

E. EVOLUTION OF THE GEOLABE DESIGN

We now return to the earlier discussion in which we use a general approach to describe the design of the GEOLABE. The instrument which is shown in Figure V-1 implicitly measures the full refraction/dispersion as it is measured by a conventional Two-Color Refractometer. However, the purpose of this design is to eliminate the effects of refraction from the stellar position measurements by the CCD rather than supply the data to correct for the effect of the refraction. This procedure for eliminating the anomalous refraction will reduce systematic errors with respect to the computed correction. In general, a null experiment in which one has eliminated the effects of a deleterious phenomena will provide a higher accuracy than a procedure which measures a deleterious affect and applies this as a correction to a measured phenomena.

1. Refractional Dispersion Nulling Wedges

The GEOLABE could be fabricated in a manner to use a set of refraction/dispersion nulling wedges which would be placed in the incident beam. This set of wedges would correct for both the refraction and the dispersion introduced by the earths atmosphere. However, the selection of such a glass wedge configuration would be affected by the following technical aspects which would have to be considered in detail.

a. Optical Quality

These are usually large wedges since they must cover the full aperture of the GEOLABE with a significant elongation since they are not orthogonal to the optical axis of the GEOLABE beam. These wedges must have high optical quality (at the level of 0.1 wave or better) with very high uniformity in the glass material over the entire aperture.

b. Matching the Air-Glass Dispersion Curves

In order to use spectral filters which have a wide band pass, in order to obtain the optimal light collection, one must match the index of refraction as a function of wavelength for the wedges to be very close to the index of refraction as a function of wavelength. The use of compound wedges becomes more difficult because of the large diameter of the wedges.

c. Offset Due To Horizontal Atmosphere

The correction method requires an adjustment to compensate for the normal refraction. Since this must be corrected with a precision of about 0.1 percent this would have strong impact on the quality of the wedges.

2. Evacuated System

There is a large fixed dispersion at the almucantor elevation. This is due to the dispersion of the atmosphere for observations which are not at the zenith. Thus at 45° one has approximately 60 arc seconds of refraction and the associated dispersion. One must provide the compensation for this fixed refraction and dispersion to a high precision and accuracy in order to properly determine the time of almucantor crossing independent of the refraction. We now consider a procedure by which this demanding requirement may be eliminated. We may eliminate this offset by enclosing the system in a chamber with a large horizontal window and evacuating this chamber. Thus we consider an instrument which operates within a vacuum. This type of instrument is shown in figure 8.

An instrument of this design does not need a set of refraction/dispersion-nulling wedges which would correct the normal refraction of about sixty arc-seconds with a precision of 0.05 arc seconds. An instrument using vacuum in this manner would require dispersion nulling- wedges which are used

only to make fine corrections in the value of the dispersion. In this manner, this design has greatly reduced the requirement on the dispersion nulling wedges. (Hu 1982)

3. Role of Vacuum

In order to illustrate the advantages of some further modifications in this design, let us consider, from a somewhat more fundamental point of view, the role of the atmosphere and the role of the material within the chamber. In particular, we wish to address their role in determining dispersion and refraction.

The refraction and dispersion produced by the atmosphere in observations of stars at nonvanishing zenith distances may be illustrated by considering the model of a uniform atmosphere between the vacuum of space and the imaginary horizontal partition contained at the top of the instrument. The space below this boundary contains the observing equipment and is evacuated. This space, like the region above the atmosphere, has a index of refraction of unity and no dispersion. Then the instrument will sense no dispersion and no refraction. (For the current discussion in this document we neglect the effect of the curvature of the earth and the earths atmosphere). The corrections for the refraction have been treated in a separate paper. (Currie 1985c)

Now let us consider two classes of hypothetical observations which might be conducted within an evacuated instrument chamber. The first of these observations would consist of observations conducted with an astrometric instrument like a conventional astrolabe or T-4 Theodolite. We will designate such observations as an "astrometric-type" observation. Such an instrument will measure the refraction, nominally at a single wavelength.

The second class of observations which might be conducted within the instrument chamber consists of observations with instruments like the Two-Color Refractometer which measures dispersion. One may deduce the amount of refraction from this data. This type of observation will be designated as a "Two-Color Refractometer-Type" observation.

In the previous discussion, we considered the results of measurements performed with the presumption that the instrument chamber was evacuated. In this case both the refraction (measurement with the astrometric-type observation) and the dispersion (measurement with the Two-Color Refractometer-type observation) vanish. Let us now consider replacing the vacuum with a material which has no dispersion but which has an index of refraction which is non zero. We will now observe, using the astrometric-type instrument, that the angle of refraction in the position is in proportion to the magnitude of the index of refraction of the material which is used to fill the instrument chamber. However, we will have no dispersion. (We are neglecting anomalous refraction at this point in the development). Thus there will be a refraction correction which is independent of the properties of the external atmosphere but which depends upon the pressure, temperature and composition of the gas contained within the instrument. In summary, one needs to know only the index of refraction of the gas within the chamber.

However, we note at this time that the second order term which involves the interaction of the temperature profile of the atmosphere and the curvature of the earth is not reduced by the use of the vacuum chamber and/or the use of helium. For this reason, in our objective of higher accuracy for astroposition this term will become relatively more important than in the conventional observation.

The dispersion of helium may be expressed in an inverse dimensionless form Ω which was developed in an earlier paper (Currie 1978). This has a value of 79.1 as compared to a value of 31.6 for air. This larger value for Ω for helium denotes a dispersion which is smaller by a factor of approximately 2.5 as compared to air. However, the above value is relevant only if we were observing through a full atmosphere of helium.

We may further reduce the effect of the residual refraction due to the helium by the use of an entrance window which has a fixed angular offset. The anomalous refraction and long term dispersion is corrected by providing fine motions on the "wedge" of air. The detailed exploration of this improvement and the mathematical expressions for the correction will not be addressed at this time.

4. On The Use of Helium

We now review some of the more concrete questions related to the use of helium as a filling gas in the instrument chamber.

A significant difficulty with the use of vacuum in the chamber is the requirement for a window to permit the entrance of the star light. Such a window must be thick enough to reduce the influences of the mechanical stresses required to support the atmospheric pressure of 15 pounds per square inch. A window of this thickness becomes quite sensitive to thermal

If the gas within the instrument chamber also has a small amount of dispersion, this will be detected and measured by the observation of the Two-Color Refractometer. This dispersion will have a value which depends upon the refraction as a function of wavelength of the internal gas, as well as the internal pressure and temperature. Thus there will be a correction in the system related to the dispersion measured, the correction required, and the calculated refraction corrections.

As we shall see in further discussions, the two types of correction discussed above are both significant, but small in magnitude. However, they are logically quite separate.

Let us summarize the numerical properties for our case of choice in which we will use helium at ambient atmospheric pressure as the filling gas in the instrument chamber. The index of refraction of the helium at 5,000 Angstroms is smaller than air by a factor of 8.0.

For this reason the correction which will be required in the astrometric type observations at a nominal forty-five degree zenith distance will have a magnitude of about 7 arc seconds rather than the normal value of about 57 arc seconds. The pressure and temperature effects on the magnitude of the correction (for non-zenith observations) will thus be reduced by about a factor of 8. This is the case for a horizontal window. We presume for the present that the helium is held at the local pressure and temperature. The required accuracy for the knowledge of pressure and temperature has now been reduced. By approximately a factor of 10 with respect to the accuracy required for a conventional astrolabe which is not evacuated. The required meteorological parameters (i.e., the pressure and temperature) may now be with relatively simple instrumentation.

gradients, causing variations in the index of refraction and wedge effects. In addition, the fact that we wish to measure dispersion through this thick glass plate requires extremely high tolerances on the uniformity properties of this plate and upon the compositional homogeneity of the glass. We will not address this tolerance since in the next paragraph we will discuss a more favorable procedure in order to eliminate the requirement for such tolerances.

For the above reasons, when using the GEOLABE, we will use an instrument chamber filled with helium at atmospheric pressure. In this case, the window need support no mechanical stresses. It is only required to contain the filling media. Thus we could use a very thin window probably made of clear 1/4 mil Mylar. This has been tested for astronomical observations and found to have an acceptable level of optical quality. (Vaughan 1973) However, the final choice between the thin plastic and a thin polished window of UVBK7 will be made on the basis of the homogeneity which one may obtain in each of these windows.

5. Effects of Star Motion

Now consider the effects, within the detector system of the GEOLABE, caused by the motion of the star. The effects of the sidereal motion will be considered separately for the CCD array detector system in the astrometric portion of the GEOLABE and for the quadrant photomultiplier system which has the image-motion stabilization by the five guidance mirrors in the Two-Color Refractometer subsystem.

a) Star Tracking for CCD Sub-System

In the normal operational procedures, the image of the star moves across the CCD. There is a computer procedure to track this sidereal motion in order to reduce the amount of recorded data. However this sidereal motion which causes the star image to intercept many pixels of the detector provides the essence of the accuracy of the astrometric determination of star position. This is the same mode of operation that is employed in the T-4 theodolite.

b) Star Tracking for the Two Color Refractometer Subsystem

The Two-Color Refractometer requires a stabilized image. In other implementations of the Two-Color Refractometer, this requirement has been met either by mounting the entire Two-Color Refractometer on a large telescope or by installing the Two-Color Refractometer in a mount which is inertially stabilized. The GEOLABE is fixed with respect to the earth and the rotation of the earth causes the images to move rapidly across the field of view of the instrument.

c) On the Use of the Air Wedge for Dispersion Nulling

The normal use of the dispersion nulling wedges, which are indicated in Figures V-3, V-4 has been discussed. (Currie 1985) We see that in the GEOLABE configuration these wedges must be rather large in dimension (perhaps 10 inches in diameter) and must be of very high optical quality. The wedges should also have an index of refraction as a function of wave length which is very similar to the refractive index of air as a function of wave length.

For the above reasons, it is very tempting to replace the glass wedges with "wedges" made of air. Let us consider, for a moment, an example for which the instrument chamber contains a vacuum. If the chamber and thus the window is tipped with respect to local gravity, we will have introduced a wedge composed of air through which the optical system located in the

instrument chamber observes. We could vary the height of one end of the chamber and this would cause a change in the equivalent strength of the air wedges. Let us consider the magnitude of the angle by which the window or interface must be tilted in order to compensate for a reasonable amount of anomalous refraction. If the magnitude of the anomalous refraction is 3 arc-seconds, then the interface for the chamber window must be tilted by 3 degrees. This would be a tilt of the air-vacuum, interface, i.e. the window. The mercury in the astrolabe would not be tilted. A physical damper might be used in the mercury pool in order to minimize the effects that such motion or vibration could have on the surface of the mercury so as not to disturb the mercury image.

d) Fixed Offset of Air Wedge

If we have used a vacuum as the media in the instrument chamber there would be no effect due to normal refraction. However, the use of helium will result in a "normal" refraction with a magnitude of approximately 7.0 arc seconds. To compensate for this, we will include both an offset in the tilt of the interface and a correction which is applied to the measured value of the elevation. Approximately 40% of this will be offset in nulling the apparent dispersion. The remaining 5 arc seconds will be a permanent correction. The magnitude of this correction will depend, rather weakly, on the pressure and temperature.

6. Star Tracking

The star image, as it is projected on the CCD array detector of the astrometric portion of the GEOLABE, appears to move rapidly because the instrument is fixed rather than moving at a sidereal rate which would allow it to track the star. For the Two-Color Refractometer portion of the GEOLABE the

tracking mirrors assure that the star remains centered on the photomultiplier. Due to the speed of the star motion and the focal length of this system, there is a rather stringent requirement on the stability of the tracking mirrors.

For the present, we presume a design which uses two tracking mirrors fixed in the azimuth and elevation axis'. However, in the future version of the GEOLABE we may mount one of these tracking mirrors on a precision rotating table in order to eliminate the need for one of the two high accuracy mirrors. In this case, we may rotate the high precision axis to the requisite angle and then use that axis to produce the high speed/high precision motion. Then a second pair of mirrors would provide the fine correction. In this approach one would have a single mirror which is capable of large amplitude motion, high accuracy and a low frequency response. There would also be two small mirrors capable of high frequency response which operate in the null mode with relatively small amplitude. The two small mirrors would be fixed in the elevation and azimuth axis and the axis of motion of the large single mirror would be rotated to account for the change in azimuth.

CHAPTER VI

GENERAL CONCEPT OF BASIC GEOLABE DESIGN

This section will concentrate on the specific aspects of a generalized design of the GEOLABE, rather than the general pedagogical development of various constituent concepts discussed in the previous chapter. This section will illustrate some of the details of the significant elements of the GEOLABE conceptual design, the general physical requirements and the specification levels of some of the various components.

A firm design for the GEOLABE has not yet been completed for the detailed components and the detailed component specifications. Several studies are required to optimize the parameters of subsystems for the best performance of the overall system. These have not yet been performed. Thus the design and the parameters discussed in the following sections should be considered as a conceptual design.

A. GENERAL STRUCTURE OF DESIGN

The primary optical components of the GEOLABE are shown in Figure VI-1. We will presume the use of helium as a filling media within the sealed case. This helium will be maintained at atmospheric pressure. A list of some of the general parameters consist of:

Telescope aperture	This will have an aperture of eightinches(200 mm).
System focal length	One meter
Photosensor	The photodetector will consist of a Fairchild Corporation. CCD222
Two-Color Refractometer	This will be similar to University of Maryland field model of the Two-Color Refractometer.
Window	This glass [UBVK7 or fused silica] or a 1/4 mil' Mylar Film.
Filling media	Helium at a pressure of one atmosphere (ambient).
Depression correction	This will be done by window tipping to use an air wedge.

B. REFRACTION-NULLING

In earlier discussions, we considered the question of wedges in order to know the refraction. The data for knowing this refraction would be derived from the Two-Color Refractometer. In this nominal design of the GEOLABE, we use "air wedges" which are generated by a tilt of the input window. This approach will be discussed in more detail later in this section.

C. USE OF HELIUM

We will now consider, in more detail, the role of helium gas at atmospheric pressure to replace a vacuum in the system.

In order to make this comparison let us consider, on the same scale, the index of refraction as a function of wavelength for air, helium and for a vacuum. Such a comparison is shown in Figure VI-2.

This data indicates the index of refraction of dry air for standard pressure and temperature (Owens, 1967) and the index of refraction for helium (Cuthbertson 1933).

We may express the refraction by the value and slope of the index of refraction as a function of wave length. Thus at 5461

n	$1/n$	$\frac{\partial n}{\partial \lambda}$	$1/n-1$	$\frac{\partial n}{\partial \lambda}$
Air		1.00029		
Helium		1.000		

Table 1

We can now discuss the comparison of the index of refraction for helium, air, and vacuum presented in logarithmic form in Figure VI-2. The index of refraction of helium is lower by the factor of approximately eight at a wavelength of 5000 Angstroms. This means that the helium is 88% as effective as vacuum in removing the effects of refraction. In other words it removes 88% of the refractive effects of observing in an atmosphere of air.

Although it is not obvious from this graph the slope of the curve for helium is proportionally lower than that of air. It has a smaller proportional dispersion, by a fraction of approximately 2.5, than the proportional dispersion of air. As a result, the absolute dispersion with respect to air has a value of 77. Thus, with respect to dispersion corrections, the Helium is more than 95 percent as effective as the vacuum, removing 95% of the dispersing effects of the atmosphere.

The design discussed here leads to another advantage in that we can use air for the wedge media. This is possible since the air has to remove the constant dispersion. Thus, the effects of this error will be a constant and not something that depends on azimuth and star type. The main advantage consists in the use of a homogenous material (air) rather than the use of different portions of the glass wedges. The latter may have variable index and variable dispersions.

D. DETERMINATION OF THE TIME OF ALMUCANTOR CROSSING

We will now address the determination of the time at which the star crosses the almucantor; That is, the time at which the star has a specified elevation (45°) with respect to the horizon. In the focal plane, one has two images of the star, one moving diagonally downward and the other moving diagonally upward. We wish to determine these times at which the two images

of the star cross, that is, the time at which they show the same elevation.

The data from the CCD for each photosensitive element for each time interval of 30 milliseconds will be recorded on magnetic tape. This consists of the white light intensity at each pixel. The data recorded will actually be for a "patch" around the star. This patch may be an area of about 10 elements. At a later time, the light intensity data for each of the two star images will be analyzed. A curve will be fitted to each of the tracks of the stars in the same manner which was used in the CCD Eyepiece System for T-4 Theodolite. For the time dependence of the position along the track of the star image, we may use the data from the entire run. This full data set will be used to determine the time at which the images cross. This will be done in the same manner as with the CCD equipped T-4 (Currie, 1983). A representation of the paths of the two stars as they traverse the CCD is shown in Figure I-4.

The dashed lines connect the two star images as they appear at one instant. The time at which the paths of the two stars cross is the time of almucantor crossing.

1. Correction for Differential Dispersion

The use of the nulling system of the Two-Color Refractometer will assure a vanishing value for the dispersion. If the ratio of the dispersion to the index of refraction of helium is not identical to the same ratio for air, then the correction to zero dispersion will leave a residual refraction correction. However, the magnitude of this term may be computed, based upon the value of local refractivity. Thus we will use a computation of this effect as a correction for the almucantor crossing time. For the nominal selection of filters, this term vanishes. For this reason, the remaining part of this discussion will presume that the relation between refraction and

dispersion for helium are equivalent to the relation for air. They are both reduced by the same factor of approximately 8.0. This will greatly simplify the discussion of the principles and will not impact the question of possible errors. Clearly there will be a modification in the final processing to correct for the small non-vanishing term. This must be implemented but it will not be a significant source of random or systematic errors.

E. MOTION OF STELLAR IMAGES FOR TWO-COLOR REFRACTOMETER

The use of the Two-Color Refractometer for setting the "wedges" will assure that the image position on the CCD has been corrected for refraction. This has been discussed in the previous section. Since the sided mirror and the fine position mirrors are in the Two-Color Refractometer optical train, not the CCD optical train, errors in the mirror position will, to first order, not affect the astrometric determination of almucantor crossing. However in second order, there is an effect if there is a failure of the servo loop to correct properly. Information on the magnitude of this effect is available from the photocount data of the quadrant photomultiplier. This data will be recorded and can be used to compute a correction.

F. REQUIREMENTS FOR THE BEAM SPLITTING FILTER.

The beam splitter divides the light between the Two Color Refractometer and the Charge Coupled Device. This filter is chosen so that it diverts different spectral passbands to the Two Color Refractometer and to the CCD. The optical configuration is defined so the light to the Two Color Refractometer is reflected and the light to the CCD is transmitted. Thus, the beam splitter reflects the beam for the Two-Color Refractometer so that it does not have to pass through additional glass which would cause further

uncertainty in the value of the instrumental dispersion. By the use of a thin substrate for the filter, we would minimize the spherical and astigmatic distortion introduced into the light which is imaged on to the CCD. A second thin transparent glass plate will remove the major portion of the astigmatism which would be caused by the substrate of the beam splitting filter.

The nominal design for the beam splitting filter will consist of an interference filter which reflects the blue (3300-4200A) and red (5600-6800 A) bands and transmits the green (4500-5300 A) and the near infra red (7,000-10,000). Successive filters will allow the choice of green or infra red in order to conduct tests. The deep red will result in a better measurement for late-type stars, the green filter will be better for early-type stars.

CHAPTER VII

PROJECTED ASTROMETRIC PERFORMANCE OF THE GEOLABE

This chapter will develop an estimate of the precision and accuracy which may be expected for the fundamental design. These estimates will, in general, be based upon operational parameters relating to the fainter stars from the FK4 catalog and will consist of procedures that would normally be used in order to obtain high accuracy for astroposition determination in a relatively short observing time. These estimates will be a preliminary approach, since we have not yet performed the optimization studies to obtain the best set of parameters, nor have we performed the procedure such as precise integration over band passes, spectral distributions, and photo detector sensitivities which must await the definition of the optimized parameters.

A. INSTRUMENTAL LIMITATIONS

In this section, we consider those limitations in the precision and accuracy which we may expect due to fundamental limitations in the GEOLABE and its nominal design parameters. In a later section we shall address those limitations which may be expected due to more general difficulties caused by the variable aspects of the earth atmosphere and those problems which arise from the fact that the FK4 catalog is not the optimal catalog for observations with the GEOLABE. As currently projected, the dominant limitation in the instrumental precision is determined by the size of the stellar image and the number of photo electrons which will be received during the observation period for a particular star.

1. Nominal Instrument Parameters:

We will now address a nominal set of parameters that define a reasonable candidate for the GEOLABE. These parameters will be used in order to evaluate the accuracy for a given set of observation times.

NOMINAL PARAMETERS FOR GEOLABE SYSTEM

TABLE 6-1

TELESCOPE APERTURE	8 inches
EFFECTIVE APERTURE (for one channel)	5 inches
STELLAR SPECTRAL TYPE	A0
STELLAR MAGNITUDE	6
PHOTOCOUNTS/SECOND/COLOR	5,000
OBSERVATION INTERVAL	10 seconds
TOTAL NUMBER OF COUNTS	50,000
PRECISION (as fractional diameter)	0.0032
PRECISION OF IMAGE SEPARATION	0.0046
IMAGE SIZE (rms diameter)	2 arc-seconds
PRECISION IN DISPERSION	0.0091 arc-seconds
RATIO OF REFRACTION TO DISPERSION	30.0
PRECISION REFRACTOR/STAR	0.273 arc-seconds
NUMBER OF STARS/GROUP	64
OBSERVATION TIME/GROUP	3 hours
PRECISION IN REFRACTION FOR ONE GROUP	0.034 arc-seconds

This table gives a sample set of parameters. Some of the parameters in this table are estimated, since either they are not well known, depend upon the site, or depend upon the specific star being observed. In particular, the RMS image size is a reasonable estimate for a good site. This measure is equivalent to three or four arcseconds as described in the normal terminology. The count rate of five thousand counts per second depends significantly upon the specific details of the spectrum of the star.

2. Review of Objective

The general objectives of the program to use Two-Color Refractometer in a helium filled astrolabe will now be reviewed.

In order to evaluate the expected precision of the helium astrolabe, we may use data obtained with the vacuum astrolabes in the PRC. A typical precision with the one group is 0.17 arcseconds. (Ye 1985) This is for a reasonably well-chosen observing site, one which is not at a mountain site but near a city. This number for the precision includes the effects of both catalogs errors and (long term) variations in the mean refraction. Thus we may expect the CCD/helium astrolabe to provide similar results for the precision. If we permit a somewhat degraded atmospheric condition, we might expect this to increase to a value of between 0.20 or 0.22 arcseconds. This is the precision of an observation of a single star within a group for the night. For a set of 64 stars, we will then expect a precision for the mean of the group of 0.03 arcseconds. At this level of precision we will expect that systematic errors, in the form of mean errors in refraction, to dominate. Thus the accuracy would not achieve this level.

For this reason, we may take the average refraction determined from the entire group and use this to determine the refraction. Thus, we expect this to be the quantity derived from the above table, that is, 0.034.

When the effects of the two types of errors discussed above are combined, we may expect an error in the accuracy for the group to be at the level of 0.048 arcseconds. This short discussion has presumed the most unsophisticated use of the data. This is clearly an upper bound on the accuracy with respect to the current sophistication of the data processing.

It, of course, presumes that there is not some undefined underlying systematic error which is dominant. The question of such underlined systematic errors must be addressed by experimental observations with an instrument of this type.

For the present, we shall neglect the unknown systematic effects (which must be determined experimentally in any case) and discuss the procedures by which we may increase the accuracy.

For a seeing disk with an RMS diameter of 4 arc-seconds and the precision discussed in Table 6-1, we may expect a precision per color of 40 milliarcseconds. For a nominal filter separation, this will result in a determination of the refraction with a precision, for this one star, of 0.75 arcseconds.

Thus, the estimate for the correction of the systematic refraction effect as determined on one star is similar to the random determined value. For this reason, we may expect the determination of each star to be relatively systematic error free and that this will reduce the r.m.s. value with further observations. Thus, if we expect the random error for a star to be 0.1 arcsecond, which is what we found with the T-4, then for observing a group of 64 stars, we might expect an accuracy of 0.01 arc-seconds.

The nominal accuracy which shall be the objective of the first series of observations will be 0.1 arcsecond for a series of observations concluded during a single night. We project that this one accuracy may eventually be achieved during half a night or approximately three hours of observations.

The primary objective of this computation is to illustrate that the fundamental limitations should not be the final problem. Thus we must explore and eliminate the systematic problems if we are to reach the fundamental accuracy discussed above.

Figure I-1 (1) T-4 THEODOLITE - OPTICAL MECHANICAL This is the diagram A of the mechanical structure and various optical paths for the T-4 Theodolite as configured for its normal mode of operations. (pg 9)

Figure I-3 DANJON ASTROLABE this figure shows the mechanical parts, the components, and the optical light path for the Danjon astrolabe.

Figure I-4 PRINCIPLE OF PRISM ASTROLABE This figure illustrates the principle of operation of a prism astrolabe. In the upper Figure we see the light paths of the light from the star as these paths pass through the Prism and focusing optics of the astrolabe. The second figure is a representation of the apparent motion of the two star images to the direct stellar image (S') and the stellar image reflected in the mercury pool (S) for a star with an azimuth of about 45 degrees.

Figure IV-1 FIELD OPERATING CONFIGURATION OF TCR This illustrate, in block structure, the method of operation of the stand alone TCR operation in conjunction with another astrometric method instrument.

Figure VI-1 PRIMARY OPTICAL SUBSYSTEMS OF GEOLABE This illustrates the schematic form of the GEOLABE which illustrates the vacuum or gas-tight case the window and the reflecting PRISM structure.

Figure VI-2 INDEX OF REFRACTION OF HELIUM AND AIR As illustrated, in graphical form, the index of refraction of function of wavelength of air, Helium and vacuum. The index is expressed in form.

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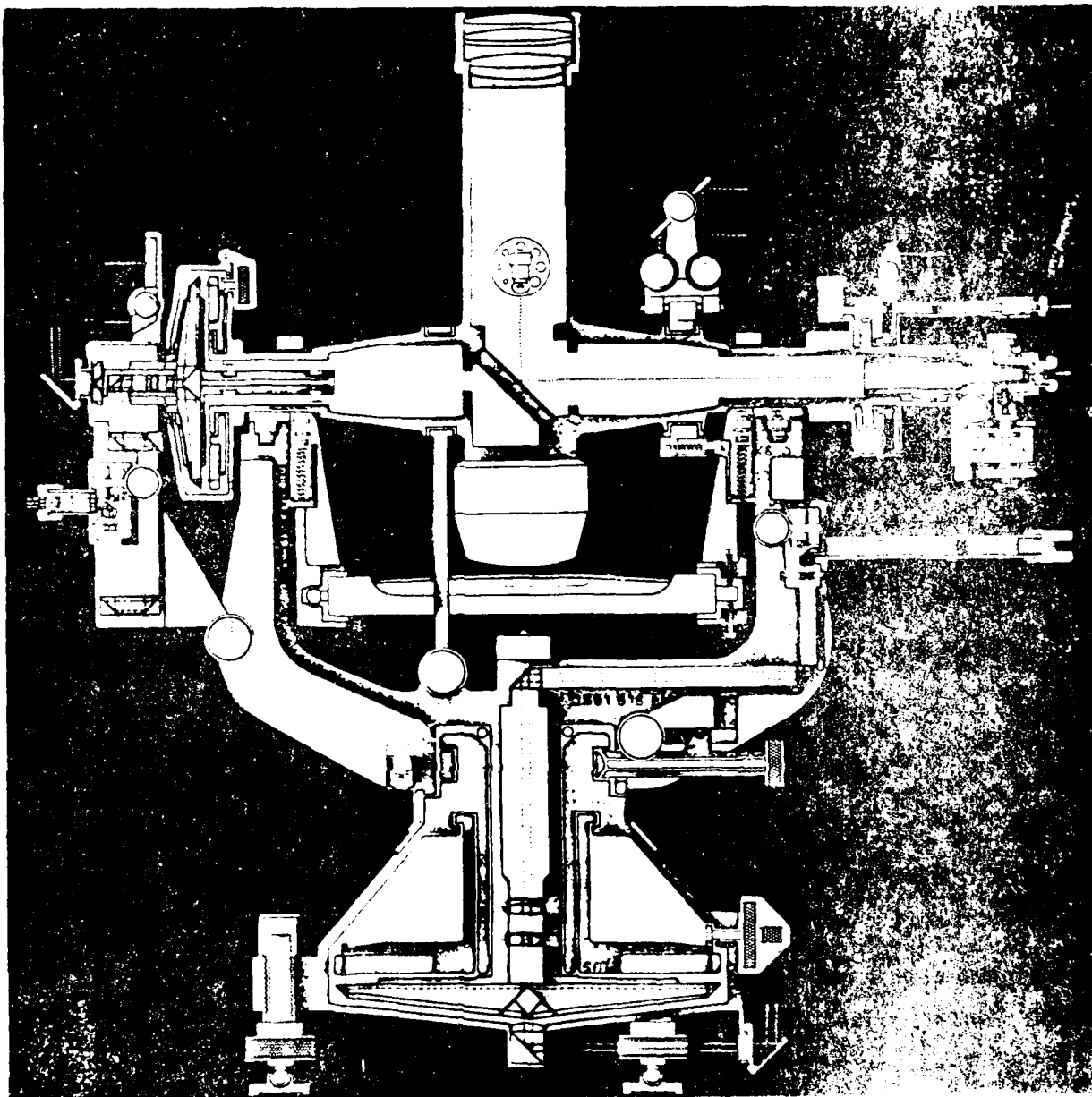
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The paths of rays through the optical system



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FIGURE I-1

THE I-1 THEODOLITE

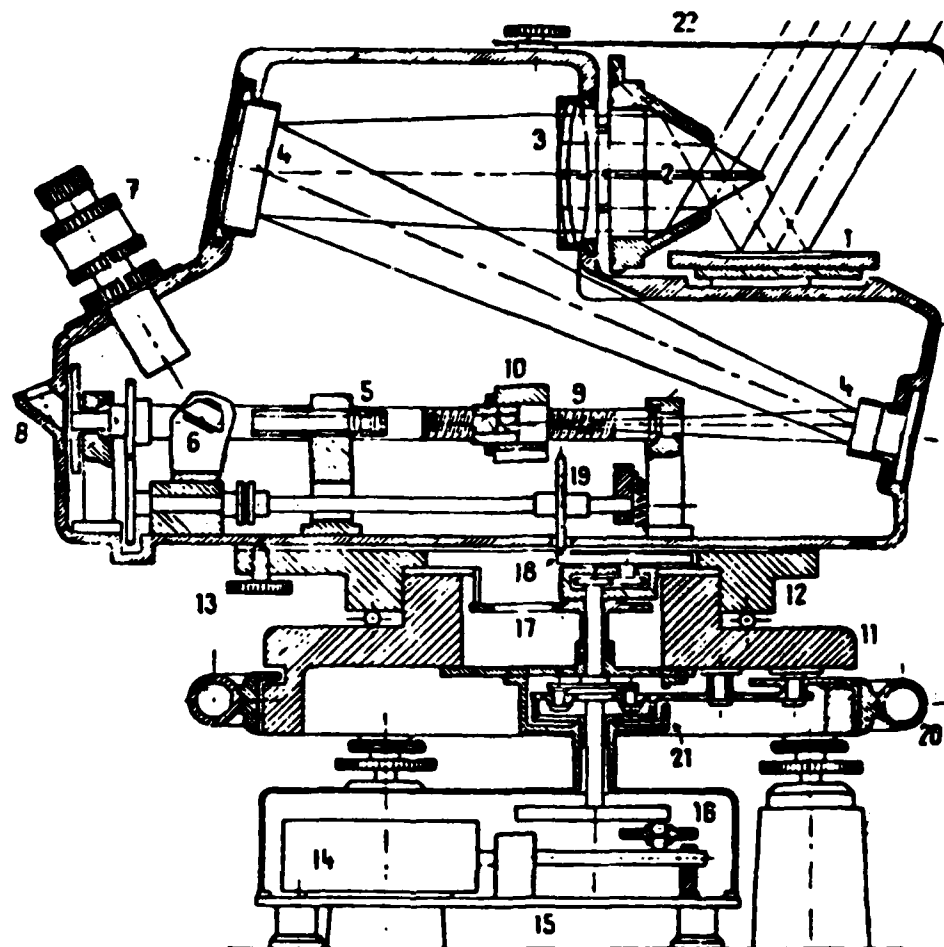


Fig. 6 - Vertical section of OPL astrolabe (schematic). 1, Mercury basin; 2, prism; 3, objective; 4, plane mirrors; 5, carriage; 6, reflecting prism; 7, eyepiece; 8, prism for reading drum; 9, micrometer screw; 10, birefringent prism and supporting carriage; 11, bell-shaped support for turntable; 12, 13, level adjustment; 14, motor; 15, speed reducer; 16, first differential; 17, gear (La Hire); 18, second differential plate; 19, second differential gear wheel; 20, differential corrector wheel; 21, differential corrector; 22, cover.

FIGURE I-3

DAJON ASTROLABE

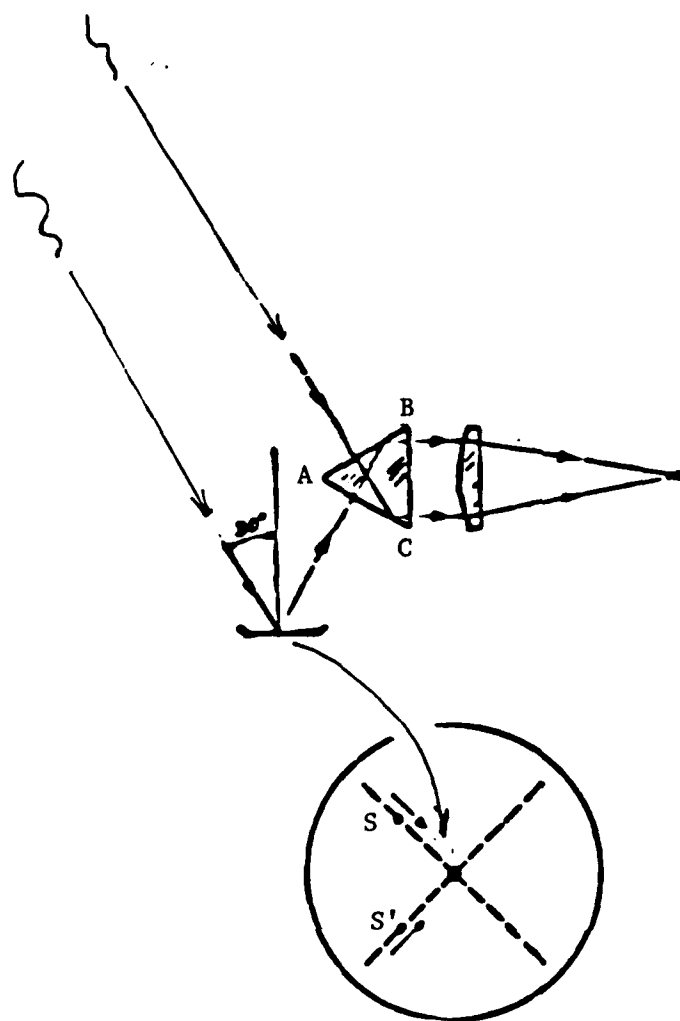


Fig. I-4. PRINCIPLE OF PRISM ASTROLABE. This figure illustrates the principle of operation of a prism astrolabe. In the upper figure, we see the light paths of the light from the star as these paths pass through the Wollaston prism and focusing optics of the astrolabe. The figure is a representation of the apparent motion of the two star images to the direct stellar image (S) and the stellar image reflected in the mercury pool (S') for a star with an azimuth of about 45 degrees.

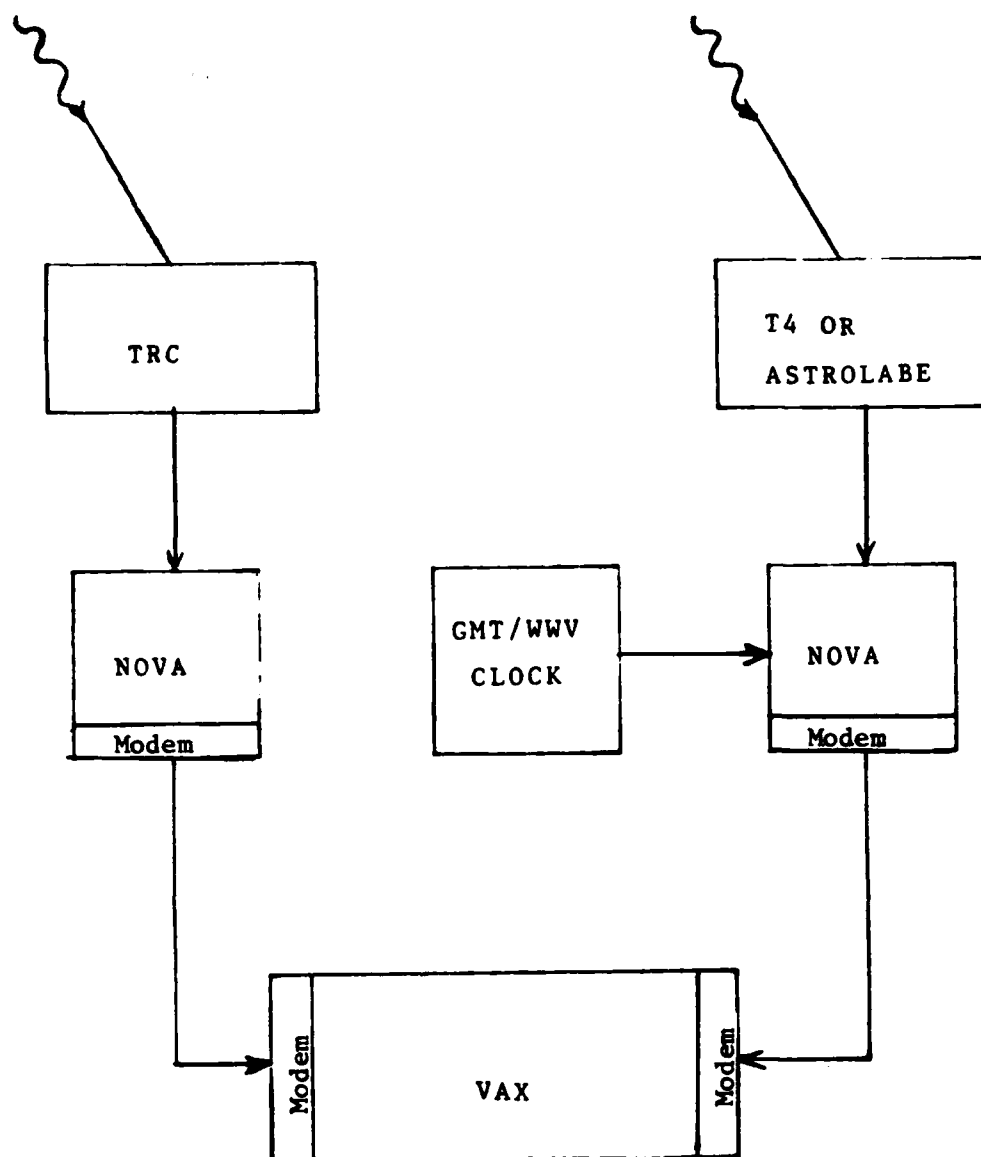


Fig. IV-4. FIELD OPERATING CONFIGURATION OF TCR. This illustrates, in block structure, the method of operation of the stand-alone TCR operation in conjunction with another astrometric method instrument.

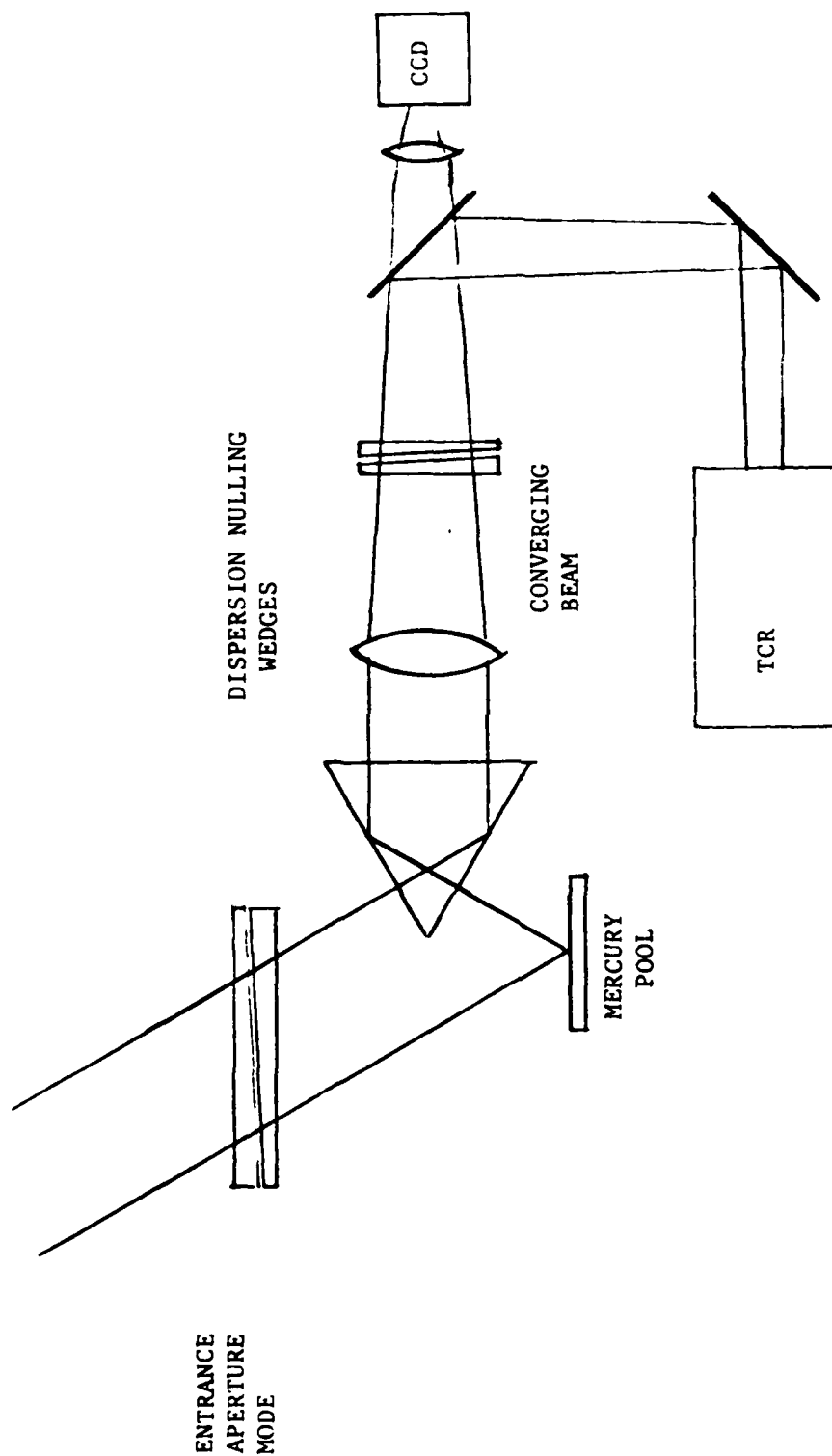


Fig. V-1. BASIC SCHEMATIC STRUCTURE OF SINGLE APERTURE INSTRUMENT. This shows, in block form, the structure of the system using a single aperture for the light for both the two-color refractometer and the CCD for astrometric use.

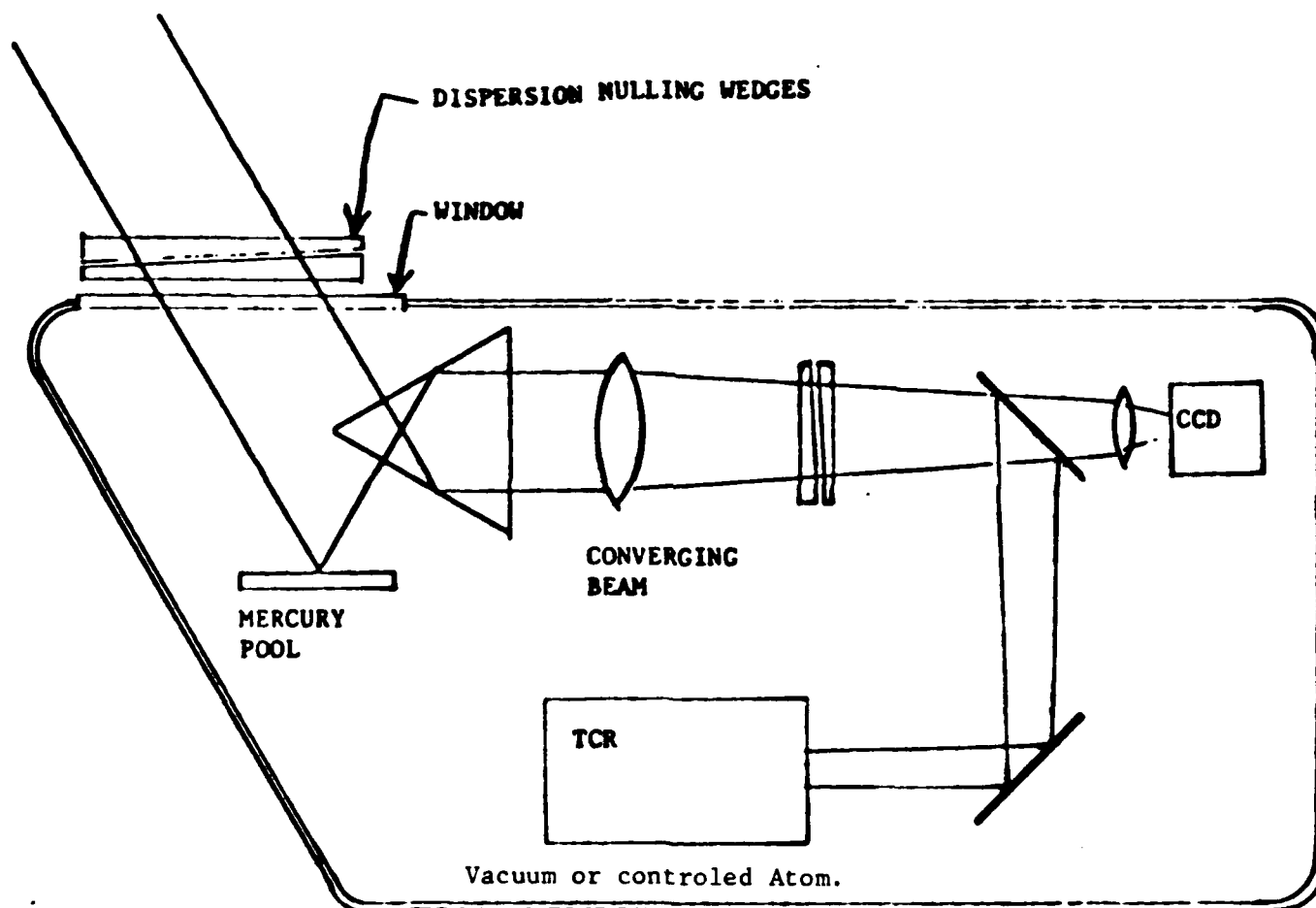


Fig. V-2. DISPERSION NULLING WEDGES. This illustrates the single aperture system enclosed in a box with a window and with the dispersion nulling prism external to the box.

GEOLABE

ELECTRO OPTICAL COMPONENTS

VACUUM CHAMBER-EXTERNAL GLASS WEDGES

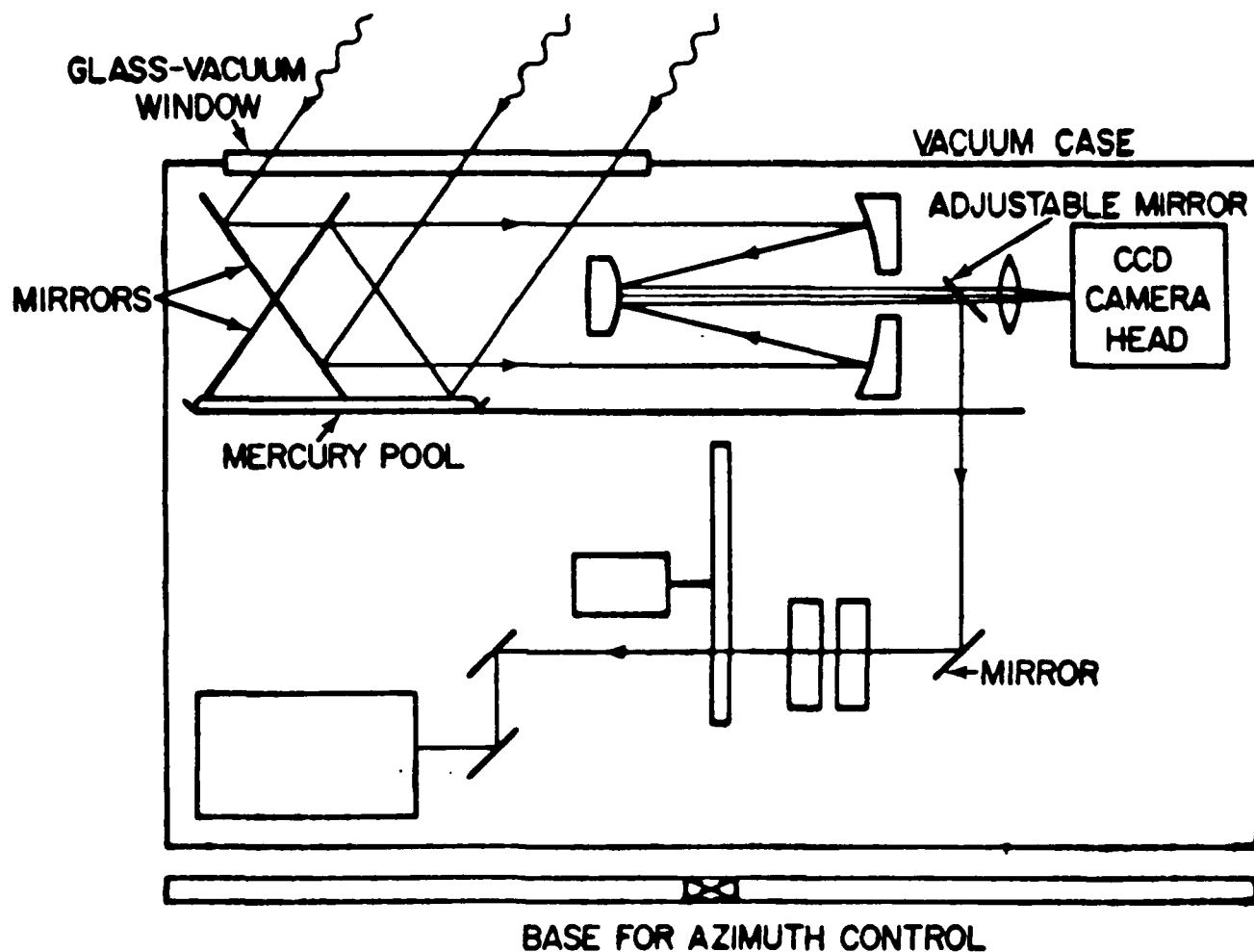


Fig. VI-1. PRIMARY OPTICAL SUBSYSTEMS OF GEOLABE. This illustrates the schematic form of the Geolabe which illustrates the vacuum or gas-tight case, the window and the reflecting PRISM structure.

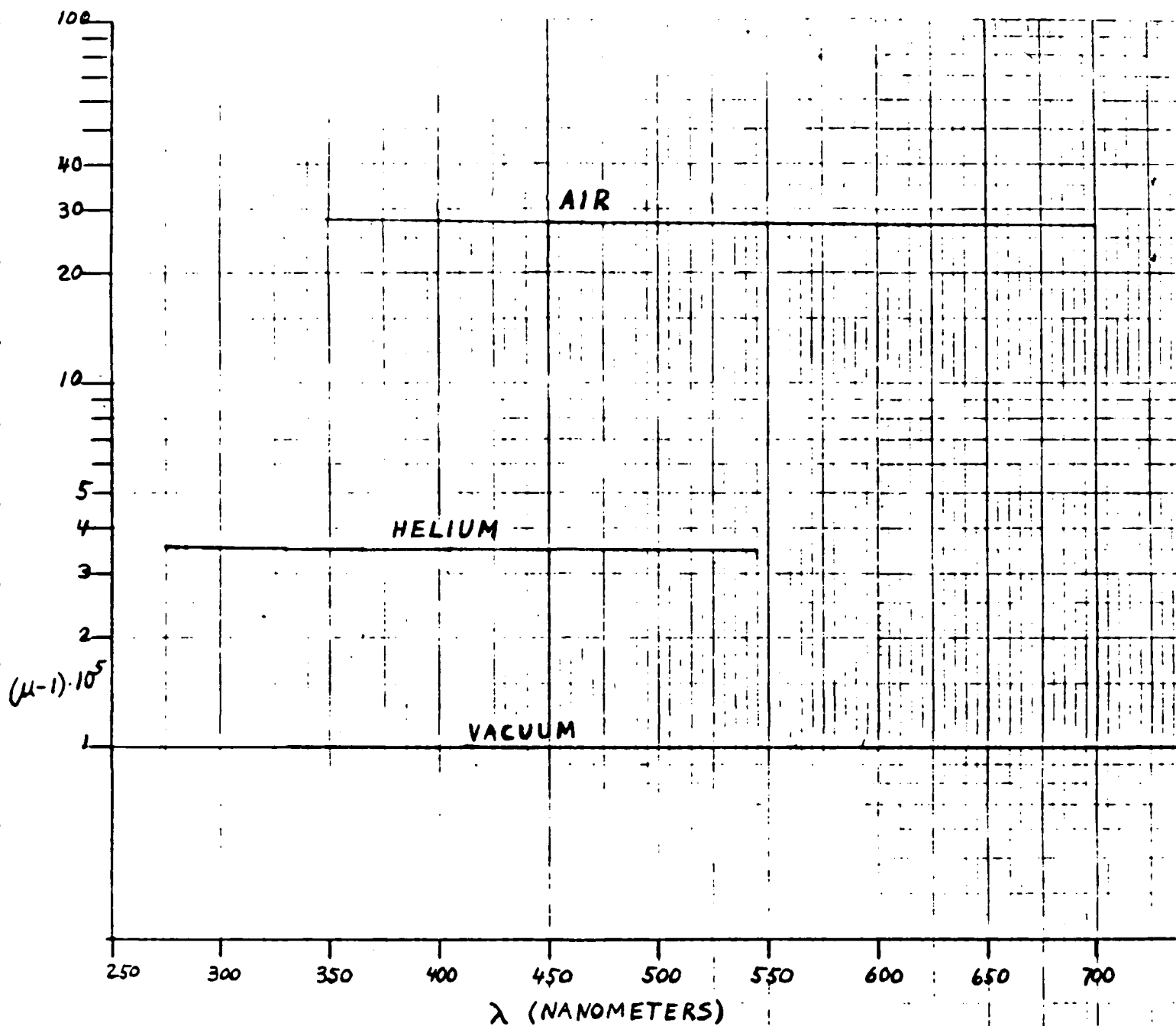


Fig. VI-2. INDEX OF REFRACTION OF HELIUM AND AIR. As illustrated in graphical form, the index of refraction of function of wave length in air, Helium and vacuum. The index is expressed in logarithmic form.

END

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