The Quest for Precision Ground-Based Astronomy: The CCD/Transit Instrument with Innovative Instrumentation (CTI-II)

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ABSTRACT

Precision ground-based photometric and astrometric measurements enable exciting new astrophysical research programs. The CCD/Transit Instrument with Innovative Instrumentation (CTI-II) is the second generation of a 1.8-m stationary, meridian pointing telescope fundamentally capable of millimagnitude photometry and milliarcsecond astrometry. Our goal is demonstrably to attain and maintain this precision in practice.

The optical design for this telescope is complete and a unique real-time metrology system is being tested. An innovative focal plane mosaic including real-time focus feedback is being finalized. We discuss the telescope system design considerations, support instrumentation and calibration techniques that allow this precision, even for measurements made through Earth's turbulent and turbid atmosphere. Ancillary instrumentation includes weather stations, cloud monitors, optical and structural metrology and monitoring instruments, a microbarograph array, an atmospheric extinction lidar and a system of cameras capable of providing real-time extinction measurements.

The stationary, fully automated CTI-II uses the time-delay and integrate (TDI) readout mode operated at the sidereal rate on a mosaic of CCD detectors to nightly generate a five bandpass, 1° wide (declination) image, nominally 120° long (corresponding to observing for an eight-hour night) strip image of the sky to limiting magnitudes fainter than 21 per bandpass. After one year CTI-II will have completed observation of a small circle on the sky at a declination of +28°.

The CTI-II data, approximately 200 Gbytes nightly, will enable a large number of astrophysical research programs including Galactic astronomy based upon motions and parallaxes of stars in the solar neighborhood, discovery and synoptic monitoring of black-hole related variability in the cores of galaxies, and the discovery of targets of opportunity based upon either luminosity variability (e.g. supernovae) or motion (e.g. asteroids and comets).

The same database can be used to construct a calibrated, homogeneous photometric and astrometric standard star catalog for northern hemisphere observers. Multi-night observations are combined to detect, classify and exclude variable stars, enhance the precision of photometry, and refine the positions and motions of more than 10^6 stars distributed in a strip continuous in RA and 1° wide in declination. Multi-year observations allow production of precision astrometry and photometry, and result in a system of faint photometric and astrometric standard stars useful to northern observers of the sky, including past, current and future large-scale surveys such as the Sloan

Digital Sky Survey (SDSS), Pan-STARRS and prototypically the Large Synoptic Survey Telescope (LSST). The always observable strip of standard stars will be useful for optical sky surveillance systems, in general.

The techniques and technologies under development for CTI-II enable new capabilities in faint object detection and characterization for low Earth orbit (LEO) and geosynchronous transfer orbit (GTO) satellites. CTI-II is being designed and implemented as part of the Near Earth Space Surveillance Initiative (NESSI), which will link CTI-II to the Hobby-Eberly Telescope (HET) at McDonald Observatory, a giant special-purpose spectroscopic telescope capable of obtaining a spectrum of any target of opportunity and synoptically monitoring any object discovered by CTI-II to its faint limiting magnitude. NESSI is funded by AFRL.

1. PRECISION GROUND-BASED ASTRONOMY

At the end of the 18th century William Herschel used transit telescope observations referred to as "sweeps" to correctly deduce the flattened geometry of our Milky Way Galaxy. For astronomers in the 19th century the transit telescope was the epitome of precision astronomical measurement. Transit instruments aided in defining celestial coordinates, discovering the motion of stars in our Galaxy and determining terrestrial time and longitude. In the 20th century (1980s) first-generation CCD detectors operated in the time-delay and integrate (TDI) mode were applied for the first time to a stationary transit telescope, the CCD/Transit Instrument (CTI), to accomplish a multicolor survey of a small circle of the sky at +28° declination [1, 2, 3, 4]. The TDI mode of CCD operation has since been applied to other projects, including the Sloan Digital Sky Survey (SDSS) [5], the Palomar-Quest Survey [6], the Flagstaff Astrometric Scanning Transit Telescope (FASTT) [7] and the Carlsberg Meridian Telescope [8].

We resurrect the transit telescope, this generation incorporating modern optics, detectors, metrology, ancillary instruments and structural design concepts to address precise ground-based astronomical measurements. The goal of this telescope and its supporting innovative instrumentation is to break the "1% barrier" to photometric accuracy apparently imposed by techniques using telescopic data alone. A second goal is astrometric measurements with precision significantly better than 0.1 arcsec rms per night. Our approach to these goals is to supplement the photometric and astrometric observations with telescope metrology and monitoring and additional instrumentation to provide calibration data on various effects in Earth's atmosphere.

A partial list of effects needed to be addressed by calibration procedures for ground-based telescopes includes the total throughput of the telescope/detector system, the wavelength- and angle-dependent effective pixel area and, of course, the effects of Earth's atmosphere, including absorption, scattering and emission. Canonical calibration procedures, including flat-field and bias corrections provide insufficient information to address all relevant instrumental and atmospheric effects at the sub-one percent level. Additionally, for a time-domain survey such as ours (and for virtually any telescope, really) attaining calibration is one task, but maintaining provable calibration is another task, requiring continuous calibration data and metadata. For the long-term synoptic survey we propose, essential timescales of calibration maintenance include minute-to-minute stability during an observation, hourly timescales related to the nightly (~ 8 hour) sweeps incorporated into single observations, night-to-night calibration essential to discovery of targets of opportunity, and multi-year calibration stability driven by the seven year proposed survey interval. Additional, very robust innovative instrumentation is required to provide the information necessary for sub-one percent calibration and the maintenance of that calibration over all timescales of interest to achieve the astrophysical goals of our project.

Luckily, effects such as those associated with Earth's atmosphere are separable from those associated with, for example, the telescope throughput. Innovative instrumentation can and will provide data and metadata that allow sustained, traceable sub-one percent calibration of ground-based astronomical observations.

Using the first generation CTI as the basis for the project, a new optical design, forefront detectors and significant ancillary instrumentation are being incorporated into the design in a quest for millimagnitude precision photometry and milliarcsecond astrometry with a ground-based telescope. This generation of the CTI, incorporating innovative instrumentation (CTI-II), will enable a multitude of scientific projects, including creation of an always-accessible precise and accurate calibration field on the sky for northern hemisphere observers. This calibration field will be of use, at least prototypically, to current (SDSS) [5], emerging (Pan-STARRS) [9] and planned (Large Synoptic Survey Telescope: LSST) [10] wide-area synoptic sky surveys.

1.1 The Quest for Precision

Precise and accurate measurements on the sky always lead to significant advances on broad fronts of astronomy. Photometric calibrations, often attempting to lead to radiometric measurements, are a significant factor for ground- and space-based observations. Initial and ongoing calibration of instruments on space-based observatories are the order of the day, and calibrations including the effects of Earth's often uncooperative atmosphere are an ongoing feature of ground-based observatory operations. The scientific rewards for observational precision and accuracy are often immense, as evidenced, for example, by the SDSS [11] and the HIPPARCOS [12] data sets.

The goal of CTI-II is to investigate the approach to and then attain the greatest possible precision and accuracy for ground-based photometric and astrometric observations. Underlying this quest is the ongoing demonstration of the utility and cost-effectiveness of ground-based astronomical observations, made ever more valuable by enhanced precision, especially related to obviating the effects of the atmosphere. The CTI-II science drivers require enhanced precision and provide examples of scientific gains made in other observing projects by applying enhanced precision. A second reason for the CTI-II project is the potential for photometrically and astrometrically calibrating a small circle of the sky in the northern hemisphere, and then *maintaining* that calibration. This aspect of our project allows comparison amongst completed surveys and other observations, as well as providing for northern hemisphere observers an always accessible strip of sky containing calibration standard stars at all observable airmasses.

1.2 Overview of CTI-II

CTI-II is a renovated version of the original CTI. It is a stationary, 1.8-m telescope that will produce a synoptic multicolor imaging photometric and astrometric survey of the night sky. The stationary CTI-II uses the time-delay and integrate (TDI) readout mode for a mosaic of approximately 30 CCD detectors to observe the same 1° wide strip at +28° declination every clear night. The observed field will largely overlap from night to night, and an entire small circle on the sky will be observed multiple times after one year. The choice of declination pointing at +28° ensures the longest possible observational sequence through the North Galactic Cap. This declination points CTI-II within 3° of the zenith from McDonald Observatory, where it will be operated. Fig. 1 shows the CTI-II survey strip in equatorial and in Galactic coordinates.

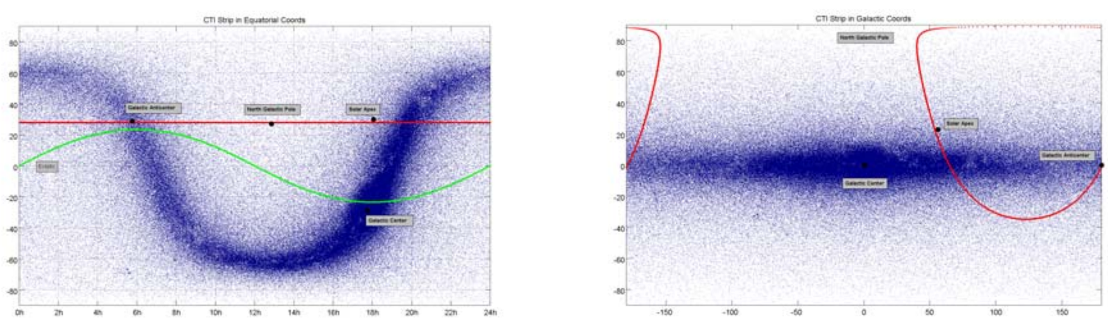


Fig. 1. The CTI-II survey strip in equatorial (α, δ) coordinates (left) and Galactic (l, b) coordinates (right). The abscissae of each plot are right ascension (α) and Galactic longitude (l), respectively, and the ordinates are declination (δ) and Galactic latitude (b), respectively. The plots are populated with stars observed by 2MASS [13] in the magnitude range 12.0 < J < 12.2, thus we see the actual locus of stars as they define the Galaxy. The red trace at δ = +28° in the left plot shows the 1° wide (declination) CTI-II strip, and the green trace shows the ecliptic. This is translated (without the ecliptic marker) to Galactic coordinates in the right plot.

A nominal eight hour night's observing will result in a sweep of the sky 120° long in right ascension, 1° wide in declination, including ~ 105 square degrees on the sky. After one year the survey will include more than 315 square degrees on the sky, and each object will have been observed 50 – 100 times, depending principally upon seasonal weather. In the course of the year, the Galaxy will transit twice, allowing observations in the direction of the North Galactic Pole, the Galactic anticenter, and the solar apex (direction of solar motion). The observed strip includes extragalactic objects in the north (and to some degree the south) galactic cap, and samples a wide range of Galactic latitude and longitude, thus enabling refined investigations of our Milky Way.

The survey will include five optical bandpasses, currently specified as the G, R, I, Z, Y filters designed for LSST [14], with each color occupying one column of the CCD focal plane mosaic, schematically shown in Fig. 2. With a pixel resolution smaller than 0.3 arcseconds, CTI-II will produce more than 200 Gbytes of data every clear night. CTI-II telescope and operational parameters that aid the quest for precision include:

- appropriate sampling of the seeing-blurred point spread function (PSF),
- observations repeated as often as possible at a one sidereal night cadence,
- multiple observations repeated annually,
- use of ancillary instrumentation to monitor the effects of the Earth's atmosphere as well as the health and welfare of the telescope and its computing and control systems,
- use of an input catalog (including prior CTI-II observations) that provides *a priori* information about objects as they are observed, and
- automated operation of a stationary, near-zenith pointing telescope with constant gravity loading on the structure and optics.

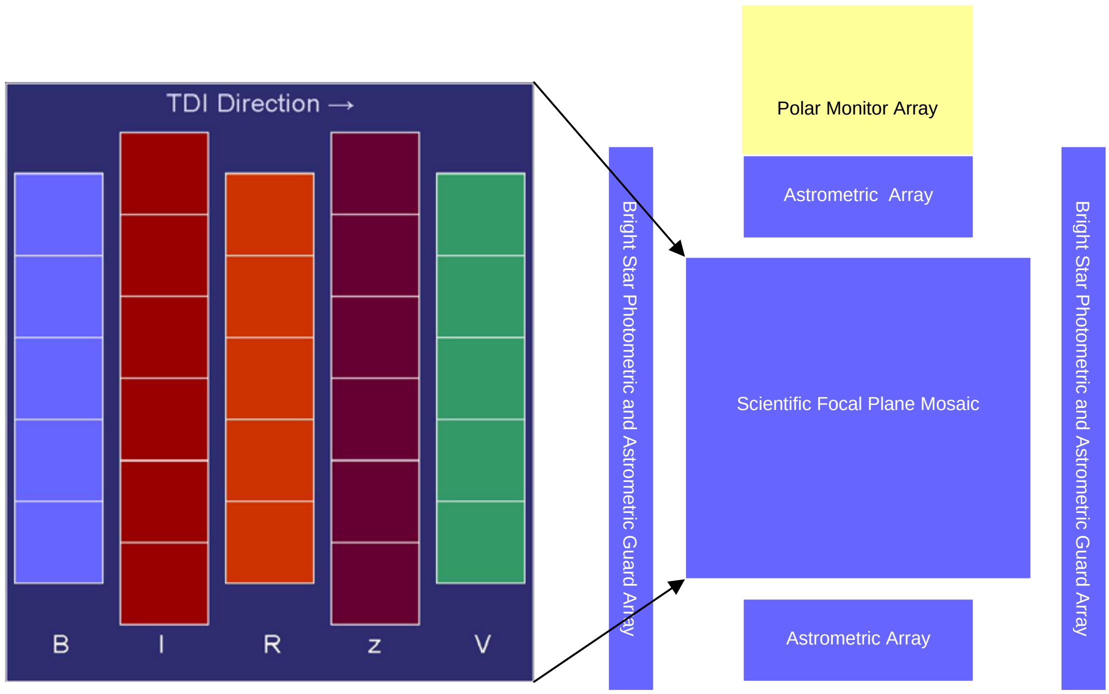


Fig. 2. Schematic CTI-II focal plane mosaic (left) and layout (right). The mosaic includes CCDs, nominally 2048 x 2048 with 15 µm pixels, for which the response is matched to the bandpass filter to obtain high throughput. Generalized broadband filters are shown here, though the project currently anticipates use of the LSST filter set. The multi-bandpass mosaic forms the Scientific Focal Plane Mosaic, shown surrounded by guard arrays (right panel) that provide measurements of (typically brighter) astrometric and photometric standard stars.

1.3 <u>CTI-II Science Drivers</u>

Of the many scientific programs that can be addressed by CTI-II data, three were chosen by the Science and Technical Teams as the "science drivers" upon which to base design criteria and against which to test and make design trade-offs. These three scientific programs are:

1. Discovery of and measurement of motion and distance for late M, L and T stars, which drives robust detection of faint objects in the solar neighborhood, especially those with anomalously red colors, and astrometric precision for accurate position and parallax determination.

2. Precise synoptic photometric monitoring of active galactic nuclei (AGN) which drives time-domain characterization of faint, variable objects superimposed on bright and variable backgrounds.
3. Discovery and near real-time detection of faint supernovae and AGN outbursts, which drives both the optical system and the computing system to implement immediate target-of-opportunity detection and response.

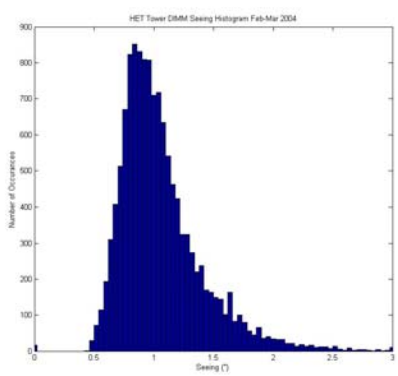
While not specifically a driver, a high priority product of CTI-II will be a well calibrated strip of sky. Calibration will center on the approximately 10^6 stars in the strip brighter than $R \approx 19$. Observation of these stars with daily and annual frequency naturally allows elimination of variable stars while increasing the multi-color signal-to-noise ratio (S/N) of potential photometric and extinction calibrators. Similarly, continued observation for multiple years will allow highly precise measurement of the positions and motions of stars in the observed strip. The value of multi-year continuous observations results from evaluating and eliminating systematic photometric errors by “closing” the calibration of the strip around the entire sky (24 hours in right ascension) multiple times, from monitoring the proper motions of stars, thus keeping astrometric measures current, and by limiting intrinsic variability in photometric standards.

2. THE CCD/TRANSIT INSTRUMENT WITH INNOVATIVE INSTRUMENTATION (CTI-II): THE TELESCOPE

Based upon the CTI-II science drivers, and incorporating constraints imposed by re-using major parts of the first-generation CTI, we initiated a new design effort leading to CTI-II. The legacy constraints from the original CTI include the requirement to re-use the 1.8 meter f/2.2 parabolic primary mirror, which has no central perforation, and the desire (but not the requirement) to re-use the highly successful thermally compensating structure. Development of CTI-II is part of a collaboration with the University of Texas at Austin; hence operation at McDonald Observatory is also a constraint that bears upon the expected seeing distribution.

2.1 Design of the Optical System

Extensive examinations of McDonald Observatory weather and seeing data were carried out to determine the seeing conditions that establish resolution criteria for the CTI-II optical design. While McDonald seeing is not as good as Hawaii or Chile, it is not as bad as anecdotally reported. From differential image motion monitor (DIMM) measurements made at the Hobby-Eberly Telescope (HET), we derive a median seeing (FWHM) of 0.98 arcseconds, and 10% best seeing of 0.7 arcseconds (Fig. 3). We use the value of 0.7 FWHM arcseconds as the fundamental input to generating the optical system error budget, and adopt the minimum criterion of 2.2 pixels per FWHM [15].



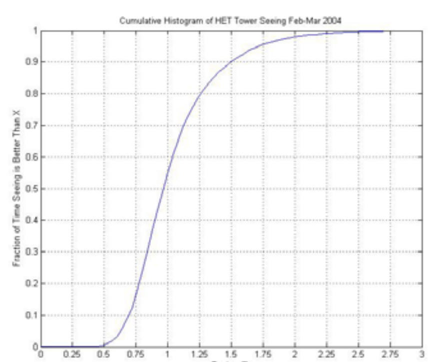


Fig. 3 The seeing histogram (left) and cumulative histogram (right) from the Differential Image Motion Monitor (DIMM) associated with the Hobby-Eberly Telescope (HET) from February and March 2004. The pixel resolution design goal for CTI-II is derived from the 10% best seeing, which occurs at 0.7 arcsec.

While the focal plane mosaic will contain multiple configurations of CCDs, the maximum pixel size for which we plan is 18 μm. Thus the minimum required focal plane field scale is 56.6 μm/arcsec, yielding a pixel resolution of 0.318 arcsec for 18 μm pixels and 0.265 arcsec for 15 μm pixels. The final design yielded 60 μm/arcsec, and pixel resolutions of 0.30 arcsec and 0.25 arcsec for 18 µm and 15 µm pixels, respectively. Thus, the design successfully addresses the measured site seeing and fully samples the seeing for reasonable pixel sizes.

A criterion of the survey is for a wide, fully corrected (instantaneous) “science field” of view (FOV) of 1° x 1° with zero distortion, inscribed in a 1.4° (circular) FOV. The focal plane resolution requires an effective focal length of 12,375.9 mm yielding a final f/6.875. Achieving the final configuration that met these criteria starting with an f/2.2, 1.8 m diameter parabolic primary mirror required an extensive examination of optical design space. Ackermann *et al*. [16] provided literally dozens of Zemax models that the Scientific and Technical Teams considered in terms of overall optical performance. These designs ranged from prime focus configurations to Gregorian systems.

The design that emerged is a “bent Cassegrain” (a Naysmith system were there an elevation axis). The design layout, an encircled energy plot, a vignetting diagram and a spot diagram are shown in Fig. 4.

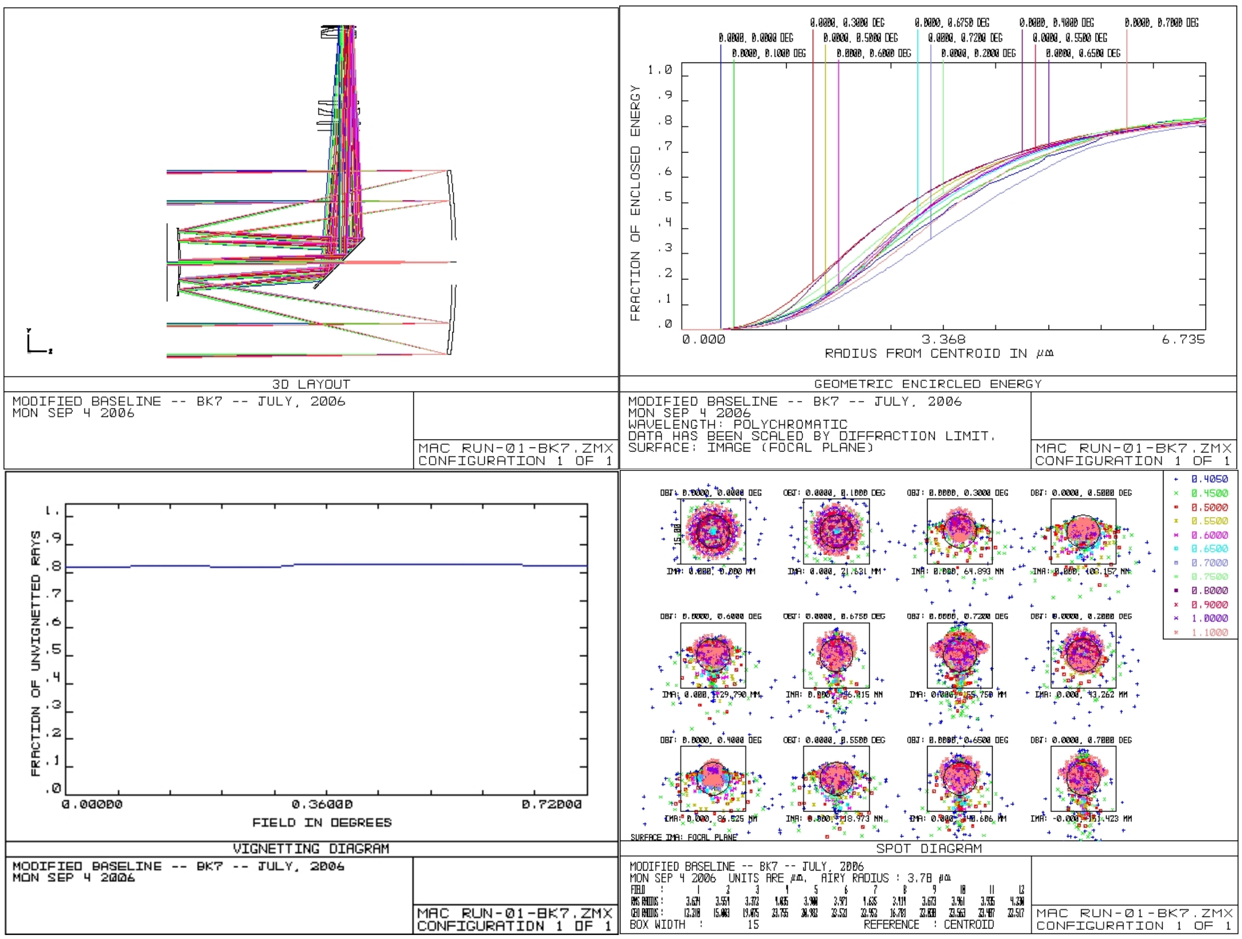


Fig. 4. Zemax outputs for the CTI-II optical design provided by Dr. Malcolm MacFarland based upon the design by Ackermann *et al.* [17]. The bent Cassegrain layout including a five lens field group is shown in the upper left panel. Three of the lens surfaces are plano and the other seven are spherical. The encircled energy for various wavelengths is shown in the upper right panel. The encircled energy reaches 83% at a radius of 6.7 microns for all colors. The lower left panel shows the vignetting function, which is sensibly constant at 83% across the entire 1.4° FOV. The lower right panel shows the polychromatic (equally weighted) spot diagram for this system. The inner circle is the diffraction limit at 550 nm and the outer square is 15 x 15 microns. The performance of this optical design meets or exceeds project requirements. An equivalent design for fused silica exists and cost-performance tradeoffs are underway.

The highly robust bent Cassegrain system requires a 45° folding flat to direct light to the detectors. A field group of five BK-7 (or fused silica, to be determined) lenses completes the design. Three surfaces are plano, and the remaining seven are spherical, resulting in a design which can be relatively easily fabricated and tested. This optical design provides less than 0.001% distortion over the full FOV, 83% encircled energy distributions of 0.25 arcsec or less, and constant obscuration yielding greater than 80% throughput. This design is described in detail and compared to other wide-field design efforts by Ackermann *et al.* [17] (the next paper in these proceedings).

In addition, this design places the entire field group outside the telescope aperture. The detector dewar and electronics are outside the optical support structure where they are easier to access, where it is easier to dissipate heat well away from the optical paths, and to minimize cable lengths and consequent electrical noise.

2.2 Focal Plane Mosaic and Readout System

The focal plane will be populated with a mosaic of CCD detectors. Specific CCDs will be selected to provide optimum efficiency and throughput dependent upon the bandpass filter they employ. Fig. 2 shows a conceptual mosaic layout, for which three different CCD architectures are planned, as detailed in Fig. 5. CCDs used with the g filter are currently planned to be e2V thinned backside illuminated devices, with 2048 x 2048 13.5 micron pixels or, because 15 micron pixels are preferred (see below), Fairchild devices, with 2048 x 2048 15 micron pixels. CCDs for the r filter will be deep depletion devices with 2048 x 2048 15 micron pixels, and the CCDs for the I, z and Y filters will be 2048 x 2048 15 micron pixel fully depleted (Hi Rho) devices. The deep depletion and fully depleted devices may require a foundry run.

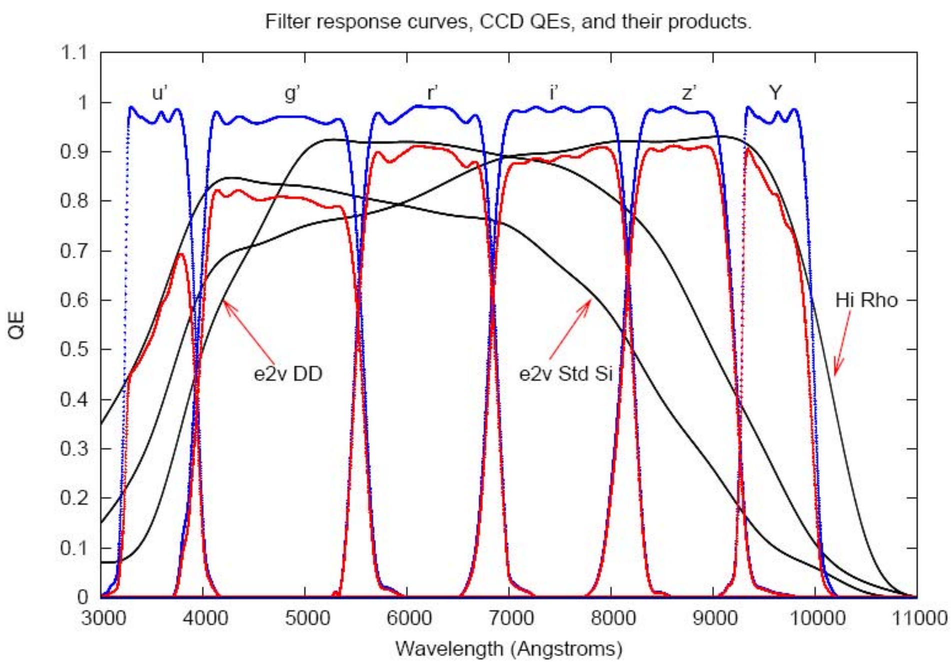


Fig. 5. Approximate filter bandpasses with overlain typical CCD response curves. Greatest efficiency and system throughput is obtained by matching the CCD response to the bandpasses. Scientific emphasis on red response dictates use of fully depleted devices (Hi Rho) for I, z and Y. CTI-II does not currently plan to use a u bandpass.

We are designing a system of guard arrays located east and west of the corrected FOV but outside the science field. These are narrow devices implemented to record the passage of brighter stars, especially photometric and astrometric standard stars. They will also be configured to provide focus information. Guard arrays north and south of the science field will be clocked at a non-sidereal rate to keep track of the precise declination of the telescope as the pixel position of bright astrometric standards are recorded as horizontal “streaks.” The transit of astrometric and photometric standard stars will be predicted by real-time input from the CTI-II Input Catalog.

The TDI pixel clock rate is a function of declination, with the northernmost devices clocked the slowest. For a focal plane field scale of 60 µm per arcsec and a mosaic of 2048 x 2048 CCDs with 15 µm pixels the nominal rate difference between CCDs at $\delta = 27.5°$ and $\delta = 28.5°$ yields a differential pixel shift rate of 0.491 pixel per second. At a nominal ($\delta = 28.0°$) TDI rate of 52.977 pixels per second, again for 15 µm pixels, a 2048 wide CCD yields an integration time of 38.7 seconds. If not corrected on a device-by-device basis, the pixel mismatch from top to bottom (N-S) of the 1° focal plane would be approximately 19 pixels after reading one 2048 pixel frame. Thus, multiple clocks are required to accommodate CCDs at different nominal declinations. The clock constraints also mandate the same pixel size on all CCDs regardless of their wavelength response or architecture.

The focal plane mosaic, its dewar and readout electronics will be assembled by the Imaging Technologies Laboratory at the University of Arizona.

2.3 Optical Support Structure

The bent Cassegrain optical design can be accommodated in the original CTI structure [1, 2, 3, 4], with some improvements and modifications. The original structure is fabricated from aluminum in horizontal sections and stainless steel in sections with vertical extent. A version of the modified structure is shown in Fig. 6. The angles between structural members are derived from the ratio, R, of the thermal expansion coefficients of the two materials ($R \approx 2$), resulting in a thermally compensating structure which is nearly invariant in length parallel to the optical axis. Use of this bimetallic structure minimizes diurnal focus changes. In addition, the structure closely replicates a pin-jointed truss, thus structural stiffness and resonant frequencies are high.

The bent Cassegrain configuration requires supporting the folding flat, lens group and detector package orthogonal to the vertical axis. This is accomplished by including a carbon fiber composite ring in the structure, with ports for the optics and metrology. This ring also provides the fundamental structural basis for an internal thermally compensating metering truss which further stabilizes focus and field scale changes relative to diurnal temperature excursions. A solid model of one version of the structure modified to accommodate the bent Cassegrain optical system is shown in Fig. 6. Resonant frequencies for this structure are all higher than 22 Hz.

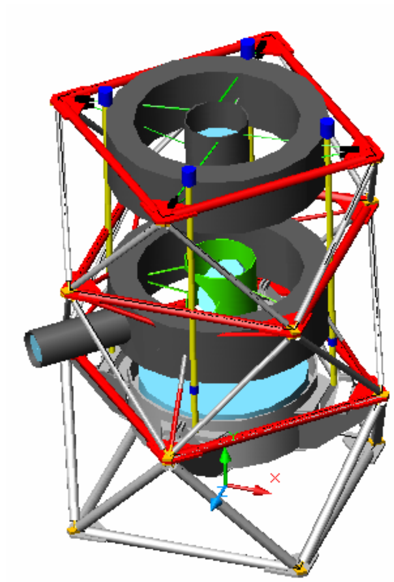


Fig. 6. Engineering solid model of the bimetallic thermally compensating CTI structure, incorporating a bent Cassegrain focus. Embedded in the existing structure is a carbon fiber composite ring (lower black internal ring) which supports the 45° folding flat and fully baffled port containing the five lens field group.

More recently, considerations of stability, stiffness, low cross section to wind loading and most importantly, the capability of intrinsically and passively “tuning” the structure to the diurnal thermal response of the optics has led to a consideration of using a structure composed entirely of carbon composite materials.

Fig. 7 shows the (much simpler) CTI-II structure constructed entirely from carbon fiber epoxy (CFE) materials.

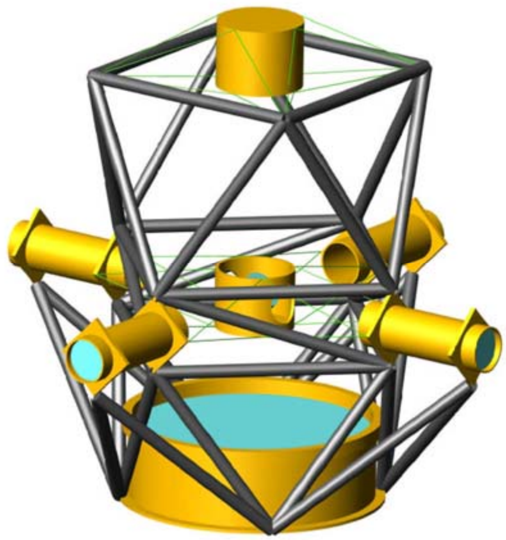


Fig.7. Solid model design for an all carbon composite CTI-II structure. The detector package resides in the port to the lower left and an infrared laser metrology system is contained in the port opposite. The coefficient of thermal expansion of the entire structure is tailored to the ultra-low expansion glass of the mirrors, and the mount for the five lens field group also compensates for thermal effects. The telescope is almost entirely passive with respect to temperature changes.

Options for a fully compensated CTI-II structure have been reported by Gerstle *et al*. [18].

An added benefit of an all-composite structure emerged from laboratory experiments on the thermal conductivity of candidate structural materials, including CFE, aluminum, steel and glass. The experiments measured the temperature at the surface and in the middle interior of sample cubes 5 cm on a side. The cubes were cooled and then allowed to return to room ambient temperature under conditions of normal (unforced) convection and with forced convection created by directing a fan on the sample. (Forced convection is the reason your soup cools faster when you employ the politically incorrect technique of blowing on it.) The cooling timescale data are shown in Fig. 8 for steel and CFE.

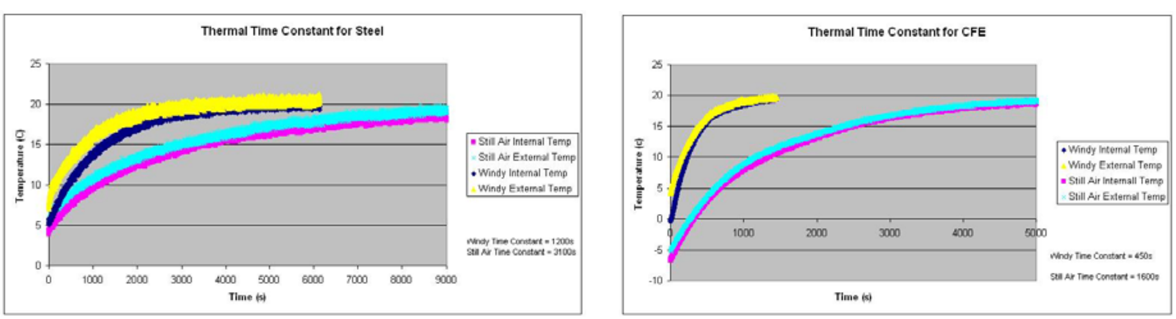


Fig. 8. Cooling timescale data for steel and CFE. The data are for temperatures in the center of the 5 cm cubic sample and for the surface. Surface measurements were made with the thermistor insulated from air. The cooling timescales derived from these plots are given in the lower right-hand corner of each plot, where “windy” refers to forced convection.

The cooling timescale for CFE is approximately two times faster than steel or aluminum, and the forced convection timescale for each material is approximately three times faster than for normal convection.

Woolf [19] has reviewed ideas for achieving high resolution images from the ground and has shown that convection from a telescope's primary mirror and OSS can be primary contributors to degraded seeing. Having the entire telescope at the free air temperature at the beginning of observations, and then having a structure that can respond thermally to diurnal variations ensures good seeing using a totally passive approach. These data lead to the interesting hypothesis that to get a telescope to shed its heat load quickly at the beginning of the night (whatever its structural materials) and to adjust its bulk temperature rapidly towards the free air temperature to minimize local convection, a period of forced convection at or just prior to opening the enclosure for a night's observing is very useful. In at least one case, anecdotal evidence involving operation of ventilation fans in telescope domes shows improved images for fans blowing into the dome (*i.e.* onto the telescope) as opposed to fans venting interior air to the outside. We shall certainly follow up on this intriguing and potentially useful result.

2.4 The CTI-II Enclosure

An enclosure is best considered the exoskeleton of the telescope inside. It is meant to protect the delicate innards at all times, and yet provide complete operational freedom for all of the functionality of the device. Most importantly, the enclosure must not compromise the best attainable astronomical seeing.

The only reason a ground-based telescope requires an enclosure is principally to protect a massive, finely-tuned, delicate, sensitive yet expensive instrument from a hostile environment.

Catastrophic effects such as high winds, lightning strikes and heavy snow and ice loads can destroy a telescope. While these effects only rarely occur, failure to protect adequately a telescope can result in multi-million dollar damages and the loss of a unique astronomical instrument. Thus, enclosures are often specified to survive 150 mile per hour winds. Heavy rain and hail are also potentially catastrophic events. The net effect is that an enclosure must be a sturdy structure capable of surviving a savage beating by the weather and still protecting undamaged the delicate instrument inside.

More mundane effects from which an enclosure is meant to protect its telescope include the full gamut of weather, precipitation in any form: hail, snow, rain, mist and fog, airborne detritus including dust and smoke, and animal life, including but not limited to insects, birds, bats, rodents, wild horses and unauthorized human visitors.

Additionally, enclosures are usually the source of necessary support functions such as air handling, power conditioning and computer control, communications and support.

Usual structures capable of performing these functions, a home or office, for example, tend to be hefty, permanent structures designed solely for protection. This brute force approach to protection is unacceptable for a telescope enclosure for a number of reasons, principally driven by operational requirements of a terrestrial telescope. The astronomer's maxim that "the best enclosure is no enclosure at all" has a basis in fact that usefully and necessarily leads to innovation in enclosure design.

Some of the key constraints on the CTI-II enclosure include a stiff base to support the telescope 10 m above the surface, a wind screen to protect the base from wind loads, an open enclosure that allows cooling of the entire telescope to the free air temperature, low thermal mass protection from the wind (when needed) during observing, a structure to support optical baffling independently of the telescope optical support structure, and reasonable security.

The current design concept that meets these criteria is shown in Fig. 9. Issues driven by the physics of the enclosure, such as thermal mass, reflectivity and emissivity of interior and exterior surfaces are being considered, along with usual issues associated with telescope support and access.

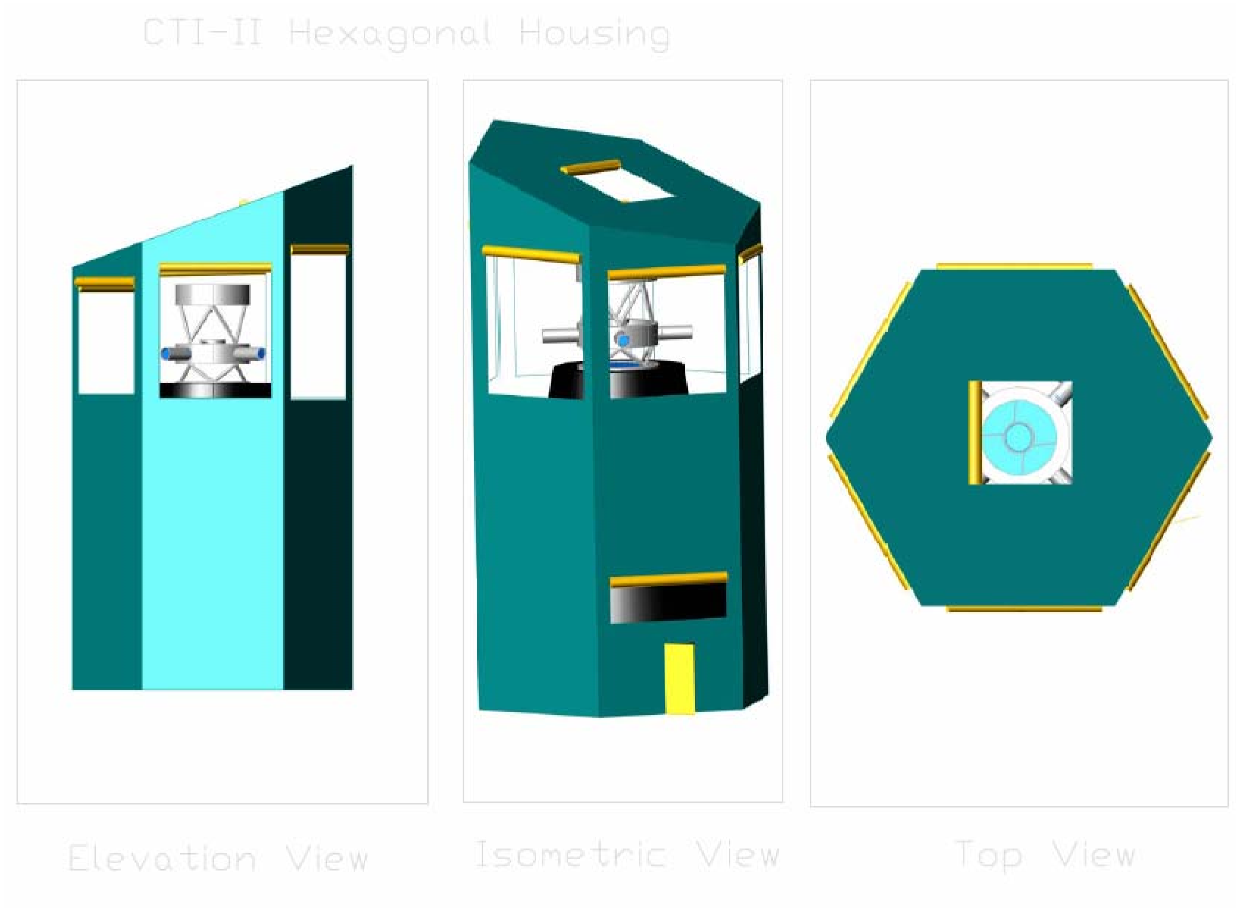


Fig. 9. A hexagonal fully-ventilated enclosure concept for CTI-II. The telescope is supported by an internal pier so that the primary mirror is 10 m above the surface. Roll-up ventilation ports are under computer control and during observations are opened according to wind speed and direction to maintain the entire telescope at a targeted temperature equal to the free air temperature.

A summary of requirements and constraints for the CTI-II enclosure includes (but is not limited to):

- Protect the telescope from inclement weather which may damage or degrade the telescope, such as wind, blowing dust, high humidity, rain, lightning, snow, sunlight, …;
- Provide a (partial) wind screen for the telescope during operation;
- Provide servicing and access routes, e.g. cranes, walkways, ladders, optics access ports, electrical power, optical alignment fixtures…

Constraints on the structure include (but are not limited to):

- Survivability in high wind;
- Operation in moderate winds;
- Low thermal mass for the entire enclosure;
- Active or preferably passive thermal control to ensure the telescope and structure are at free air ambient temperatures at evening opening, and remain in thermal equilibrium throughout the night;
- Minimum power dissipation in and around the enclosure;
- Simple, computer-controllable operation;
- Local weather: annual rainfall, snowfall, wind rose, solar irradiance (uv exposure),…;
- Power outage failsafe mechanisms to ensure the security of the telescope and enclosure;
- COST.

2.5 Control and Data Systems

Every aspect of the control and operation of CTI-II will be automated, and thus require computers. Data acquisition is accomplished by an array of computers, and data reduction, analysis and dissemination requires more computers. We turn to the experience of the astronomical community in its forefront applications of computing to all these problems and, with the help of a separate UNM collaboration with Computer Science and Electrical and Computer Engineering Departments, will design systems to accomplish these tasks, including the best the computing disciplines have to offer. Nonetheless, CTI-II has special, somewhat taxing computing needs.

Table 1. The preliminary CTI-II Input Catalog (CIC). CIC will be real-time accessible to the data acquisition system and will provide all available information about objects in the field of view, as they are encountered. The USNO NOMAD merged catalog includes the starred catalog in the Table. NOMAD is the merged, calibrated catalog of choice for CTI-II.

Survey	Data
CTI-I	Photometry, variability
HIPPARCOS*	Astrometry and photometry
2MASS*	Infrared stars and galaxies
SDSS	Galaxies
USNO UCAC2*	Astrometry
USNO B1.0*	Astrometry
Stetson	Photometric standards
GCVS	Variable stars
VLA FIRST	20-cm radio sources
*USNO NOMAD	Comprehensive merged astrometry

The target of opportunity science driver requires that CTI-II data be processed within minutes of acquisition, with the goal of identifying high value targets for spectroscopic and imaging follow-up within 1.5 hours of detection. This represents a significant computing problem, but not one unfamiliar to the astronomical community.
The CTI-II focal plane will include 25 to 40 CCDs read in TDI mode at approximately 50 Hz. The focal plane thus produces a sustained data rate of about 4×10^6 16-bit pixels per second, and a data volume of about 130×10^9 pixels, or 260 Gbytes, of imaging data every clear night. The data system that must correct for the instrumental signature and identify potential targets must be fast, robust, and relatively sophisticated with respect to "decision making." Including engineering data streams and metadata, the real-time data system and the data pipeline are being designed to handle 400 Gbytes of CTI-II data daily. Data system design is described by Zimmer and McGraw [20].

A key feature of the real-time system is that it will have available the CTI-II Input Catalog (CIC) which will include data on every object observed by previous surveys. Ultimately, astrometry and photometry must be referenced to the sky. The CIC will explicitly include data from astrometric and photometric catalogs, including first-generation CTI data and CTI-II data from previous nights. The initial CIC will include (at least) the catalogs listed in Table 1.

3. THE CCD/TRANSIT INSTRUMENT WITH INNOVATIVE INSTRUMENTATION (CTI-II): INNOVATIVE INSTRUMENTATION

The initial strategy for accomplishing high precision astrometry and photometry with CTI-II includes considering an entire night's observation as a single image. With sufficient control of the CTI-II and with multiple sources of information about the quality of the night, we plan to achieve this goal.

Our approach has been to list significant sources of error that might preclude precision measurements and attack them individually. We list in Table 2 impediments to precision that we must address, knowing full well (so to speak) that others will inevitably arise. Here we address reduction elements that are either fundamental to achieving our high precision goal or require research and new techniques to successfully observe through the Earth's atmosphere. Other photometric and astrometric effects, such as precession, nutation, aberration, overlapping observations and transformations amongst observed and defined coordinate systems [21, 22] will, of course, be included in our data processing system.

We thus sequentially consider the impediments to precision and work to minimize them to the required degree. Because CTI-II is an astrometric and photometric telescope, similar considerations produce different effects on the measurements. We here separate the effects, but point out that these effects are not entirely independent. Ultimately we conclude that astrometry requires the greater rigor in striving for precision, and that the assured ability to produce precise astrometric measurements virtually guarantees the ability to produce precise photometric measurements.

Table 2. Impediments to precision. It is useful to list the impediments which must be overcome in the quest for precision. In particular, the same parameter can have a different effect and importance depending upon whether astrometry or photometry is the current key measurement.

Astrometry	Photometry
Sampled PSF – centroid precision	Sampled PSF – S/N
Atmosphere – anomalous refraction	Atmosphere – extinction
Optics – distortion, stability	Optics – throughput
Telescope – pointing, flexure, focus	Telescope – instrumental signature
Specific – Coordinate control, timing	Specific – multiple bandpasses
Specific – Earth rotation corrections	Specific – cosmic ray rejection

3.1 Features of the Sidereal TDI Readout Mode

The use of the time-delay and integrate readout mode for CCDs embedded in a stationary telescope is a significant innovation leading to precision astronomical measurements. There are unique advantages in terms of photometric and astrometric homogeneity, precision, accuracy and observing efficiency that derive from treating an entire night's observation as a single image. These features are facilitated by never closing the shutter, so the focal plane is 100% "active," thus maintaining a continuous record of sky brightness and transparency, as well as continuous observations of astronomical objects. It is further facilitated by the fact that the TDI readout effectively averages over the area-format instrumental and optical signatures such as flat-field and bias structures, making corrections more stable than for area-format corrections. Further, PSF corrections are largely only a function of CCD column because they have been averaged in the readout process. These TDI "averaging" processes result in more stable and robust imaging. Finally, operating in the meridian near zenith also minimizes the airmass and differential refraction, positively affecting astrometric precision.

The principal drawback to TDI imaging is that the readout adds to the PSF because of the curved tracks of stars on the CCD detectors resulting from their projection from the celestial sphere onto planar, rectangular arrays [7, 23, 24]. These effects can be minimized, however, by appropriate tradeoffs between integration time and the physical length of CCDs. We have modeled these geometrical effects and appropriately traded this component of the image PSF with the required pixel resolution and integration time on each CCD.

3.2 Site Testing and Monitoring

To support the photometric goals, site testing at McDonald Observatory is currently underway. Given the image quality at McDonald, our goal is to select the best site with the consistently smallest geographic and orographic surface layer seeing effects. Two extremely stiff 7-m high towers for DIMM measurements have been designed and installed, along with microthermal towers and weather stations. One site testing station is on a southwest trending ridgeline of Mt. Locke, the other is on the southwest face of Mt. Fowlkes, near the location of the HET. Both sites are chosen to position CTI-II into the prevailing winds [25].

After site selection, the tower at the selected site will become a monitor providing independent DIMM seeing measurements and microthermal surface layer turbulence data. These data will, as will all CTI-II Observatory time-dependent data, be embedded in a time-synchronized engineering and metadata stream (EMS) that supports operation of the CTI-II Observatory and later supports reduction and analysis of its science data.

3.3 Optical Support Structure and Optical Metrology

The bent Cassegrain optical layout allows a unique metrology system. An infrared laser located in the optical support structure (OSS) port opposite the detector can illuminate two primary Michelson interferometric configurations (refer to Fig. 7). The first measures displacement between the detectors and the vertex of the primary mirror, the second measures displacement between the detectors and the vertex of the secondary mirror. A system of spatially encoded reflectors capable of providing both displacement and tilt information is under development. The goal will be to monitor the performance of the structure, especially if the carbon composite structure is implemented. The interferometers also obviously provide feedback for active tilt and piston adjustments presumably induced by thermal effects.

The OSS will also be heavily instrumented with an array of calibrated thermistors to monitor both the external and internal temperatures of critical structural members. The goal of these sensors is to record lateral and vertical thermal variations that might affect focus and flexures resulting in displacement of the optical axis on the sky. A second use for the array is to allow active cooling of the structure and optics in an effort to obviate the onset of convection induced by the telescope itself.

The OSS will also host an array of accelerometers used principally to detect unacceptably large wind-induced accelerations, and possibly to provide engineering data from which the displacement of the optical axis on the sky can be deduced.

3.4 Calibration Procedures

A fundamental decision made by the project involves calibration of the CTI-II photometric system. CTI-II plans to implement the end-to-end calibration suggested by Stubbs and Tonry [26] using a tunable laser to create the instrumental response function (flatfield), and simultaneously calibrating the photometric system response to sub-one percent precision relative to a NIST-traceable photodiode.

The atmosphere is monitored by using a separate small telescope to obtain spectra of stars in or near the CTI-II FOV, and wavelength dependent scattering, absorption and emission will be measured directly as a function of time [26]. The spectra can be calibrated to 527 nm by applying Earth atmosphere extinction coefficients measured with an extinction lidar (see **3.5**, below). Using the calibrated spectral data as input to detailed atmospheric models will provide direct extinction measurements across the filter set bandpasses, as well as measurement of fringing sources. Minor variants of this technique planned for CTI-II include the use of multiple diode sensors for measuring the flatfield flux to provide illumination uniformity data, as well as to detect aging or degrading calibration of the NIST standard diode. We plan a flatfield screen that is essentially part of the entrance aperture baffling system, thus ensuring that spatial frequencies included in the flatfield are precisely those seen by the detectors during normal operation.

3.5 ALE: Astronomical Lidar for Extinction

The most significant adjunct to atmospheric monitoring for CTI-II is the inclusion of an eye-safe extinction lidar [27] normally operated near the zenith in the direction of the CTI-II FOV. Dawsey *et al.* [27] provide a full description of the lidar transmitter and receivers. The lidar, which operates at 527 nm, will detect sources of extinction, such as aerosols and particulates, but will also provide a Rayleigh return proportional to the atmospheric density profile during "photometric" conditions against which the monochromatic total extinction can be calibrated to better than 1%. The combination of lidar and spectroscopic data will provide the best measure of atmospheric extinction thus far used for ground-based photometry.

In addition, the lidar air density data will provide real-time index of refraction profiles potentially crucial to ground-based astrometry.

3.6 A Precision System Clock

Robust models of the CTI-II telescope and focal plane mosaic predict that a $S/N \geq 100$ will be achieved for $R \leq 18.5$. Achieving the required astrometric precision in right ascension of 0.003 arcsec rms per night for these bright stars is accomplished by requiring this uncertainty be distributed over one night's observation of 120°, which in turn requires a CCD mosaic parallel shift clock precision of 7×10^{-9}.

This precision timing is provided by an off-the-shelf GPS-slaved rubidium clock, which can typically provide a 10 MHz oscillator with 10^{-12} frequency accuracy and with 30 ns rms accuracy referenced to UTC. Thus, the first fundamental issue with respect to CTI-II generating an image suitable for milliarcsecond astrometry in right ascension is very well addressed by readily available timing and CCD readout technology.

The GPS-slaved clock provides sufficient timing precision and absolute accuracy referenced to UTC to accomplish the CTI-II astrometric goals. The system clock frequency and stability must be designed to maintain this precision throughout the computational sequences of parallel and serial clocking that physically generates the rows of pixel data.

The requirement of 3 mas rms astrometry during a nominal eight hour night (120° on the sky), accomplished with 0.3 arcsec pixels has several clocking implications. The first is that the 120° image contains 1.440×10^6 rows of pixels. To accommodate a 10 hour long winter night, we adopt 1.800×10^6 pixel rows in right ascension as the design image length. The second is that the oscillator output of the clock must have a sufficiently high frequency to ensure that counting oscillator pulses generates CCD parallel clocks with: a) an accurate parallel shift frequency for each row of CCDs (~50 Hz), and b) the slightly different frequencies required to clock parallel rows of CCDs at different declinations across the 1° FOV. The set of CCD parallel clocks must not generate phase errors larger than 0.01 pixel. This can be accomplished by using the instrument control computer to monitor clock phase errors and actively modify the count required to generate the parallel clocks.

The CCD controller must respond at the clock frequency and maintain constant latency to this precision thereafter. The technique used to accomplish this is to execute a one instruction "program" in the CCD controller and allow the master clock-driven CCD parallel clock counters to provide an interrupt that executes within one CCD controller clock period. A linear interrupt routine ensures constant latency thereafter.

At the fundamental instrumentation level, right ascension control can be maintained to achieve the astrometric goal of 0.003 arcsec rms nightly positional accuracy.

This clock will provide all CTI-II Observatory time references, including time-tagging the engineering and metadata stream (EMS). Allowable observing time will be generated based upon this clock, and all scientific data will be time-tagged by reference to this same clock.

3.7 Declination Control

Precision clocking during an entire night's observation, and from night-to-night over an interval of years, assures precision astrometry in right ascension. Because the CTI-II field on the sky is a small circle only 1° wide, we need another technique to control declination, or equivalently, the position of the pole of the equatorial coordinate system. Three concepts are being evaluated. The first is to allow variable rate clocking of CCDs placed in the CTI-II 1.4° FOV both north and south of the inscribed 1° x 1° science field. As bright astrometric standard stars transit these "guard" devices, they are clocked at a rate faster than sidereal to produce a streak image. The N-S position of the streak fixes the declination of the telescope to a precision determined by the uncertainty in the declination of the astrometric standard convolved with the pixel resolution.

The second technique is similar. Using the precision oscillator to clock guard CCDs at a known nonsidereal rate the length of the resulting star streaks can be accurately interpreted as declination.

The third technique is to use a siderostat to direct an image of Polaris and surrounding stars into the CTI-II optical system. A polar monitor CCD placed to the apparent north of the science field in the focal plane mosaic is read at a rate of approximately 100 Hz, with each readout yielding a centroided position for Polaris with S/N ≥ 100. A schematic focal plane layout that can accomplish one (or more) of these declination control techniques is shown in the right-hand panel of Fig. 2.

3.8 A Microbarograph Array

We are investigating implementation of a microbarograph array (MBA) surrounding CTI-II to monitor anomalous refraction. When combined with vertical atmospheric density profiles measured by ALE, an MBA provides real-time horizontal structure information about the wave structures, pressure gradients and velocities induced in the atmosphere.

In a very real sense we have thus far addressed impediments to astrometric precision that are "easy" to deal with compared to the effects of the atmosphere. The principal astrometric effects expected to affect CTI-II astrometry are three manifestations of refraction: normal, differential (chromatic) and anomalous. Of these, normal and differential refraction are well known phenomena [21]. While its cause is still not confirmed, anomalous refraction is most probably the effect of large cells in the atmosphere which can refractively perturb image positions by ~ ±100 mas on time scales of a few minutes [7, 28]. Because CTI-II is a meridian-pointing telescope that always observes within three degrees of the zenith, we here consider the classical refraction effects to be solvable. Anomalous refraction, however, remains a little-known phenomenon, but of potentially great significance to astrometric measurements.

Canonical wisdom is that anomalous refraction will ultimately limit the astrometric precision of CTI-II [28, 7, 32]. It is becoming more certain that anomalous refraction is caused by the superposition of atmospheric gravity waves. A well-known visible example of an atmospheric gravity wave is periodically-spaced lenticular clouds formed in the lee of a mountain. Clear air gravity waves also exist, and their large scale perturbations can induce large scale angular tilts resulting in simultaneous displacement of stars by ~ 0.1 arcsec over the entire field of view of a telescope.

Our goal is to consider the airmass above CTI-II as an optical element, variable in real-time, which can be modeled to provide precise astrometry. We are developing differential microbarograph arrays with baselines of meters that can measure surface pressure differences with amplitudes of microbars created by the passage of a gravity wave. Multiple microbarographs with different baselines and precise geometrical layouts surrounding CTI-II will allow reconstruction and modeling of the waves. The ALE atmospheric density profiles provide additional measurement of the wave structures.

Our hypothesis in following this tack is that should we not be fully successful at mitigating "anomalous refraction," we will at least learn more about the physical structure of Earth's atmosphere with respect to its time-dependence which will be of value for other astronomical surveys. As the Parthian shot to the anomalous refraction issue, CTI-II will make numerous measurements of astrometric standard stars during an observing season over which anomalous refraction should average out.

4. PHOTOMETRY AND ASTROMETRY WITH CTI-II

Having implemented CTI-II, we shall make time-domain photometric and astrometric measurements of the survey strip. We have described some (but by no means all) of the innovative instrumentation we shall bring to bear on photometry and astrometry, the fundamental measurements to be made by CTI-II. Here we describe the observing procedures that will result in precision astrophysical measurements of the sky.

4.1 Photometry

An important benefit of continuous, overlapping observations is enhanced capability for photometric calibration. After one year of observing, multiple 120° (nightly) strips will overlap, allowing for multi-night comparisons and calibrations. This ensures a complete small circle of the sky, 1° wide in declination, which contains thousands of standard stars with known stability in brightness on timescales longer than a year, with minimal right ascension-dependent systematic errors, to faint limiting magnitudes.

With the promise of precision photometric measurements from a unique telescope, the CTI-II Science Team investigated the external effects that determine if these measurements can actually be accomplished, and if so, how the observations should be made. The answer is to design a telescope that makes precise astrometric measurements! There is an adage that if a telescope can produce precise astrometric measurements it can *de facto* produce precise photometric measurements. This adage principally arises from the demands of astrometry for well-defined images with a well-sampled point spread function (PSF). In the case of a terrestrial telescope, this is the seeing-blurred PSF, thus the site seeing for CTI-II is a major issue. We hold this adage to be true, and are designing CTI-II to accomplish the most precise astrometry of which it is reasonably capable, with the knowledge that the design criteria that assure precision astrometry will also support precision photometry.

4.2 Astrometry

The first problem to solve to ensure that the area-format data can be considered as a single astrometric image is the pixel registration over the nominal 1° x 120° image. For CTI-II, the issue is essentially, how well can we create a virtual grid of pixels on the celestial sphere, and to what precision can we consistently populate this grid? In right ascension, this is a question of how precisely can we establish a time base from which we can derive CCD parallel shift timing. In declination, we require another sky-based or optical mechanism to continuously determine the pole of CTI-II observations.

TDI readout implies that the image is “built” one row at a time. “Stitching” these rows into a well-defined single image is accomplished by maintaining precise control of the CCD clocks and any computational latency in the readout system.

We can consider CTI-II astrometric capability from the standpoint of successful predecessor projects, such as the HIPPARCOS space astrometric mission. The HIPPARCOS catalog includes measurements with precision of 0.001 arcsecond for astrometry and 0.002 magnitude for photometry for approximately 118,000 stars to a magnitude limit of 12.5. The more general Tycho catalog produced 0.025 arcsecond astrometry and 0.06 magnitude photometry for approximately one million stars to a magnitude limit of 11.5. These catalogs suggest measurement techniques, measurement goals and an assessment benchmark for CTI-II astrometry and photometry.

A key design feature of the highly successful HIPPARCOS satellite was that it accomplished large angle astrometry (LAA) for parallax determination [29]. The HIPPARCOS primary aperture consisted of a split siderostat set at an angle of 29° feeding a single primary mirror. Thus HIPPARCOS simultaneously images two fields accurately separated by 58°. One field contains the parallax star, and the other contains the reference stars.

The basic principle is that classical “single field” astrometry requires a correction factor because the reference stars do not form an “infinitely distant” reference frame, but require a statistical correction based upon photometric inferences for the finite distances to the reference stars. The fundamental idea is simultaneously to observe a parallax star and its comparison field separated by a large angle on the sky, for which the parallax factor is far better. This technique was implemented by HIPPARCOS and will be used by GAIA and other space astrometry missions.

A variation on this scheme is to have the parallax star and its large angle comparison field appear in the same image. This is the technique attempted by CTI-II. Because an image is typically 120° in length, it contains reference stars over a range of angles (up to 120° in right ascension) relative to any star in the field. Thus, we return to the idea that large angle astrometry can be accomplished with CTI-II, with the added benefit that there exist comparison stars distributed over a large range of angles as opposed to but one wide angle, provided that the image registration can be made sufficiently precise. In addition, after one year of observing, every star will have appeared as an object overhead at sunset, then at sunrise, and again at sunset. This pattern, favorable for parallax determination, recurs annually.

HET DIMM measurements of the seeing at McDonald Observatory show the seeing to be 0.7 arcsec or better for 10% of all available observing time. Using the Bally *et al.* [15] empirically derived appropriate sampling for the seeing-blurred PSF of 2.2 pixels per FWHM implies the CTI-II pixel resolution should be at least 0.31 arcsec/pixel. Benedict *et al.* [30] have shown that centroid determination to ~ 3% of a pixel is possible for images with sufficient S/N, even for undersampled PSFs. More recent estimates [31] use the full-width at half maximum divided by twice the signal-to-noise of a star image to estimate the astrometric centroiding errors, which in the case of CTI-II, predicts astrometric errors of less than 0.005" for seeing conditions better than 1.0 arcsec for objects brighter than R = 18.5 (S/N > 100) per observation. Thus, CTI-II astrometric data will be accumulated into a time-defined fundamental grid with precision of better than 0.001 arcsec. Image centroids can be estimated to 0.010 arcsec nightly. Averaging over 100 nights, or approximately one observing year, should result in parallaxes approaching 0.001 arcsec precision.

Because refractive effects (including anomalous refraction) are limiting factors, Earth's atmosphere must be measured and modeled as an optical element. ALE measurements will provide the required vertical density profiles, and will simultaneously provide precise measurement of total atmospheric extinction.

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