USNO AUTOMATED PLANET FINDER FACILITY

Contracts:
N62306-03-M-B014 , Automated Planet Finder Facility Telescope
N62306-03-C-B001, Solar Planet Finding Facility Telescope Enclosure

Principal Investigator: Steven S. Vogt, PhD
UCO/Lick Observatory
University of California
Santa Cruz, CA 95064

Final Technical Report

For the Period: May 30, 2003 through July 31, 2009

GENERAL DESCRIPTION

In 2003 The United States Naval Observatory (USNO) contracted with UCO/Lick Observatory (UCO) to build a dedicated facility to find extrasolar planets around nearby stars. The Telescope and Enclosure were administered as two separate contracts however they must work together as a single integrated instrument. This report is intended as the final technical report for both contracts (N62306-03-M-B014 Telescope and N62306-03-B001 Enclosure).

This facility will provide valuable reconnaissance groundwork for programs such as the NASA Space Interferometry Mission and the Terrestrial Planet Finder. Limited access to current, shared facilities has been a major hindrance in the search for extrasolar planets. Increasing the precision of the radial velocity measurements to a level at which we can search for sub-Saturn sized planets is a difficult task which demands instrument stability and observation frequency. A dedicated facility with a purposefully built instrument is necessary to maximizing the number of new low mass planet discoveries.

APF is a 2.4 meter altitude-azimuth automated telescope and enclosure located near the 20 inch Astrograph Site atop Mt. Hamilton, California. It will have its own dedicated spectrometer optimized for planet finding situated at the Nasmyth focus. The telescope, enclosure and its associated instrumentation will be called the Automated Planet Finder or “APF” facility. USNO has provided the funding for the telescope and enclosure. Instrumentation has been primarily funded by NASA and built by UCO.

When fully operational, this facility will function totally autonomously. The robotic software being developed for the facility will have sufficient intelligence to decide when and if observations can begin; to acquire targets and guide stars; to take data; to solve and resolve foreseeable problems; to move to the next target; to finish the observing program and close down at the end of the evening. It is expected that the spectrometer will provide radial velocity precision better than 2 meters per second.

Ref.	Feature	Requirement
	Telescope	
2.1	Mount type	altitude-azimuth with two Nasmyth foci
2.1	Primary mirror diameter	2.4 -m nominal
2.1	Un-vignetted field of View	2 arcminutes diameter
2.1	Final focal ratio of telescope	f/15
2.2	Optical performance	80% encircled energy within 0.50 arcsecond diameter; 90% encircled energy within a 1.0 arcsecond diameter (over 0-70 degree zenith angle)
2.1	Central Obscuration	total projected area <4 % of the primary mirror area
3.2	Instrument Capacity	850 kg at each of the Nasmyth foci
	Guider	
2.3	CCD/TV FOV	2 arcminutes diameter (as needed for acquisition and guiding)
2.3	CCD/TV limiting stellar magnitude	at least V=15.0
	Tracking and Pointing	
2.9	Absolute pointing accuracy	<10 arcseconds (over 0-70 degree zenith angle)
2.10	Open-loop tracking (for 10 minutes)	0.5 arcseconds (over 0-70 degree zenith angle)
2.10	Open-loop tracking (for 60 minutes)	2.5 arcseconds (over 0-70 degree zenith angle)
2.10	Closed-loop tracking	0.20 arcseconds (over 0-70 degree zenith angle)
	Primary Mirror Details	
	Focal ratio of primary mirror	F/1.5
2.6	Coating	aluminum
	Primary Cover	remotely deployable with full coverage
	Substrate material	Astrosital
	Secondary Mirror Details	
2.6	Coating	protected silver (reflectance > 96% from 0.48 to 1.2 microns)
4.6	Focus travel	5.0 mm
4.6	Focus resolution	5 microns
4.6	Alignment adjustments	manually adjustable tip/tilt and piston for initial alignment
	Substrate material	Zerodur
	Tertiary Mirror Details	
2.6	Coating	protected silver (reflectance > 96% from 0.48 to 1.2 microns)
2.5	Deployment between foci	software control to rotate between both Nasmyth foci
2.5	Reconfiguration time	45 seconds
	Substrate material	Zerodur

TELESCOPE TECHNICAL SUMMARY
Contract No. N62306-03-M-B014

DETAILED TELESCOPE SYSTEM REQUIREMENTS

Optical Layout

The APF telescope is a 2.4-meter diameter primary, plus secondary and tertiary mirrors. The optical configuration is Ritchey-Chretien. The telescope produces a focusing beam with an overall convergence of f/15. The projected area of all obscurations is no more than 4% of the primary mirror area. The f/# of the primary mirror and position of the secondary is sized such that the obscurations are small and the total length of the telescope is minimized to reduce the size the required dome.

Image Quality

Image quality after reflection off the tertiary has an 80% encircled energy diameter of less than 0.50 arcsecond, over a 2 arcminute diameter field of view for elevation angles from 20 through 90 degrees. Additionally, the 90% encircled energy diameter is less than 1.0 arcseconds for elevations angles from 20 through 90 degrees.

Acquisition Camera

The telescope includes a CCD/TV system for acquisition and guiding. This system is an integral part of the telescope drive and control system, and capable of fully automated acquisition and guiding on a list of targets. This CCD/TV camera system is able to guide on the light reflected from a 45-degree tilted flat mirror just ahead of the Nasmyth focus. This guider mirror sends roughly 4 percent of the star light to the TV guider while allowing the remaining light to enter the spectrograph slit. Since it is our desire to guide on stars as faint as V=12th magnitude, the absolute limit of the TV camera is V =15 or fainter. This TV system will be used to initially acquire an object in the 2 arcminute field of view, and then to center it on the science aperture and hold it there to 0.2-arcsecond accuracy during typical 10-60 minute exposures. The TV system is integrated with the telescope drive and control system, with compensation for and knowledge of field rotation. The camera is in a fixed orientation system, guiding directly on the on-axis image.

Acquisition Software

UCO/Lick software will provide a target list of objects, with accurate coordinates and brightnesses. This list will be prioritized, and arranged in sequence to maximize the altitude of each observation, and to minimize telescope slewing time. The acquisition software is able to slew sequentially to each target in the night's observing list, acquire the field in the guider field of view, identify the proper star (either the first- or the second-brightest in the field) and then center it on a designated CCD/TV pixel. Since the University currently doesn't have plans for an optical field de-rotator, the guider software will have to compensate automatically for field rotation. The software therefore includes a coordinate transformation to convert the CCD/TV coordinates into telescope coordinates as a function of telescope azimuth and altitude. Once a target is acquired, the software then switches into guider mode and initiates closed-loop guiding, holding the light centroid of the star at fixed location on the CCD/TV. This fixed location is centered on the rotating field that also corresponds to the center of the spectrometer slit. At the same

time, a box (defined to trace the outline of the spectrometer entrance slit) is used to collect intensity information about the star. Numerical values of intensity over pixels in the box are output to an "exposure meter" software routine that computes the total amount of light passing into the box vs. time and updates the instrument computer at a rate of once per second. This data is then used to compute both an intensity-weighted time centroid for the observation, and an accumulated exposure measure. The star is observed for either a preset maximum time, or by a time determined by the accumulated exposure measure. Then the exposure is terminated, the telescope slews to the next object on the target list, and the process is repeated.

Tertiary Mirror

The tertiary can rotate in its mount about the primary's optical axis to point at either of the twin Nasmyth foci under remote control, and in under 45 seconds, with < 4 arcseconds positional repeatability of the focal plane axis.

Coating

The secondary and tertiary mirrors specified above are delivered with a protected silver coating with an average reflectance greater than 75% from 0.38 μm to 0.47 μm and greater than 96% from 0.48 μm to 1.2 μm. The primary is coated with bare aluminum.

Finish

Finishes on the mirrors are 80/60 for the primary and 60/40 on the secondary and tertiary.

Mount

The mount is an altitude-azimuth design. The range of motion of the alt-az mount is at least 420° for azimuth and zenith-to-horizon for elevation. The zenith blind spot is less than 1.0 degree in diameter. The telescope has an unobstructed view down to an elevation angle of 15 degrees. The telescope is designed to allow safe storage at the zenith and horizon limits.

Pointing Accuracy

Telescope engineering tests of the APF Telescope were conducted remotely from UC Santa Cruz on the nights of June 10, June 23, and July 16. These tests demonstrated that we could successfully operate both the telescope and dome remotely and that the telescope points and tracks adequately to routinely acquire and track stars in all parts of the sky. The telescope easily meets the specified pointing requirement of 10 arcsecond rms from 0 to 70° zenith angle after mount modeling corrections.

Tracking Stability

Based on the tracking performance measurements completed so far, we expect that the tracking performance requirements for the APF Telescope will be met over the required range of sky positions later this year, once the final optical alignment of the telescope and guide camera are completed and the windscreen-functionality of the dome shutters is fully operational. Exhibit D contains a detailed analysis of the current tracking stability and supports our claim that the APF telescope will track better than 0.5 arcsecond rms for at least 10 minutes and 2.5 arcsecond for one hour for elevations greater than 20 degrees (0 to 70° zenith angle).

Slew Rates

The Slew rate is 2 degrees per second with a maximum minimum acceleration rate of 1 degree per second^2.

Emissivity and Rust Protection

All ferrous surfaces are primed and painted with industrial paints designed for maximum longevity and durability. All telescope parts in view of the primary are painted with flat black paint to minimize stray light reflections from the telescope.

Temperature Compensation

The secondary mirror assembly includes a quasi-static tip/tilt/focus assembly to compensate for temperature variations and to maintain the nominal focus of the telescope. Additionally, low expansion glass is used for the mirror substrates. The telescope is parfocal over the 20 – 90 degree F temperature range and over the 0 to 90 degree elevation range.

Structural Stability and Seismic Design

The lowest structural resonance of the telescope structure is 7 Hz. The lowest mode can be characterized as a rotation of the secondary around the optical axis. This mode is a direct function of the secondary spider vane size. The telescope is designed, built and installed in a manner that meets all applicable requirements of the current version of the Uniform Building Code (UBC). Any optics that could possible come out of their supports or that have supports that could get destroyed (like delicate flexures) includes safety clips and restraints to prevent damage in the event of an earthquake. Any structural components that rely on gravity for stability have a safety restraint in the event that the ground motion exceeds –1 g acceleration (opposite of gravity).

Static Deflection

Residual image motion (non-repeatable) and image blur due to flexing of the telescope structure over 0° to 90° elevation angles and for azimuth angles of 0 to 360 degrees is:

Residual Image Motion	$\leq$ 0.05 arcsecond
Final Image Size due to Image Blur	θ_{80} <0.50 arcsecond diameter

Residuals are assumed to be hysteretic in nature and are therefore not pure flexure.

Baffles

The telescope is baffled to ensure that only rays that follow the optical path can enter the field of view. The sizes and positions of all baffles are optimized to minimize the central obscuration.

Mirror Re-coating

All mirrors can easily be removed (less than 4 hours) from their mounts for periodic re-coating. All mirrors will have the capability to be mounted inverted (down-looking) within the coating chamber. All handling fixtures necessary for safe removal, transportation (truck or air) and re-coating are included with the telescope. The primary mirror includes a dedicated turning cart to assist mirror recoating at the Shane telescope.

OPTICAL MECHANICAL INTERFACE DESCRIPTIONS

Summary of UCO Supplied Hardware

The science requirement of the Automated Planet Finder facility will be met with the addition of the NASA funded instruments described below. Together the Telescope, Enclosure and Instrument suite will allow the facility to meet and exceed the intended science requirements.

Planet Finder Spectrometer (PFS)

This is a specialized echelle spectrometer that is being built for installation at one of the Nasmyth foci. The instrument design is shown in Exhibit A-C. The instrument is nearing completion at UCO instrument fabrication facility and soon will be ready for factory testing.

Atmospheric Dispersion Compensator and Image De-rotators

Telescope structure near the final focus provides sufficient space and an attachment point for the addition of an atmospheric dispersion compensator and an image rotator. The ADC has been installed in the telescope and currently is undergoing calibration and testing on sky.

Iodine Cell

This is a calibration unit that lies in the collimated on-axis telescope beam, some 200 mm ahead of the telescope focal plane (see exhibit III for a diagram). Because it is heated to 50 degrees C heat convecting from this unit could seriously corrupt the seeing and is therefore a concern. This sub unit is inside the Planet Finder Spectrometer and is actively cooled to prevent seeing degradation. The Iodine cell is mounted to a translation stage to move it in and out of the beam as needed.

Calibration Lamp System

The calibration lamp system, which feeds light from calibration lamps, is mounted in the upper portion of the Planet Finder Spectrometer just ahead of the telescope focus. This system closely mimics the telescope's exit pupil.

ELECTRICAL AND SOFTWARE REQUIREMENTS AND INTERFACES

Computer Hardware

The high-level control software runs on a set of off-the-shelf PC's, which provide satisfactory reliability at reasonable cost.

Operating Systems

The telescope and dome control systems run under Windows XP Professional. The control systems for the science camera, spectrometer, autoguider, and autonomous observing suite all run under the CentOS 5 Linux distribution.

Software Interfaces

All of the software control systems are implemented using a client/server model, and can be controlled via graphical interfaces, command-line tools, scripts, and/or C or C++ libraries. All API's have been documented. End user documentation is in progress. All source code is either owned by UCO or will be held in software escrow. ***Error Handling and Recovery***

The telescope software includes procedures for detecting and handling unsafe operating conditions, malfunctioning hardware, and internal software errors.

Telescope Drives

The telescope uses direct drive motors to move the azimuth and elevation axis of the telescope.

Encoding System

Encoders have been provided to encode each axis of the telescope. The resolution and accuracy of the encoders is sufficient to ensure that the servo system can comfortably meet the pointing and tracking specifications. All relative encoders will include a homing device and necessary software to initialize the absolute position of the axis.

Secondary Mirror Focus Stage

The telescope secondary mirror has a focus stage that also is capable of servo-controlled tip and tilt of the secondary mirror. The resolution and range of the secondary mirror is ± 5 μm over ± 1.0 mm, respectively.

Limits and Interlocks

The telescope has travel limits and associated interlocks to ensure fail-safe operation. This includes a complete weather monitoring package (hardware and software) to control the opening and closing of the dome/enclosure. The weather interlock is capable of sending out an email message when it commands the dome/enclosure to close due to poor weather and is capable of initiating a closing via remote control (e.g. from a similar incoming email message or via a command from the network). This is to allow a second level of weather protection based on observations by the telescope technicians at adjacent telescopes.

Cable Wrap

The facility includes a cable wrap to accommodate all the cabling necessary for the operation of the telescope, plus the cabling required by UCO supplied instruments.

Primary Mirror Cover

The primary and tertiary mirrors are protected by motorized covers. These covers keep the two mirrors clean at any elevation angle and also provide impact protection in the event a tool were to accidentally get dropped from higher up in the dome. All covers can fully open or close in less than 30 seconds total elapsed time and at any elevation angle.

Weather Station

A reliable weather station that is integrated with the remote operation control software is included with the telescope as a deliverable. The weather monitoring equipment monitors outside air temperature, wind speed, wind direction, and humidity. The system also includes a rain sensor to determine if it is wet or dry (rain or temperature below the dew point.). The system can also detect snow conditions and respond

appropriately. All the data from the weather monitor is available to UCO/Lick through a software interface.

ENVIRONMENTAL REQUIREMENTS

The telescope is designed to operate within the environmental extremes specified below. The telescope is protected in its dome/enclosure when weather conditions become adverse. All mechanical and electrical components are rated to operate and survive the environmental conditions listed below.

Temperature Range to Meet Image Quality Specification	-6 °C to + 30 °C
Max. Operating Temperatures	-15 °C to + 35 °C
Storage Temperature	-20 °C to + 40 °C
Altitude	Sea Level to 5,000 ft.
Relative Humidity	5% to 95%
Wind Speed*	Up to 50 mph outside the dome.

* Wind speed inside the dome is assumed to be 50% of the exterior wind speed

ENCLOSURE TECHNICAL SUMMARY
Contract No. N62306-03-C-B001

ENCLOSURE REQUIREMENTS

Summary

The APF enclosure is a co-rotating dome. This dome type has two benefits over traditional domes. The first is the small footprint on site because the dome rotates with the telescope in azimuth so the overall diameter does not need to include space for the telescope tube to sweep through when it moves. Secondly since all the equipment is rotating in azimuth with the telescope, a major cable wrap is eliminated. Cables can therefore run directly between the spectrometer computers and the Planet Finder Spectrometer.

The enclosure is designed to protect the telescope from the elements and to provide a dry/ leak-free environment under the worst possible combination of elements at the maximum values that are listed in the table below.

The dome includes provisions to minimize telescope windshake. This is accomplished by tracking the telescope in elevation with the bi-parting over-under shutter.

The first level of the dome provides room to house all computers associated with the telescope and facility. There is a small work-space for one or two operators who will be on-site during the first few months of operation to de-bug and optimize the facility.

Enclosure Performance Specifications

	Operational	Survival
Temperature	-6 C to +30 C	-15 C to +35 C
Wind	50 mph outside enclosure	Sustained 120 mph for 1 hour
Snow	0.2 meters	0.8 meters
Ice	Not applicable	75 mm solid ice on the entire dome
Rain	Not applicable	Leak proof
Earthquake	Not Applicable	Seismic zone 4, UBC 1997

Mechanical services to the building include electrical, water and high speed network. Restroom facilities are not included with the building due to the close proximity of similar facilities and the short commissioning time required for this facility.

The enclosure includes a rail system and custom mirror cart to remove the M1 mirror when it needs recoating. The mirror and cart are designed to roll clear of the telescope onto a bridge structure that is attached to the dome service balcony. From this location the mirror is removed from its cell using a dedicated lifting fixture and a mobile crane.

ACCEPTANCE TESTING

Acceptance testing of the Telescope and Enclosure was successfully conducted with Dr. Kenneth Johnston of USNO on June 11, 2009. Copies of the Telescope and Enclosure test report are provided in Exhibits E and F, respectively.