JPL Table Mountain Facility Support of the Ground/Orbiter Lasercomm Demonstration

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On 23 nights between October 30, 1995, and January 13, 1996, the JPL Table Mountain Facility (TMF) was the site of the ground stations of the Ground/Orbiter Lasercomm Demonstration (GOLD). These 0.6-m and 1.2-m telescopes acted as terminals in a bent-pipe optical communications link. This link went from the ground to an optical communications transceiver terminal on the Japanese Engineering Test Satellite (ETS-VI) and back to the ground. This article describes how the TMF supported this novel optical communications experiment. This experiment was a collaborative effort between JPL, NASA's Deep Space Network (DSN), the Japanese National Aeronautics and Space Development Agency (NASDA), and the Japanese Communications Research Laboratory (CRL), which operates the ETS-VI. The 0.6-m telescope, in the coudé configuration, was used to uplink a 514-nm modulated laser to the transceiver on the ETS-VI communications satellite. The 1.2-m telescope, in the Cassegrain configuration, was used to detect an 830-nm diode laser signal downlinked from the ETS-VI terminal. The downlink was sent only if the uplink beam was detected. The uplink beam had to be kept within a box 5 arcsec on a side and centered on the position of the ETS-VI. This required that the 0.6-m telescope track the ETS-VI to a precision of ± 2 arcsec. The 1.2-m telescope was required to track to a precision of 4–5 arcsec because the downlink detector had an aperture with a 13-arcsec-diameter field of view. This article describes how the above tracking performance was met by both telescopes. Equipment designed for the experiment at the transmitter and receiver stations, acquisition methods, and software developed to support this project are discussed, as are experiments performed to establish the suitability of the TMF telescopes for this demonstration. This article discusses upgrades to the TMF electrical power system needed to support GOLD; mechanical, optical, and servo-control aspects of the transmitter and receiver; and problems encountered during telescope operation.

I. Overview

Because an overview of the Ground/Orbiter Lasercomm Demonstration (GOLD) experiment is given in [1], this overview is limited to those aspects of the project peculiar to the Table Mountain Facility (TMF). The 0.6-m and 1.2-m astronomical telescopes at the JPL TMF were used to support a novel demonstration of one- and two-way optical communications. A one-way link was established with the

Japanese Engineering Test Satellite (ETS-VI). Confirmation of the link was provided by telemetry from the satellite relayed to Table Mountain by NASA's Deep Space Network (DSN), the Japanese National Aeronautics and Space Development Agency (NASDA), and the Japanese Communications Research Laboratory (CRL). This relay included two 56-kbit/s digital communications lines and digital signal units (DSUs) at the end of each line. It also required considerable cooperation from the local telephone service provider, Contel. The system was installed by JPL's Communications Systems and Research Section. A two-way link was also established in which, upon acquisition of the uplink laser beam by the ETS-VI, a downlink laser beam was pointed at the receiver. This was received at the TMF by a detector mounted at the Cassegrain focus of the 1.2-m telescope.

Methods were developed to make possible the acquisition of the satellite which, at apogee, was only as bright as a star of $V = 14$ mag. Software and methods were developed to generate position updates to keep the telescopes tracking the satellite to an accuracy of ± 2 arcsec. Transmitter and receiver operations required three TMF staff members each night. One was required to operate the receiver telescope, one to operate the transmitter telescope, and one (the Resident Astronomer for the 1.2-m telescope) acted as a consultant during contingencies.

A regular operation was in place by mid-December 1995. This involved the generation of ephemerides for the satellite, their installation on the transmitter and receiver telescope control computers, the preparation of the transmitter and receiver, weather reporting, nightly telescope operations, downlink and seeing data acquisition, and transmission of data to JPL in Pasadena.

II. The Transmitter

A. General Description of the Transmitter

The transmitter consisted of a 10-W argon-ion laser, a modulator, a beam splitter, a collimator lens system, an optical delay line, a high-power dichroic beam splitter, four fold mirrors, and the coudé optical train of the 0.6-m telescope. The latter consisted of two flat mirrors (the first and second coudé flats), the convex coudé secondary, and the 0.6-m-diameter Ritchey–Cretien (RC) primary mirror. The dichroic beam splitter divided the laser beam equally into two parts. One beam was passed through the delay line. This produced two temporally uncorrelated beams. The coupler lens system made them converge at the iris at the coudé focus. A PulNiX DN-007-F3 mini-intensified charge-coupled device (CCD) video camera detected reflected sunlight from the satellite at the same focus. This was used to visually acquire the satellite prior to turning on the uplink laser. At this time, the iris was closed down to a diameter equal to the width of the beam, which was set by the collimator lens.

The 0.6-m telescope has an RC and a coudé optical train. By rotating the secondary mirror cell to place the coudé secondary in the light path, the telescope was switched from an f/16 RC to an f/41 coudé system. This longer focus was brought to a large optical bench in the coudé support room by the addition of three flat mirrors in the train (see Fig. 1). The first coudé flat was placed between the coudé secondary and the primary mirror. It bent the beam to the second coudé flat, which bent the beam down the polar axis of the telescope and into the support room. These mirrors were manually flipped in and out of the light path as needed. A third fold mirror was placed in the beam to bend it onto the optical table.

B. The 0.6-m Telescope Servo System

The motion control system of the telescope consisted of a Compumotor A106-205 stepper motor driven by an SXF106-205 microstepping driver and a model 2100 indexer. This configuration is identical for both the hour-angle and declination axes of the telescope. The indexers are remotely controlled from an Everex Step 25 MHz 386 PC through two serial ports. The indexers allow the hour-angle and declination motor torques to be ramped up and down for smoother motion. They also provide high- and low-speed

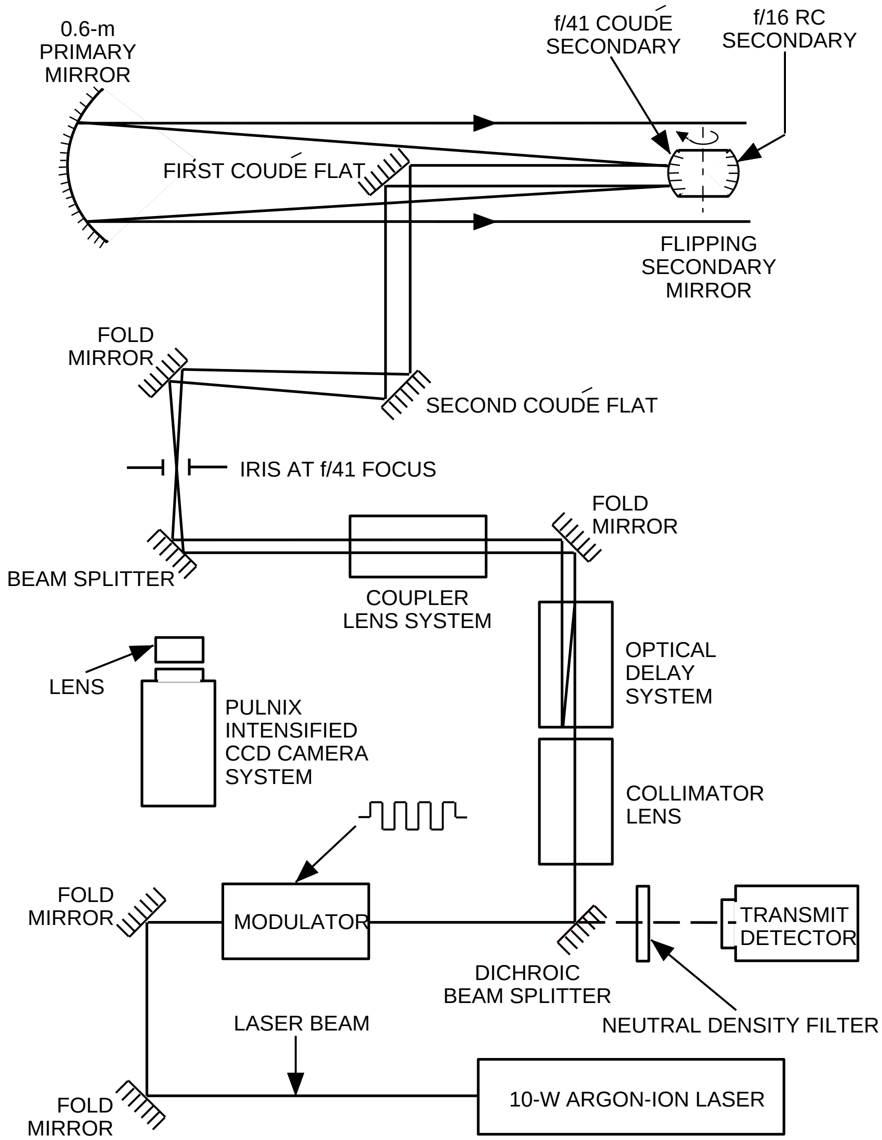

Fig. 1. Schematic of the transmitter optical train showing the argon-ion laser, modulator, dichroic beam splitter, collimator, optical delay system, coupler lens system, transmit detector, acquisition camera (intensified PulNiX), and 0.6-m telescope coude optical system.

control for slewing and tracking. The hour-angle and declination servo loops include BEI H25-SS-2400 encoders. Each provides angular position signals through the same Compumotor IPC-2 two-axis encoder reading card to the telescope control program (TCP) in the PC. Calculations of telescope position and current velocity by the TCP are based on the encoder counts. Desired velocity control signals to the indexer from the TCP close the servo loop on each axis.

The drive train for each axis consists of a motor that drives the input shaft of a 10:1 differential gear. The output of the differential meshes with a worm gear that drives a large flat gear concentrically with the axis of rotation (see Fig. 2). The motor has a resolution of 25,000 steps/rev. The output of the differential gear rotates once per 10 revolutions of its input. Tooth pitches were chosen so that the flat gear rotates

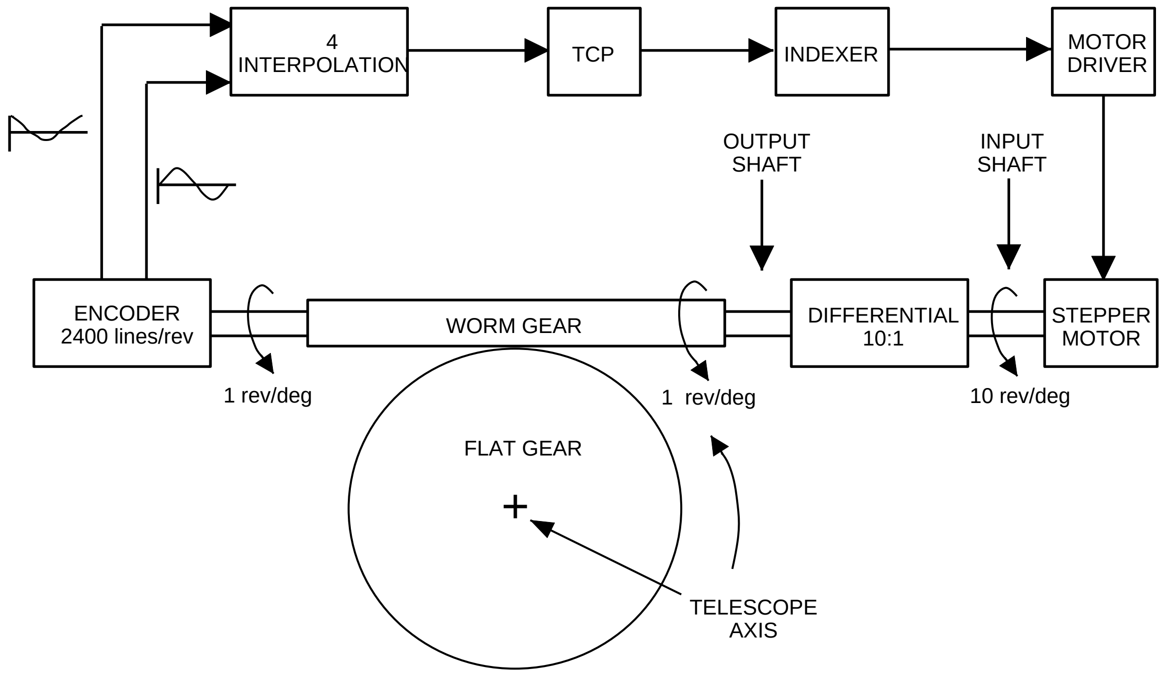

Fig. 2. Schematic of one-half of the motion control system of the 0.6-m telescope, showing the relative placement of the stepper motor, the 10:1 differential gear, the worm gear, the flat gear, and the encoder. The system is the same on both telescope axes.

1/360th of a revolution for every revolution of the worm gear. Thus, one turn of the motor results in 1/360th of a turn of the telescope. Also, one step of the motor results in 1/25,000th of this motion. The number of motor steps per revolution of the telescope is the product of the last two numbers. Thus, 90,000,000 steps of the motor are required to move the telescope axis through one complete revolution. Therefore, the pointing resolution of the telescope is 0.014 arcsec.

A BEI rotary optical encoder is attached to one end of the worm gear. This encoder includes a transparent disk with 2400 radial dark lines ruled on it at equal intervals. This disk rotates on a shaft rotating with the worm gear. Pairs of light-emitting diodes (LEDs) are arranged at 90-deg intervals around the disk so as to shine through it. The variation in amplitude of light transmitted through the disk is detected by pairs of opto-sensors on the other side. These sensor pairs are arranged facing the LEDs. Interruption of the illumination by the rotating lines produces a periodic signal whose frequency is proportional to the angular distance moved by the disk. Diffraction around the dark lines results in sinusoidal signals from the sensors, which are separated by a phase shift of 90 deg. These are combined in the encoder reading electronics to produce a signal with four times the frequency of the sensor output. This common encoder signal processing technique is referred to as quadrature detection. Quadrature produces an interpolation (subdivision) of the angular measurement resolution of the encoder of four times. Since the worm gear rotates 360 times for a complete revolution of the flat gear, the encoder also rotates 360 times. The product of this last factor, the number of lines on the disk and the interpolation factor, dictates that the position of the flat gear can be measured to 1 part in 3,456,000. Thus, the angular position of a telescope axis can be measured to an effective resolution of 0.375 arcsec.

C. Limiting Speeds of the 0.6-m Telescope

There is a limit on how slow a satellite may be for the telescope to track with maximum accuracy. The limit is set by the product of the encoder step size (0.375 arcsec) and the frequency with which the TCP updates the telescope position. Random errors in position read out from the encoders occur at this rate of motion. The update frequency is 20 Hz. The low speed limit is, therefore, approximately 7.5 arcsec/s. The minimum angular velocity of the satellite in the track direction is approximately 10 arcsec/s at apogee. By this estimate, the tracking of the ETS-VI near apogee was near the low speed limit of the telescope. The upper speed limit of the stepping motors is 7200 arcsec/s. However, the maximum speed of the servo system as a whole is about 5600 arcsec/s. At this speed, the probability of the telescope stalling becomes significant. Recent trials indicated that the telescope will stall in 1 of every 60 satellite tracking runs at this speed. There is some indication that this probability may be reduced by precisely balancing the telescope in the coudé mode.

D. Preparation and Operation of the 0.6-m Telescope

Several aspects of telescope preparation and operation were important to the success of GOLD. They were maintaining telescope mirror alignment for both Cassegrain and coudé operation, repeatability of optical train changes, ephemeris accuracy during encounter, and calibration methods for pointing accuracy. These are discussed below.

GOLD operations were carried out while coexisting with other, astronomical, users. Astronomical users almost always required the RC telescope mode. On some nights, an RC user was scheduled for the hours prior to midnight and GOLD for the hours after midnight. Switching between the RC and coudé optical trains was required. Switching to the coudé optical train required a procedure to carefully rotate the secondary mirror cell to select the coudé mirror and to consistently flip the first coudé flat. Tests prior to GOLD operations indicated that failure to perform this mirror flip carefully resulted in variations of optical alignment of 60–90 arcsec on the sky. An aluminum wedge was positioned as a stop against the framework supporting the mirror swinging mechanism. This reduced optical alignment variations to less than ±5 arcsec. This improvement was a determining factor in allowing mixed operations during GOLD.

Ephemerides for the current pass of the ETS-VI and the next pass (3 nights later) were provided by the Navigation and Flight Mechanics (NFM) Section at JPL. These were based upon osculating orbital elements, derived from radar tracking, provided by NASDA every 3 days. Ephemerides based on two different sets of tracking data were usually available for each satellite pass. This provided some insurance against unexpected satellite orbit corrections. It was found that ephemerides based on the most recent tracking were likely to be the most accurate.

E. Acquisition of the ETS-VI at the 0.6-m Telescope

Acquisition of the ETS-VI was performed in the following way: The ephemeris was loaded into the TCP and the approximate right ascension and declination of the ETS-VI was noted. Then the position of a bright star, from an on-line catalogue, was loaded into the TCP. The telescope was then positionally calibrated using this star at the coudé eyepiece or on the video display in the center of the iris (calibrated optical path position). The satellite ephemeris was once again loaded into the TCP and the telescope moved to the satellite. The ETS-VI was always found within 30 arcsec of the center of the field of view (FOV). More current ephemerides usually allowed initial acquisition within 10 arcsec of the center of the FOV. Further correction to place the satellite in the center of the FOV was made by adding small position offsets via the TCP.

During the pass, the 0.6-m-telescope paddle (via the TCP) was used to make small corrections for random differences between the ephemeris and the actual position of the ETS-VI. This was necessary to keep the uplink beam pointed at the satellite to ±2 arcsec. This strategy worked well for about 75 percent of the passes. It proved less effective when the ephemeris was not generated from the most current tracking data, because random differences were too large to correct quickly. At these times, the uplink beam did not remain pointed at the satellite to the required positional tolerance.

III. The Receiver

A. General Description of the Receiver

The receiver consisted of an optics module attached to the Cassegrain focus of the TMO 1.2-m telescope. The optics of this telescope consisted of an f/6.5 1.2-m-diameter parabolic primary mirror, a hyperbolic secondary mirror, and a flat tertiary mirror placed between them. The primary/secondary mirror combination produced an f/29.5 beam that was bent by the tertiary to exit at the side of the tube near the fulcrum of the telescope. The GOLD optics module was attached at this point (see Fig. 3).

The optics module included an avalanche photodiode (APD), a video camera and image intensifier combination, a SpectraSource Lynxx 2000 CCD camera, a low-pass beam splitter, a bandpass beam splitter, and an ND/1.5 neutral density filter. The low-pass beam splitter ensured that 90 percent of the downlink beam light (830 nm) reached the APD and that scattered uplink beam light (at 514 nm) was rejected. The bandpass beam splitter divided the rejected light equally between the seeing camera and the intensified video camera. The intensified video camera was used for acquisition of the ETS-VI. Acquisition involved moving from a bright positional calibration star to the much fainter satellite. The ND/1.5 filter was rotated into the beam to attenuate the starlight to avoid saturating the intensifier. It was rotated out of the beam when looking at the satellite. This operation was remotely controlled from the 1.2-m telescope control room. The CCD camera was used to collect time-integrated images of bright stars for focusing the telescope. It was also used to image the satellite every 15 min when illuminated by the downlink laser. These images were used to monitor changes in atmospheric scintillation and variations in seeing. The use of these data is discussed further in [2]. The APD was used to detect the modulated downlink beam from the satellite. The signal from the receiver was analyzed by a bit-error rate tester. This is described in [1].

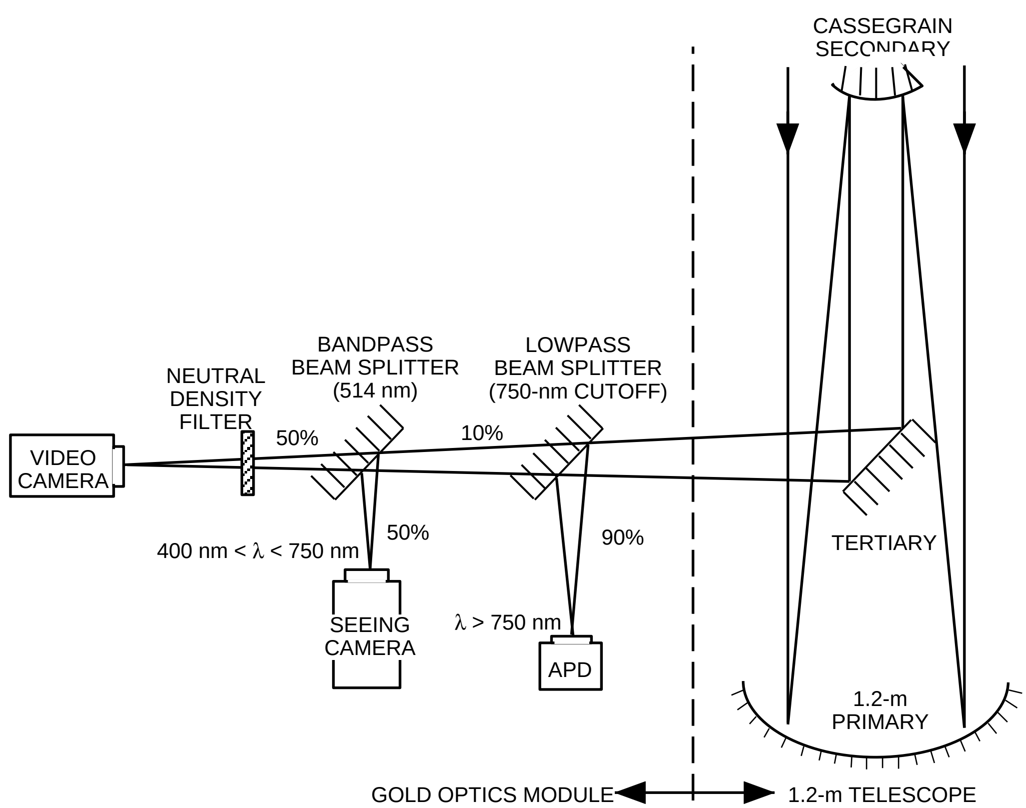

Fig. 3. Schematic diagram of the receiver optical train showing the 1.2-m Cassegrain optics, APD, video camera, seeing camera, beam splitters, and neutral density filter.

B. The 1.2-m Telescope Mount

The 1.2-m telescope is on an alt–alt mount. This design has two axes of motion in perpendicular planes that intersect at the zenith. The direction of motion perpendicular to the mount is referred to as the Track (Tr) direction, and the one parallel to the mount is the cross-track direction (XTr). The tube is wider than the distance between the forks of the mount and so cannot pass through them. Therefore, this telescope can move from the horizon to approximately 5 deg past the zenith in XTr. It has a rotatable base that allows the entire telescope to be rotated in azimuth. This allows it to track satellites in all parts of the sky.

C. The 1.2-m Telescope Servo System

The motion control system of the 1.2-m telescope consists of a torque motor, an Advanced Motion Control Systems 30A20AC servo amplifier, and a preamplifier/summer/filter on each axis. The instantaneous velocities of each axis are set by a voltage sent to the preamplifier from a 12-bit digital-to-analog converter (DAC). Its output is ± 2.5 V peak-to-peak. The DAC is controlled through the 1.2-m TCP running on another Everex Step 25 MHz 386 PC. A tachometer generator (tach) provides a velocity feedback signal. This signal is passed through a low-pass filter (7.5-Hz cutoff) to attenuate high-frequency noise before summing with the signal from the DAC. The tachometer response was found to be linear from -500 arcsec/s to $+500$ arcsec/s with a slope of 0.55 mV/(arcsec/s) and an intercept of zero. Proper phasing of the tach signal relative to the DAC signal produces a difference signal at the output of the summing amplifier, which determines the instantaneous velocity of the telescope in one axis (see Fig. 4).

The DAC side of the summing amplifier has high- and low-voltage gain settings. Switching between them is controlled by the TCP. The low-gain setting allows tracking of astronomical objects (low speeds), and the high-gain setting allows slewing (high speeds) of the telescope to the object. In astronomical usage, these settings are distinct. The low gain (16) was chosen so that a large DAC voltage was needed to produce rates several times sidereal. This choice minimized error due to noise in the DAC signal. A DAC signal of 1 V saturates the summing amplifier. This signal level corresponds to a desired velocity of 205 arcsec/s. The maximum tracking speed of the telescope, thus, was fixed at about 200 arcsec/s. This

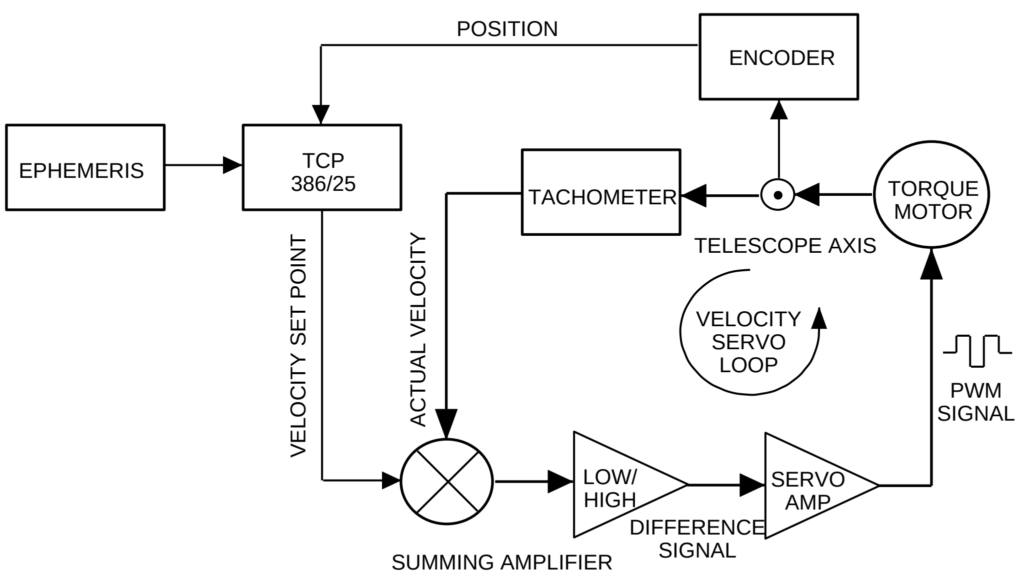

Fig. 4. Flow diagram of the servo system on one axis of the 1.2-m telescope showing how the ephemeris, through the TCP, sets the desired velocity and how the velocity servo loop achieves that velocity. Position feedback to the TCP via the encoders is indicated. This configuration is repeated on the other axis.

servo arrangement also allowed the 1.2-m telescope to track the ETS-VI near apogee, where the rate of motion of the ETS-VI was typically 80 arcsec/s. Tracking periods were 5–8 hours long. This forced the servo amplifiers to run for long periods of time with large output pulse widths, which caused overheating and temporary shutdown of receiver operations on one occasion. The high-gain setting provides a gain of 264, which causes the telescope to be driven at full torque until it reaches a velocity of approximately 4000 arcsec/s. This is the slew mode. The TCP switches from slew mode to track mode when the difference between the commanded and actual positions of the telescope is less than 1000 arcsec.

The input stage of the servo amplifier provides proportional gain to control the rate at which the telescope ramps to the desired velocity. This gain can be varied between zero and unity. A second stage, which includes a 1.0-μF capacitor, provides integral gain to hold the system at the desired velocity. The loop gain of this stage can be varied between 1 and 10. The above system constitutes a classic proportional-integral (PI) servo loop. The servo amplifier converts its input to a 33-kHz pulse-width-modulated (PWM) signal of 15 A at 170 V. This configuration is used on both axes.

Pulse widths must be at least 10 μs to overcome friction in the telescope bearings. They are controlled by the potential on the integrating capacitor. This is determined by the input voltage and the product of the input stage gain and the loop gain. Thus, at low tracking speeds, more gain is required to overcome friction than at high speeds. At the low speeds characteristic of the ETS-VI at apogee, more loop gain was used than typically is used in sidereal tracking. This made the servo more sensitive to noise at its inputs and to sudden commanded changes in position, resulting in a tendency toward servo-loop oscillation. This was seen on January 3, 1996, when the telescope started to oscillate after it was commanded to move 10 arcsec to recenter the downlink beam in the APD aperture. The oscillation was damped by reducing the loop gain of the Tr servo amplifier, using its external potentiometer.

The angular position of the telescope is measured by a Heidenhain RON905 incremental optical encoder on the Tr and Xtr axes. These encoders operate in a manner similar to the encoders on the 0.6-m telescope. They have an intrinsic resolution of 36,000 lines/rev. Their sine and cosine outputs are electronically interpolated by a factor of 1024 before being sent to the computer via a general purpose interface bus (GPIB) parallel interface. The encoder and interpolation electronics comprise the position measurement system. The motors, tachometers, and encoders are coupled directly to the Tr and Xtr axes. The product of the intrinsic resolution and interpolation factors gives 36,864,000 encoder resolution steps per revolution of the telescope axis. Therefore, the angular resolution of the position measurement system is 0.035 arcsec.

D. Limiting Speeds of the 1.2-m Telescope

The low speed limit of the 1.2-m telescope is the product of the 1.2-m TCP update frequency (20 Hz) and the position measurement resolution (0.035 arcsec). The low speed limit, therefore, is 0.70 arcsec/s. This is well below the slowest angular rate of the ETS-VI during any of the GOLD passes.

E. Acquisition of the ETS-VI at the 1.2-m Telescope

The differential pointing approach used at the 0.6-m telescope was used at the 1.2-m telescope to place the telescope on the predicted track of the ETS-VI. The acquisition camera at the 1.2-m telescope had a smaller FOV (48×18 arcsec) than the acquisition camera at the transmitter (100×79 arcsec). The satellite was never in the initial FOV. The satellite was acquired in this camera by searching a rectangular grid on the sky around the predicted position. The real-time image on the monitor was so faint that it was almost indistinguishable from spots caused by intensified noise. However, it moved when the telescope moved, and the spots did not. This fact considerably aided acquisition. The grid search was possible because the ephemeris predicted the rate of motion of the satellite so accurately that its apparent motion was very small. The ETS-VI was always found no more than 40 arcsec from the predicted position.

The satellite was simultaneously acquired in the acquisition camera, seeing camera, and APD. The seeing camera and APD had very small FOVs of 15 arcsec $\times 17$ arcsec and 13-arcsec diameter, respectively. Placing the satellite in these FOVs required accurate centering in the acquisition camera and mechanically stable detector mounts in the receiver module. It also required good relative alignment of the detectors. This was performed at the Cassegrain focus of the 1.2-m telescope prior to the first GOLD night. Apparent motion of the ETS-VI in the seeing camera indicated a long-term error in tracking of only 5 arcsec/h. This was easily compensated for by applying small offsets to the telescope pointing from the TCP.

IV. The Atmospheric Visibility Monitor

The atmospheric variability monitor (AVM) is an automated observatory at the TMF provided by the Optical Communications Group for collecting statistics on atmospheric transmission. The downlink seeing data taken at the receiver were compared with the AVM data from the GOLD transmission nights. The AVM consists of a 0.3-m (10-in.) equatorially mounted telescope, a CCD photometer, an autonomous TCP, and a modem link to JPL in Pasadena. Photometry of bright stars in various parts of the sky is stored and downloaded to a PC using the LapLink protocol twice a month. At startup, the AVM measures the intensity of the westernmost star in a stored list of 25 stars. Every 15 min, it moves east to the next star in the list. The AVM cycles through the list every 375 min. Stars as faint as $V = 5.29$ are surveyed. AVM data were used to plan enough observing nights to maximize the probability of a successful demonstration. Success depended on collecting a large amount of data on many nights (see [1]).

V. Ephemerides

The ephemerides listed the apparent positions of the ETS-VI in right ascension and declination coordinates at intervals of 15 s of Universal Time. Two downlink ephemerides and one uplink ephemeris were provided for each pass. One downlink ephemeris allowed visual acquisition of the ETS-VI at the location of the 0.6-m telescope. The other downlink ephemeris allowed acquisition at the location of the 1.2-m telescope. The uplink ephemeris was generated for the 0.6-m telescope only. It included offsets to the telescope pointing for light travel time to the satellite. With this, the 0.6-m telescope was pointed ahead of the predicted track so that the uplink beam illuminated the satellite. The point ahead varied from 1.3 arcsec to 2.1 arcsec during satellite passes. Without this correction, an unacceptably large systematic pointing error would have existed. Acquisition at both telescopes was performed with the appropriate downlink ephemeris. Tracking at the 0.6-m telescope during uplink periods was performed using the uplink ephemeris.

VI. Facility Modifications Required to Support GOLD

An upgrade from 200-V AC to 440-V three-phase AC was required to run the uplink laser at the 0.6-m telescope facility (TM 12). It was verified that the shared underground 220-V AC conduit (wiring) to TM 1, TM 12, TM 22, and the AVM was capable of handing 440-V AC. The placement of a new step-down 440 V-to-220 V transformer at TM 1 separated the power systems of TM 1, TM 22, and the AVM from the new 440-V AC supply at TM 12. The step-down transformer that supported TM 1, TM 12, TM 22, and the AVM was taken from the central power building and located at TM 12, supplying the existing 220-V requirements as well as the new 440-V GOLD requirements. The areas affected included the outside structure wall of TM 1 for mounting the 440-/220-V transformer and new disconnects, providing TM 1 and TM 22/AVM with stand-alone 220 V. The lobby area of TM 12 provided internal mounting of the relocated step-down transformer. Power was also supplied to an external water chiller, which was used to cool the uplink laser. Some 65 m of ditching for supply and return water lines from the external chiller to the coudé room/GOLD support equipment were dug. The electrical upgrade was completed in approximately 3 weeks.

VII. Experiments in Support of Future Laser Communications Experiments

Laser communication experiments are proposed between a ground station and low Earth orbiters (LEOs). One such proposal is a Space Transportation System mission that will carry a laser transceiver similar to that on the ETS-VI and capable of a 1.44-Gbit/s data rate. Communication with this device will require tracking at rates of approximately 5000–7000 arcsec/s with considerably greater precision than was required for GOLD. The suitability of the TMF telescopes for this task is being investigated.

The NFM Group has provided the TMF with ephemerides for the Ocean Topography Experiment (TOPEX) satellite. The telescopes were made to move in accordance with this ephemeris. Acquisition of TOPEX was not attempted. TOPEX is in a 1200-km orbit, and its ephemeris caused the telescopes to move at a maximum speed of about 700 arcsec/s in one axis. Ephemerides with time intervals of 2.0, 1.0, 0.5, and 0.25 s were used. In all cases, the 0.6-m telescope moved smoothly. Differences between the telescope position and the position required by the ephemeris were indicated by the TCP. For a 2-s ephemeris, the maximum difference was 2 arcsec. For a 0.25-s ephemeris, the maximum difference was 8 arcsec. Differences of about 8 arcsec were found when the telescope was made to move in accordance with ephemerides for satellites in circular orbits as low as 450 km. The rate of motion of the telescope was approximately 5100 arcsec/s. These results prompted a closer look at the TCP routines that interpolate between the ephemeris points in order to reduce the differences mentioned above. After this is completed, attempts will be made to visually acquire TOPEX.

The 1.2-m telescope failed to move in accordance with the TOPEX ephemeris. It was found that the servo system could not drive the telescope fast enough to catch the satellite using ephemerides with coordinates listed at any of the above time intervals. The desired tracking rate (700 arcsec/s) was above the maximum tracking rate of the telescope (200 arcsec/s) and below the slew rate (4000 arcsec/s). The TCP continually switched between the two rates as the telescope approached the satellite position.

At LEO tracking rates, the 12-bit DAC is capable of 3.0-arcsec/s velocity resolution. During a TCP update cycle (0.05 s), a LEO satellite will have moved 300 arcsec. It is expected that this velocity resolution is insufficient. An order of magnitude improvement will allow combinations of pointing accuracy and uplink beam divergence sufficient to complete the proposed link.

VIII. Telescope Improvements

A. Telescope Dome Upgrades

The current Ash Domes of both telescopes are rotating hemispheres with a slit that affords a view covering only 15 deg of azimuth. These slits extend from the zenith to near the horizon and cover nearly 90 deg of elevation. One rotation of each dome takes 3–4 min. LEOs will pass from horizon to horizon in a matter of minutes. Most orbits will not pass through the zenith. These limitations make following a LEO over its entire pass impossible with both telescopes.

The domes will need to be replaced with weather covers that allow an unrestricted view of the entire sky. A clamshell structure would serve this purpose. Such a weather cover would consist of several segments that fold down to expose the telescope to the sky. An alternative is a collapsible dome that folds down below the rim of the telescope building. Both would have the added advantage of allowing immediate equilibration of the air around the dome with the surroundings. Both have the disadvantage of leaving the telescopes at the mercy of the wind during passes. The 1.2-m telescope tracking precision decreases markedly for wind speeds greater than 16 km/h. The deployment of a flexible windshield in the 1.2-m telescope's dome slit allows this telescope to retain its high tracking precision in winds up to 32 km/h. The 0.6-m telescope is much less affected by wind than the 1.2-m telescope because it has a heavier and more compact mount and tube than does the 1.2-m telescope.

B. Servo System Upgrades for the 1.2-m Telescope

The following modifications to the 1.2-m telescope's servo system must be made to support LEO tracking:

(1) Increase the maximum tracking speed to at least 6000 arcsec/s.

(2) Make software and hardware changes to allow a smooth transition from slewing to tracking.

(3) Improve the velocity resolution of the DACs.

(4) Replace the analog DAC-to-summing amplifier signal line with a noise-free transmission system, such as an opto-electronic/fiber-optic connection.

(5) As an alternative to (4), replace the analog signal line with an RS232 connection and place the DAC in proximity to the servo system.

(6) Re-engineer the servo system to allow servo gains that automatically vary as the tracking conditions demand.

(7) Improve the noise rejection of the tachometer signal to allow a velocity feedback signal of sufficient resolution.

(8) Replace the intensified video camera with a more sensitive unit. This should be a PulNiX DN-007-F3 fiber-coupled GenIII camera similar to the receiver acquisition camera. It should be mounted in the 0.4-m finder attached to the 1.2-m telescope.

IX. Conclusions

At the Table Mountain Facility, both the transmitter and the receiver performed very well in support of GOLD. Only one significant technical problem occurred with either of these systems. This was the oscillation of the 1.2-m telescope on January 3, 1995. This was quickly corrected and did not result in significant loss of data. The procedures developed to acquire the satellite visually at both telescopes proved to be efficient and reliable despite the relative faintness of the satellite. A considerable amount of seeing data was recorded in the form of images from the Lynxx 2000 camera. TMF telescopes and staff were very capable of tracking the ETS-VI satellite and maintaining a consistent two-way optical communications link.

References

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