Development of a 1-m class telescope at TMF to support optical communications demonstrations

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ABSTRACT

With the impetus towards high data rate communications in inter-satellite and space-to-ground links, the small size, low-mass, and low-power consumption of optical communications is seen as a viable alternative to radio frequency links. Recent NASA/JPL optical communications field demonstrations have shown some of the operational strategies needed for space-to-ground optical links. In preparation for the optical communications demonstrations planned for the turn of the century, NASA/JPL is building an Optical Communications Telescope Laboratory (OCTL) with a 1-m class telescope. The OCTL will be located at JPL's Table Mountain Facility complex in the San Bernadino mountains of Southern California and will be capable of supporting demonstrations with satellites from LEO to deep space ranges. In addition, it will support advanced optical communications research, astrometry and astronomy research.

Key Words: Optical communications, telescopes, adaptive optics, astrometry, Table Mountain Facility

1. INTRODUCTION

Optical communications is evolving as a viable telecommunications approach between Earth-based stations and near-Earth and deep-space spacecraft. As demands increase for higher data volumes from smaller spacecraft, the lower mass, smaller size and high-data-rate advantages of optical communications subsystems make this technology attractive to mission designers[1]. To respond to the developments in this technology, JPL is building an Optical Communications Telescope Laboratory (OCTL) at the NASA Table Mountain site in the San Bernadino Mountains of Southern California. The Laboratory is designed to support the following functions:

1. Serve as a test bed that will allow validation of optical communications technologies needed for a future NASA operational optical communications capability.
2. Provide the necessary transmit and receive capabilities, and telescope tracking rates to successfully demonstrate optical communications in near-term experiment opportunities, including low-Earth orbiter opportunities, e.g. the International Space Station[2].
3. Provide a flexible research environment for developing required and/or performance enhancing technologies for future operational optical communications such as adaptive optics for deep space links.
4. Provide support for other telescope applications, e.g., wide field astrometry.

Construction of the OCTL building is scheduled to start in June '98 with completion scheduled for November '98. First light on the telescope is scheduled for December '99. This paper describes the OCTL, JPL's first optical communications station. The building, the optical train and key performance requirements are given in Section 2. The site selection criteria are given in Section 3, and strategies to effect safe laser beam transmissions in Section 4. Acknowledgments are given in Section 5 and references in Section 6.

2. OCTL DESCRIPTION

The schematic of the OCTL telescope, dome enclosure, coude and cassegrain foci, laser lab area and foundation are shown in Figure 2.1. The Laboratory is housed in a 200 sq. m building that includes in addition to the area shown, an operations control area, and an electronics lab for equipment maintenance and repair. The telescope, its pier support, and the floor of the laser lab at coude focus are vibrationally isolated from the building and are all supported on a 0.9 -m thick concrete pad anchored into bedrock. The telescope is a 1-m class Ritchey-Chretien design with nominally 10% primary aperture obstruction supported on an Az/El mount. The telescope has both cassegrain and coude foci that can be accessed by changing out the secondary mirror and removing or inserting the M3 coude flat. Mirror designations are as follows: M1 - primary, M2 - secondary, M3 - first coude turning flat between the primary and secondary, M4 - second coude flat, M5 - third coude flat, M6 - fourth coude flat is located at the base of the telescope's azimuth axis, and M7 - the final coude flat that couples the laser beams to and from the coude room. Mirrors M6 and M7 are located in the hollow coude path pier. The f/7 cassegrain focus is designed to support wide-field astrometry research, and will use a field flattener in the optical path to reduce the field curvature to less than ±50 microradians focus shift across over a 3 cm x 3 cm area in the focal plane. A de-rotator with less than 50 microradians field rotation error in image space will also be located in the cassegrain path to compensate for the field rotation during the track, a characteristic of the Az/El mount configuration.

Optical communications experiments are supported at the nominal f/30 coude path. The M7 mirror is supported by a rotatable pedestal that allow access to one of four optical tables and experiments at the coude focus. Among these are LEO communications, and high power laser propagation for laser guide star adaptive optics experiments, and deep space communications. Acquisition of LEO satellites is accomplished using a 20 cm finder telescope with 0.3 degree field that is attached to a small optical bench at the side of the main telescope and boresited with it. Some of the key optical characteristics of the telescope assembly are:

Primary aperture size:	1 meter, nominal
Dome	6-m, slaved to telescope pointing direction
Operating wavelength:	400 nm to 2500 nm
Cassegrain focus field-of-view	~0.5 Degrees
Coude focus field-of-view	~ 100 microradians
Aperture obscuration	~10 percent.
Mirror reflectivity	>80% 400 nm - 700 nm
	>98% 700 nm - 2500 nm
Mirror wavefront error	<0.063 um RMS (1/10 wave)

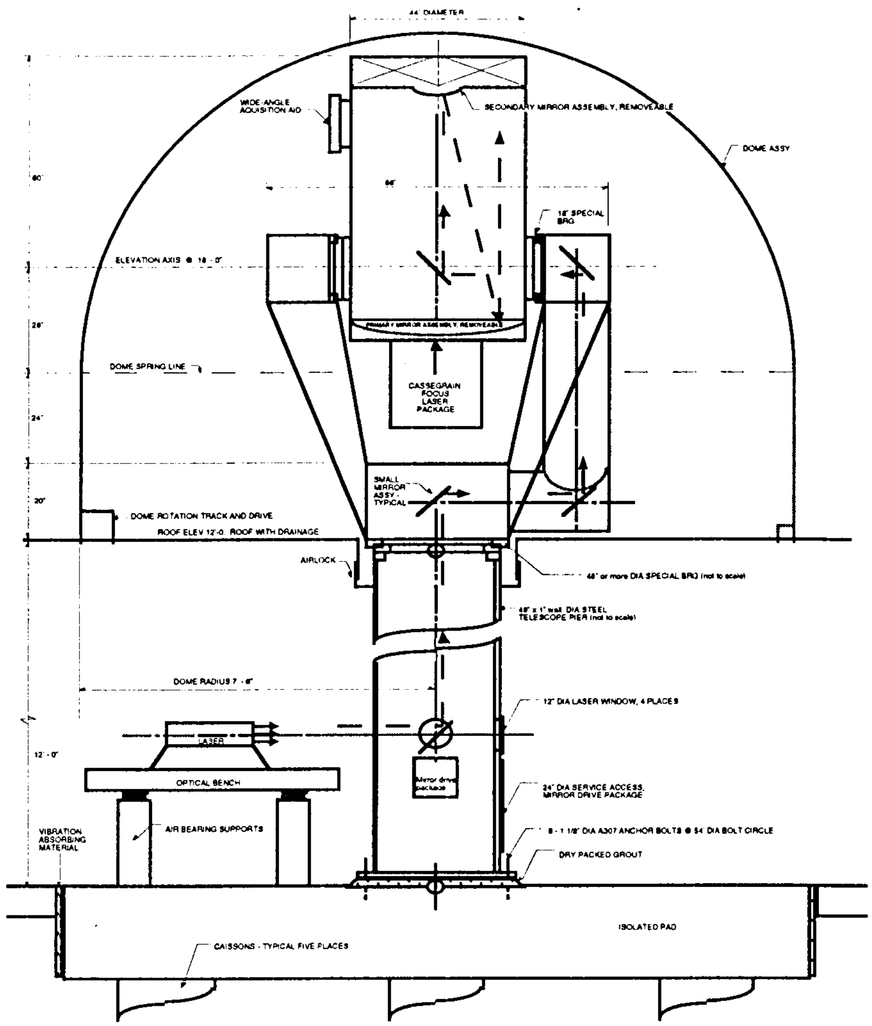

Figure 1a. Telescope Conceptual Drawing
(not to scale)

Figure 2.1: Schematic of OCTL telescope with pier supported on concrete pad anchored into bedrock.

The travel limits are –5 and 90 degrees in elevation and ±270 degrees in azimuth. The telescope will support azimuth tracking speeds up to 20 deg./sec, and accelerations up to 20 deg./sec^2. Maximum elevation axis speeds and accelerations are 5 deg./sec and 5 deg./sec^2, respectively. The rms tracking error requirements are given in Table 2.1 below. The small residual tracking error at sidereal rates are driven by the requirement to propagate near-diffraction limited atmosphere-corrected laser beams to deep space probes. The larger error tolerance at higher tracking rates shown in Table 2.1 reflects the acquisition and tracking strategy that we intend to implement for uplinks to LEO satellites. That is, we plan to take advantage of the large uplink margin to spread the uplink beam to approximately ten times the rms tracking error, and in so doing cover the telescope pointing uncertainty.

Velocity in Deg./Sec	Frequency band, Hz			
	0.1–10	10–20	20–200	200–1000
0.0 for any valid position	0.5 μrad	0.2 μrad	0.1 μrad	<0.1 μrad
0.004	0.5 μrad	0.2 μrad	0.1 μrad	<0.1 μrad
1.0	10.0 μrad	0.4 μrad	0.2 μrad	<0.2 μrad

Table 2.1. Maximum rms tracking error as a function of frequency for key tracking rates.

3. SITE SELECTION

Proper location of the OCTL is key to meeting the requirements described in Section 1, and we performed a site selection study to ensure that the OCTL's location met these requirements. Designed to be an R & D laboratory for optical communications research, astrometry, and astronomy, the selection criteria weighed heavily on atmospheric considerations. However, logistical considerations such as infrastructure (electricity, roads, water, etc.), the security of equipment, and of the research staff were also weighed in the selection process.

Important astronomical and astrometric site requirements for OCTL are 'good seeing' and 'dark skies'. The requirement of 'good seeing' is also an important consideration in the selection of the site for a ground transmission station. Atmospheric seeing introduces scintillation and wander in the uplink beam, and these effects degrade the quality of the uplink beam transmission. Sky darkness is characterized as the magnitude of the faintest star which can be observed, limited by background light from nearby cities. While dark skies are not critical to the ability of the OCTL to support optical communications, they are an important consideration in the site selection because of the multi-function nature of the laboratory. Highly desirable sites were therefore those that had existing telescopes and support facilities.

To ensure that the site would provide maximum support for laser communications demonstrations, we included a category for cloud cover. We also included as a separate category atmospheric transmission. Aerosols, pollutants, and particulates can scatter the optical beam and result in large transmission losses. These two criteria tend to favor locations that are near desert climates and removed from large cities.

Proximity to JPL was also one of the selection criteria. A lab close to JPL will be readily accessible to JPL's research staff and will facilitate experiment modifications. As with any new construction in a nationally protected area, the OCTL must demonstrate that it poses no significant impact on the local ecology. The Finding of No Significant Impact (FONSI) is a critical element in the site selection process, and one that can impact construction schedules. Locating the OCTL at a previously developed site would reduce the likelihood of an adverse finding. A final criterion was the requirement that the site possess a level of security deemed acceptable for protecting the OCTL's equipment.

With these criteria in mind, the site survey conducted for the OCTL facility considered a dozen sites within the south-western United States. The location of the sites considered is shown in Figure 3. 1.

Category	Criteria	FAIR	GOOD	EXCELLENT
transmission	altitude compared to aerosol layer	below 5,000′	5,000′ to 10,000′	above 10,000′
seeing	typical seeing in arcseconds	desert floor	~ 2″	less than 1″
cloud cover	regional daily fraction of sky that is opaque	more than 0.35	0.35 to 0.25	less than 0.25
dark skies	magnitude of faintest star observable	brighter than 18th magnitude	18th to 22nd magnitude	fainter than 22nd magnitude

Table 3.1. Ratings applied to site selection categories

Each site was rated in atmospheric transmission, seeing, cloud cover, and sky darkness according to the criteria described in Table 3.1. Ranking of the sites was performed by first combining these characteristics into a single parameter representing the optical science quality of the site and subsequently sorting the sites based on the optical science quality, proximity, site security, and Federal Aviation Administration (FAA) and FONSI considerations. Table 3.2 shows how atmospheric transmission, seeing, cloud cover, and sky darkness were combined into a single parameter. Sorting proceeded first with a conjunctive sort of good or excellent optical science quality and good or excellent proximity. The sites were then sorted according to site security, and finally by FAA / FONSI.

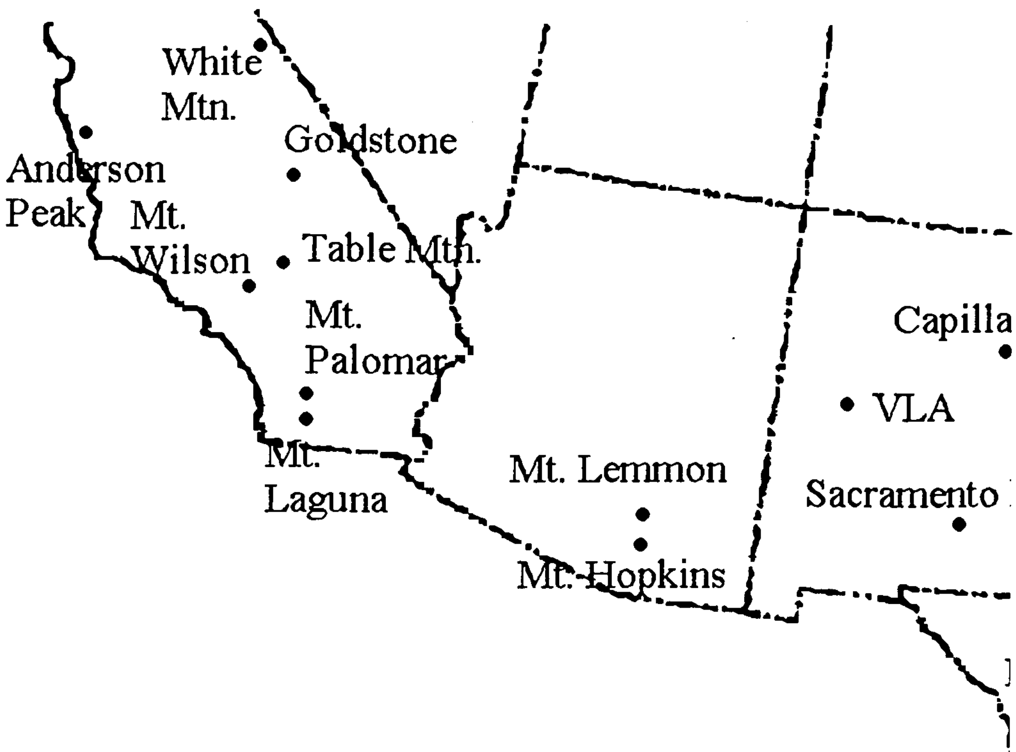

Figure 3.1: Location of the sites considered in the site selection survey.

	atmospheric transmission	seeing	regional cloud cover	sky darkness	**NET optical science**
Table Mountain, CA	✓	✓	—	✓	✓
Mount Wilson, CA	✓	✓+	—	✓	✓
Mount Laguna, CA	✓	✓	✓	✓+	✓
Mount Palomar, CA	✓	✓	✓	✓	✓
Mount Lemmon, AZ	✓+	✓	✓+	✓	✓+
Mount Hopkins, AZ	✓	✓+	✓+	✓	✓+
White Mountain, CA	✓+	✓	✓+	✓+	✓+
Sacramento Peak, NM	✓+	✓	✓	✓	✓
Mount Locke, TX	✓	✓	—	✓	✓
Capilla Peak, NM	✓	✓	✓	✓	✓
Goldstone, CA	—	—	✓+	✓	—
VLA, NM	✓	—	✓	✓	—
Anderson Peak, CA	—	✓	—	✓	—

Table 3.2: Combining atmospheric transmission, seeing, regional cloud cover, and sky darkness to create a net optical science rating for each site. Dash (—) marks, check (✓) marks, and check-plus (✓+) marks indicate fair, good, and excellent, respectively.

Table 3.3 shows the result of the sorting process, producing a net suitability rating for each site. The most suitable candidate sites were Table Mountain and Mount Wilson in California. Neither site possessed the best optical science qualities available, but their combination of good optical quality, proximity, site security, and FAA / FONSI considerations made them the top choices. Table Mountain was selected over Mt. Wilson because of its infrastructure, its past history of supporting optical communications experiments, and because it is not open to the public.

4. LASER TRANSMISSION SAFETY

Propagation of laser beams in the atmosphere is regulated by the FAA and the Laser Clearinghouse. During the GOLD[3] and GOPEX[4] demonstrations, the FAA required that aircraft in the proximity of TMF be monitored. During these demonstrations aircraft spotters had to be posted on the grounds at TMF to alert the laser operator of aircraft approaching the uplink beam. This approach would clearly be unacceptable for an operational facility. As a precursor to the development of automated optical communications stations, OCTL will incorporate, test and evaluate automatic aircraft monitoring and uplink laser beam interrupt strategies that will automatically interrupt the uplink laser when an aircraft is detected. Among the systems being consider for implementation are: (i) the Remote Airspace Monitoring System (RAMS) that was developed by the Department of Energy, and (ii) the Automated Optical Aircraft Spotter (AOAS) system, developed for the Multiple Mirror Telescope (MMT) at the University of Arizona. The RAMS uses the output from the FAA's aircraft monitoring system and allows the uplink beam to be interrupted when an aircraft enters a predetermined zone of exclusion around the laser pointing direction. The AOAS system has a more global application and consists of a visible and near infrared camera that detects the aircraft and allows automatic triggering of a laser interrupt shutter when the aircraft enters a prescribed exclusion zone.

	optical science	proximity	site security	FAA / FONSI	**net suitability**
Table Mountain, CA	✓	✓+	✓+	✓	✓+
Mount Wilson, CA	✓	✓+	✓	✓	✓+
Mount Laguna, CA	✓	✓	✓	✓	✓
Mount Palomar, CA	✓	✓	✓	✓	✓
Mount Lemmon, AZ	✓+	–	✓+	✓	–
Mount Hopkins, AZ	✓+	–	✓	✓	–
White Mountain, CA	✓+	–	✓	✓	–
Sacramento Peak, NM	✓	–	✓	✓+	–
Mount Locke, TX	✓	–	✓	✓	–
Capilla Peak, NM	✓	–	✓	–	–
Goldstone, CA	–	✓	✓+	✓+	–
VLA, NM	–	–	✓	✓	–
Anderson Peak, CA	–	–	✓	✓	–

Table 3.3 Ranking of sites by overall suitability. Sites were first sorted by the conjunction of good or excellent optical science and good or excellent proximity. Site were then sorted by site security and finally by FAA / FONSI. Dash (—) marks, check (✓) marks, and check-plus (✓+) marks indicate fair, good, and excellent, respectively.

The laser Clearinghouse monitors the transmission of laser beams out of the atmosphere. Coordination of laser beam transmission is especially critical for transmitting high peak power Q-switched lasers such as were used during GOPEX. High peak power lasers are the design baseline for deep space communications uplinks. Beacons for Earth-orbiting satellites will typically use non-Q-switched lasers as uplink beacons, either cw or low rate modulation. As with the GOLD experiment, we expect to receive unrestricted Laser Clearinghouse permission for uplink transmissions to Earth-orbiting satellites.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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