IPN Progress Report 42-183 • November 15, 2010

Deep-space Optical Terminals (DOT) Ground Laser Transmitter (GLT) Trades and Conceptual Point Design

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A conceptual design for the Deep-space Optical Terminals (DOT) Ground Laser Transmitter (GLT) has been developed. Two trade studies were performed: one to determine the most cost-effective uplink pointing system including the use of multiple and single apertures, and the second to determine the optimal type of laser transmitter for use as a beacon reference source. The baselined design resulting from the trade studies incorporated a single 1-m aperture capable of 16-μrad pointing accuracy with multiple fiber-laser sources providing up to 5 kW average optical power at 1030 nm.

I. Introduction and Overview

The Deep-space Optical Terminals (DOT) project is intended to demonstrate the feasibility and efficacy of deep-space optical communications, and retire perceived risks associated with the implementation of and eventual reliance on the technology. The system consists primarily of a Flight Laser Transceiver (FLT) in deep space (e.g., in orbit about Mars), which communicates over free-space optical channels with ground-based optical systems [1]. These ground-based optical systems consist of a Ground Laser Transmitter (GLT) system, which transmits a beacon to the FLT, and Ground Laser Receiver (GLR), which receives and decodes the downlinked optical signal [2]. Because of this bistatic design, it is not necessary to have the two ground systems located at the same site; it is, however, desirable to have them located within a few hundred kilometers of one another to prevent pass-shortening associated with the relative temporal horizons of the sites.

Operations begin with the GLT pointing blind to the predicted location of the spacecraft (predicted at the time the beacon light arrives at the spacecraft) and transmitting a bright, narrow beacon beam. Meanwhile, the spacecraft transceiver is pointed back toward Earth, and begins searching for the beacon. Once the transceiver observes and identifies the beacon, it then uses the beacon to refine and stabilize its pointing, and offset to the point-

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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ahead location to which it must transmit its downlink signal. Much more detail on the system design and concept of operations is found in a companion paper [3].

II. GLT Requirements

The most significant, driving requirements levied on the GLT system by the DOT system engineering team are shown in Table 1.

Table 1. Uplink transmit beacon requirements.

Requirement	Value	Comment
Uplink Power	2.5 kW	Power exiting system
Number of Beams	At least 9	For atmospheric fade reduction
Beam Divergence	40 μrad	Narrow beams to reduce required power
Pointing Accuracy	16 μrad	Must meet this 99% of the time
Near-Sun Angle	5 deg	Operate to within this angle of solar limb
Beam Separation	10 cm	Beam edges must be at least this far apart

The GLT must emit a laser beacon pointing reference for the FLT. This requires that the GLT blanket the region of space surrounding the FLT with a uniform irradiance sufficient to reliably be seen by the flight-based image sensor. Because of the extreme distances involved (65 million to almost 400 million km), meeting this requirement involves both the transmission of high levels of power and transmitting that power in a narrow, accurately pointed beam. Based on currently available laser technology, the systems engineering team concluded that transmitting 2500 W from the aperture of the GLT in a 40-μrad beam represented the best point on the continuum of trading available laser power for beam divergence, given pointing uncertainties and atmospheric effects.

The requirement for a very narrow 40-μrad beam flows into a very tight requirement on beam-pointing accuracy on the ground station. The station must be able to direct the beam with an accuracy of 16 μrad to limit the beam-pointing-loss to an acceptable level. In general, because the apertures of the candidate beam director systems are relatively small and the round-trip light time is so long, the GLT cannot see the FLT and use that as a pointing reference. As a result, the GLT must be capable of blind-pointing the beams to within this accuracy.

To reduce the number and severity of significant beacon fades at the FLT, a requirement was levied to propagate at least nine separate beams (or beam sets), each separated from all of the others by at least 10 cm, to assure they traverse statistically independent atmospheric paths. In addition, the beams exiting the aperture of the telescope are required to be diverging, and the final optical element of the beam transmitter must be within the confocal parameter of the exiting beam. The purpose of this is to keep the beam size smaller than an atmospheric cell to prevent beam breakup in the lower atmosphere.

III. GLT Platform Trades

There are several different ways of accomplishing the requirements levied on this system, including telescopes, flat-mirror beam directors, and distributed (arrayed) telescope systems. With so many potential candidates, any of which is probably (with enough money and effort) capable of achieving the required performance, the final selection is made based on cost and complexity.

Two main categories of systems were considered: monolithic systems, in which all of the beams are projected from different parts of the pupil of a large optical system, and distributed-aperture systems. Among the monolithic systems are large astronomical telescopes and large-mirror beam-director systems. Among the distributed-aperture systems are (1) arrays of inexpensive small telescopes, (2) multiple small telescopes attached to single high-load, high-accuracy gimbals, and (3) arrays of independent small beam-director flats. Examples of these systems are shown in Figure 1.

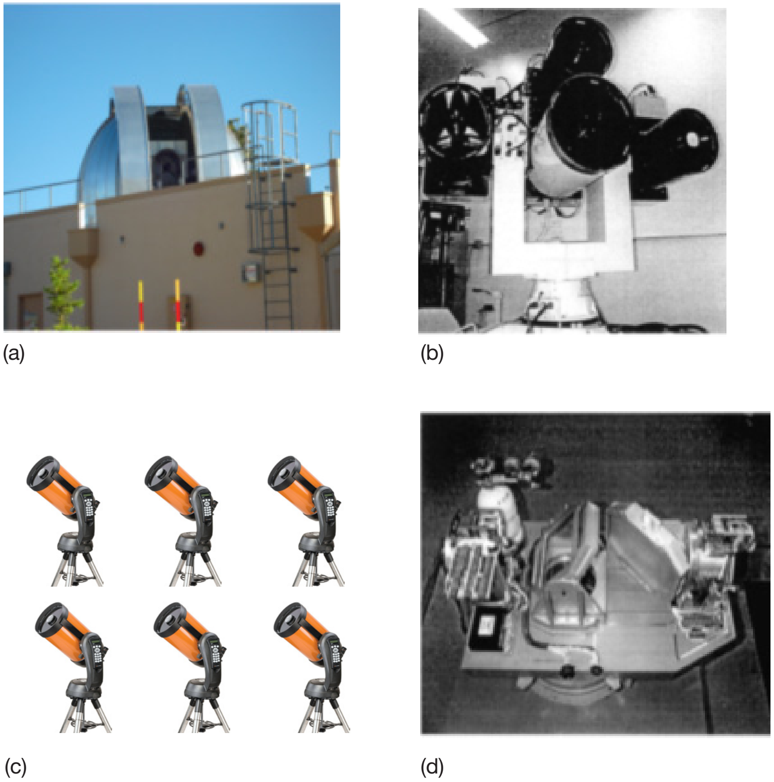

Figure 1. System types considered for uplink beacon transmitter: (a) single-aperture telescope; (b) individual transmitters on a single mount; (c) individual transmitters on separate gimbals; and (d) two-axis beam-director mirror (multiple beams may be uplinked with each mirror).

Though distributed-aperture systems have some advantages in redundancy and optics costs, they appear to be largely incapable of meeting the all-important pointing requirements. For telescope arrays to be cost effective, they need to have inexpensive mount systems, based on the economy of scale afforded by the amateur astronomy community. For purposes of cost discussion, an arbitrarily chosen value, X, will be used to identify relative expected costs among candidate systems. A survey finds that very good, precise amateur astronomy telescopes and mounts cost on the order of 0.03X to 0.1X, and can achieve all-sky blind-pointing accuracy of about 1 arcmin (291 μrad).[1] Unfortunately, this is more than an order of magnitude worse than our blind-pointing requirement, and essentially forces these types of systems out of the running.

It is possible to use a larger precision beam-steering flat in a hybrid approach, in which several beams are directed off of one of several beam-director apertures. In our example, in which 20 individual lasers are required to achieve 5 kW of beacon power, one might employ an array of five beam directors, each of which points four separate beams. To allow for four beams of 4-cm diameter, with edge-to-edge spacing of 10 cm, and to allow for the 1/cos(θ) spot footprint elongation as the beam director is pointed, the clear aperture of the optical flat must be approximately 40 cm in diameter. This can be accommodated with systems that cost in the range of 0.3X to 0.6X. This constitutes simply the pointing mechanism, so that when all of the beam-forming optics and pointing calibration optics are considered, the system costs grow to over 3X for implementing all 20 lasers on five steering flats.

A single-flat beam director was also considered, and would require a 1.1-m aperture to accommodate 19 beams, once the beam separation requirement and pointing elongation are considered. A similar type of system was designed for the U.S. Air Force approximately five years ago with a 0.75-m aperture.[2] This system was expected to point to sufficiently high accuracy, though their data obtained from similar systems could not directly verify it. This system was projected to cost approximately 4.7X, for a system smaller than our required size. Thus, this may be a viable system if a laser is used with enough power per beam such that only nine beams are required.

Another slight disadvantage to the use of beam-steering flats is the lack of ability to address the entire celestial hemisphere. When a fixed beam reflects from a fold flat, the projection of the beam onto the flat produces an elliptical footprint. In order to address almost the entire sky, the mirror would have to grow unreasonably large. Thus, using the mirror at angles of incidence beyond 50 deg becomes unproductive. For the applications envisioned here, in which the target is almost always within a few degrees of the ecliptic, it is reasonable to place the laser source in a fixed location to the south of the fold flat (for an uplink terminal sited in the northern hemisphere). In this case, the fold flat could easily direct the beam to any point within 20 deg or so of the ecliptic. However, pointing to points that are far to the north of the site, or to points far outside the ecliptic will be difficult, if not impossible. While this may only impact deep-space missions to other planets during the early cruise

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[1] These figures were arrived at by comparing the published costs and performance specifications of various high-end amateur telescopes online. Examples of the various systems considered were the ASA DDM85 high-precision mount, the Takahashi EM-400 Temma IIM high-precision mount, and the Meade LX200-ACF telescope.

[2] Dr. Robert Johnson and Starfire Optical Range telescope, personal communication, 2010.

phase of the projects, it would prevent the use of these ground systems for experiments with highly-inclined earth satellites.

By comparison, telescopes are well-known, high-reliability systems available as fully engineered systems from multiple manufacturers. Good, professional-grade telescopes often have mount systems with the required blind-pointing accuracy on the order of 10 to 15 μrad.[3,4] They can generally cover the entire sky, and because the telescope's entire aperture can be used to collect light from dim stars, they can generally build better mount models than the other systems discussed, further enhancing their ability to establish and maintain high-accuracy pointing.

Coudé telescopes direct the collected light into a controlled space called a coudé room, where it can interact with stationary instruments. These instruments are held in a controlled, dark, clean, thermally stable environment, which is a major advantage for an operational system. The telescope is the only portion that is exposed to the external environment, as shown in the 3.5-m Starfire Optical Range (SOR) telescope shown in Figure 2. These advantages result in telescopes routinely being used for satellite tracking and observation for many applications. The main drawback to this type of system is that the instruments are maintained stationary through a system that rotates the image of the pupil. Thus, there can be temporary periodic spider occultation of some beams unless a pupil rotator is implemented in the coudé optics.

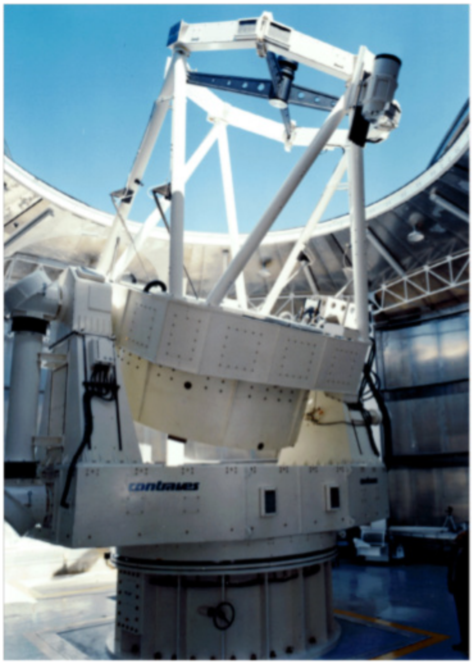

Figure 2. SOR Cassegrain telescope in a coudé configuration. The telescope is allowed to come to thermal equilibrium with the external environment, while instruments are held in a clean, controlled environment in the coudé room beneath the telescope.

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[3] Mr. Robert Thicksten, Site Manager of the Palomar Mountain Observatory, personal communication, 2005.

[4] Mr. Mark Kelly, DFM Engineering, personal communication, 2009.

A summary of the results of the trade study is shown in Table 2. A succinct description of each of the main requirements is called out in the leftmost columns of this table, and the general performance of each type of system is displayed for each requirement. These requirements are listed in order of importance from top to bottom. Green backgrounds indicate that the particular system meets the requirement or is in some other way advantageous. Yellow backgrounds indicate systems for which the requirement can probably be met with effort, or that the system is perhaps somewhat limited in this respect, but not fatally so. Red backgrounds indicate serious problems with meeting the requirements.

Table 2. Uplink beam-pointing system trade study considerations and results.

Parameter	Requirement	Coudé Telescope	Nasmyth Telescope	Beam Director	Multi-mount	Array
Pointing, μrad-3 σ	16	16	16	20	150	150
Near-Sun Operations, 5 deg	Minimize thermal effects	Demonstrated	Can be designed	Even solar load on optics	Solar rejection filter	Solar rejection filter
Required Aperture for 9 beams, m	Minimize	0.45	0.45	0.7	0.06 × 9	0.06 × 9
Divergence Verification	Simplify	Focal, target board & sat.	Focal, target board & sat.	Target board & sat.	Target board & sat.	Target board & sat.
Co-alignment Verification	Simplify	Focal, target board & sat.	Focal, target board & sat.	Target board & sat.	Target board & sat.	Satellite
Beam Delivery	Simplify	Fixed focal point	Cooling & power to focus	Fixed-beam system	Fiber delivery	Fiber delivery
Complexity	Simplify	Single system	Single system	Single system	Multiple systems	Multiple systems
Fault Tolerance	High tolerance	Single-point failures	Single-point failures	Single-point failures	Single-point failures	High redundancy
Sky Coverage, π sr	2	2	2	1 (ecliptic)	2	2

The mostly-green columns of the telescope systems considered on the lefthand side of Table 2 demonstrate the advantages of these systems, and reasonably account for their popularity in the satellite acquisition and tracking community. The large beam director comes close to the telescopes in its ability to achieve the requirements, its main drawback being the limited ability to verify beam divergence and co-alignment of the beams on the sky. The other two systems are severely limited by their ability to point accurately enough using inexpensive optical mounts. It should be noted that the values shown here are slightly more optimistic (in pointing accuracy and cost) than those recently shown by MIT Lincoln Laboratory at the Lunar Laser Communications Demonstration (LLCD) critical design review (CDR).[5]

IV. GLT Transmitter Point Design

JPL has a coudé telescope at the Table Mountain Facility — the Optical Communications Telescope Laboratory (OCTL) — designed for and dedicated to optical communications ex-

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[5] LLCD CDR, page 7-DAF 32, 2009.

periments. The telescope is a 1-m Cassegrain telescope with an F/1.5 primary mirror and an effective focal length of 75.8 m. Light collected by the telescope is reflected into the coudé path by the tertiary mirror, after which it is directed by four additional mirrors to the coudé room below the telescope. The final mirror, M7, is on a high-precision rotation platform to allow the telescope beam to be directed to any of four optical tables to accommodate multiple users and multiple experiments with switch-over times of a few seconds.

This telescope has already demonstrated the required pointing, though it is expected that it will improve beyond that with the implementation of certain upgrades recently approved. The facility and operating crew have already demonstrated high-precision beam control through multiple narrow-beam tracking demonstrations in which 30-μrad beams have been consistently bounced off fast-moving low-Earth orbiting (LEO) satellites. Recently, the OCTL was used to successfully perform bidirectional optical communications with the Laser Utilizing Communications Equipment (LUCE) terminal on the Japanese LEO Optical Inter-orbit Communications Engineering Test Satellite (OICETS) [4,5].

There are several additional advantages to the use of the OCTL facility as the beam director, which may not be apparent initially, but will certainly reduce the operating costs and risks associated with the complete uplink facility. Not least among these is the excellent weather, accessibility, and availability of the site on a year-round basis. The proximity of the site to JPL also allows for convenient access and interaction with personnel, facilities, and laboratories that cannot be positioned at the site for long periods of time. Another advantage is that the facility is located in a secure, fenced-off, government-controlled facility that is continuously staffed. This is absolutely essential for an expensive facility projecting multikilowatt beams into the sky. Another tier of security is afforded by the existing aircraft avoidance system developed for and extensively tested at OCTL [6]. Although the 1030-nm uplink beam is not visible, it is still far from eye-safe, requiring a sophisticated and reliable aircraft detection system interlocked with the laser system. OCTL's system employs a pair of thermal infrared imagers for the acquisition of both small, slower aircraft and larger, faster-moving aircraft. A sophisticated algorithm is used to prevent lasing in the case of clouds near the line of sight, from which an aircraft might suddenly emerge and encounter the beam. Finally, the entire system is backed up by a scanning radar. Any of these systems can trigger a shutter to prevent lasing until an all-clear signal is received from each of the observation systems. Testing has shown the system very reliably detects aircraft, determines whether there is a threat of intersecting the beam, and shuts the beam down until the threat is gone, all with almost no false alarms to unnecessarily interrupt the beam.

An initial conceptual design for the uplink system has been developed, relying on commercial off-the-shelf optics to generate the required beams. An example of the expected placement of the 20 beams on the telescope aperture, meeting the requirements for beam spacing levied by the systems engineering team is shown in Figure 3. Each of the red dots shows the placement of a 4-cm-diameter (to $1/e^2$ intensity) beam on the blue 1-m aperture of OCTL. The dark circle in the center is the secondary mirror obscuration. All of the beams fit well, and afford plenty of clearance to prevent diffraction from the edges of the aperture. These beam locations will be perturbed somewhat to assure that only one beam at a time is significantly obscured by the telescope spider at any time during operation.

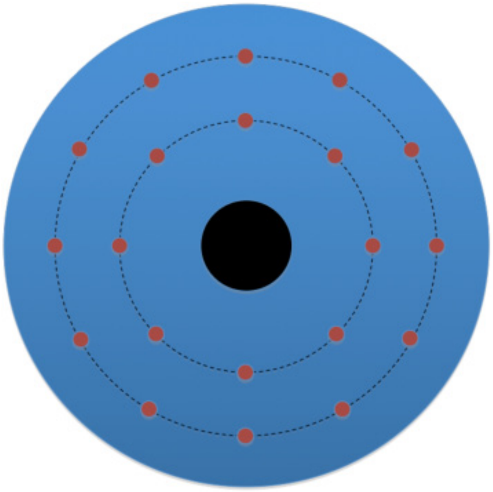

Figure 3. Beam sizes and locations on 1-m OCTL telescope.

Figure 4 shows the $1/e^2$ beam radius for the beam propagating through the entire coudé optical system and out the telescope. The optics are initially designed to generate a 38-μrad beam for an input Gaussian beam, which is expected to generate a 40-μrad footprint on the sky for a real beam with an M^2 of 1.05. These values will be refined once the laser is completed and more accurate measurements of the beam quality are available.

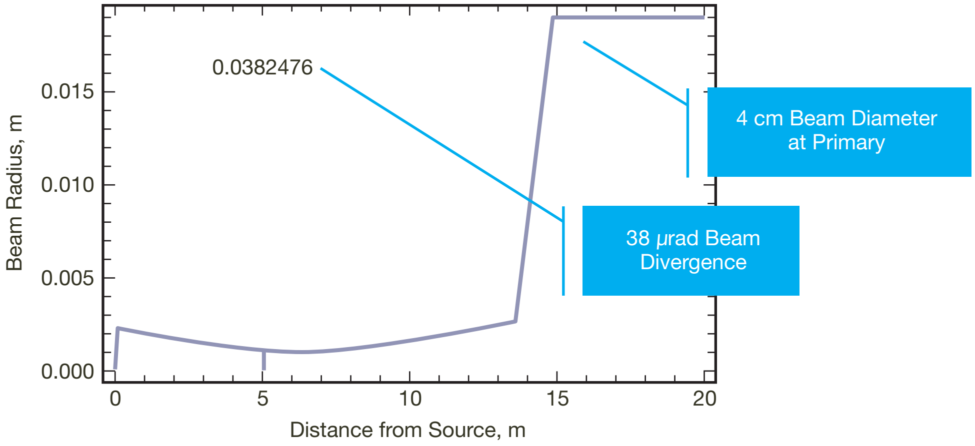

Figure 4. Radius of an individual beam as it makes its way through the OCTL telescope.

The 20 beams will be combined using a single lens near a pupil plane in the coudé room to cause the beams to overlap at the nominal telescope focus. Each of the combined beams continues to concentrate, coming to a waist in the telescope coudé tube between M7 and M6. This completely enclosed region is a conveniently safe location to form the beam focus. As shown in Table 3, initial calculations indicate that neither the peak power nor the average power density from the lasers come within 20 dB of the damage threshold for the mirror coatings to be used.

Table 3. Power densities at elements through the OCTL telescope.

Optical Element	Power Density, kW/cm^2	Peak Power Density, kW/cm^2	Comments
Collimating Lens	3.1	199	
Beam Overlap	$5.6 \times 20 = 112$	7168	Atmospheric breakdown about 3×10^5 times higher than peak
M7	14.3	916	Requires special coating and airflow
M6	10.3	660	Requires special coating
M5	6.6	423	Requires special coating
M4	4.1	263	Requires special coating
Tertiary	2.9	186	Recoat with protected silver, 1 MW/cm^2
Secondary	2.3	148	Recoat with protected silver, 1 MW/cm^2
Primary	0.044	2.82	Recoat with protected silver, 1 MW/cm^2

V. GLT Laser Trades

The other aspect of the GLT to benefit from trade studies involves selection of the laser itself. An initial survey of available laser technology, sorted by various candidate wavelengths was performed with the systems engineering team [3]. The selection of a particular laser wavelength involves system interactions such as diffraction spread, atmospheric scattering and absorption, atmospheric turbulence perturbations to the transmitted beam, and the detectivity of flight system detectors. The laser team inputs to this general top-level trade study are shown in Table 4.

Table 4. Considerations and potential of current laser technologies at various wavelengths.

	Wavelength, nm						
	532	775	1030	1030	1064	1550	2130
Laser Type	Doubled 1064 nm	Doubled 1550 nm	Planar Waveguide	Fiber	Fiber	Fiber	Fiber
Single-Mode Average Power, W	100	50	>4000	250	200	100	800
Number of Lasers for 5 kW	50	100	2	20	25	50	7
Peak/Average	100	100	2500	80	100	100	300
Linewidth, nm	>1	>1	0.5	0.3	>1	>1	>1
Average PRF, kHz	2–1000	10–100,000	4–10,000	4–1000	2–1000	10–100,000	10–500
Extinction Ratio, dB	20	20	20	20	20	20	20
TRL	4	4	4	4	5	4	3
Cost	Low	Low	High	Mod.	Low	Low	Mod.

The systems engineering trade study identified the 1030-nm wavelength as the lowest risk option, and levied an initial set of Level III requirements shown in Table 5 for the laser transmitter. It is also worth noting that some systems have only been demonstrated in continuous wave (CW) or for a limited pulse repetition frequency (PRF) range. The 1030-nm fiber laser has demonstrated CW power at about 250 W, single-mode. Some development

Table 5. Requirements for 1030-nm projected laser beacon.

Requirement	Value	Comment
Average Output Power, P_{avg}	5 kW	≥9 beams link budget
Max Peak Power, P_p	370 kW	Derived requirement
Max Pulse Repetition Rate, PRF	500 kHz	Support data rate up to 292 kbps
Minimum PRF	4 kHz	Derived from signaling
Wavelength, λ_{CL}	1030 nm	Nominal
Linewidth, $\Delta\lambda$	0.5 nm	From Interface Control Document
Wavelength Tunability	±0.1 nm	—
Pulsewidth, τ	128 ns	Match slot width
Beam Quality, M^2	<1.2	Concentrates beam
Polarization	Random	Reduce complexity
Pulse Extinction Ratio	20 dB	Broadband
Uplink Modulation	PPM-2 Outer, PPM-16 Inner	Nested with guard slots

would be required to combine and operate all lasers in a cohesive system, and to build an amplifier to support the higher rate PRF in a master oscillator power amplifier (MOPA) configuration, similar to what has been demonstrated for 1060-nm fiber-based MOPA lasers. Also, the indicated extinction ratio is a broadband value, meaning that the extinction is measured as just optical power over all the spectral range. Employing a 2-nm spectral filter on the FLT allows us to meet the 30-dB end-to-end extinction ratio requirement of the link budget.

To identify which of the two candidate laser systems at 1030 nm resulted in the lowest cost/performance ratio, a more focused trade study was conducted. The principal drawback of the fiber amplifier–based system was the limited power each individual laser can produce. Since the available power in a single-mode fiber amplifier system has been demonstrated at about 250 W, 20 lasers are required to achieve 5 kW. Though this is likely near the practical limit of the number of beams that can be transmitted out of our candidate 1-m telescope, it is nevertheless a viable option. Some development would be required to properly combine and synchronize the groups of pulses, but the 128-ns pulse length is sufficiently long that this is not expected to be a concern.

Some backup concepts were also investigated to obtain high output power in a single-mode source. Photonic crystal fiber technology or "holey" fibers have demonstrated peak powers up to 1 MW [7] while maintaining good beam quality. Here, the fiber mode is spread over a larger fiber core by using multiple air-filled holes that run through the fiber, producing an effective large numerical aperture. Splicing and pump combining into these fibers requires some novel schemes that are currently being pursued [8] to bring this technology to maturity in a robust system.

Table 6 qualitatively compares the two candidate laser concepts, with darker shades representing higher risk or higher cost. Both systems are primarily amplifiers, so they will require the development of a high-rate seed-laser source. Although that is not a significant risk and

Table 6. Laser architecture trade summary.

Trade		Power	PRF	Beam Quality	Develop- ment	Complexity	Implemen- tation Costs
Laser System	Fiber Amplifier	▒			░		$X
	Planar Waveguide				░	▒	$5X

utilizes readily available commercial fiber technology, the integration of the high-rate seed source with both the fiber-based amplifier and planar waveguide (PWG) amplifier would require some technology development to ensure that all the performance requirements could be met. The relative implementation costs are based on vendor rough order of magnitude (ROM) estimates.

Fiber amplifiers are primarily limited in their peak power output, so following this route would require up to 20 units to meet the 5-kW average power requirement. There is relatively little risk in following this path because the lasers have been demonstrated at these powers and modulation rates, and versions of these amplifiers are commercially available with similar performance characteristics. As mentioned above, the modulation would be supplied by a fiber-based master oscillator source for both architectures. Although a single planar waveguide amplifier concept has demonstrated high powers at these wavelengths, the system is based on bulk optics with significant complexity and implementation cost. In contrast to fiber-based solutions, there is a very limited vendor database to undertake the PWG development. Extending commercial fiber-based amplifiers to support the high peak powers would be a significantly less costly approach with lower risk. Moreover, if the detector baseline does not have to account for Si-based devices, the uplink wavelength could be shifted to 1064 nm where high-peak-power fiber lasers are more readily available.

VI. GLT Conceptual Point Design

The conceptual design was based on a CW fiber laser that has demonstrated 242 W of output power at 1030 nm with subnanometer full width at half maximum (FWHM) linewidth [9] and single-mode output from a large-mode-area (LMA) Yb-doped fiber with 20-μm core and 400-μm cladding diameter. High PRF requires a pulsed-fiber master oscillator power amplifier (MOPA) design and these have demonstrated multikilowatt peak powers at 1064 nm.[6] The conceptual design leverages both of these technologies to deliver the required performance. Given the technology development of fiber lasers being undertaken for the material processing industry, it is anticipated that the average powers could be scaled by a factor of at least 2 to 3 in the next few years, which would match the timeline for when the systems would need to be available given current funding predictions.

To support a high data rate for near-range and low-rate modulation for far-range acquisition and tracking, the signaling involved a nested modulation scheme [3]. An outer modu-

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[6] S. Gupta, Fibertek, personal communication, 2010.

lation on the order of kilohertz PRFs enveloped a high-rate modulation up to hundreds of kilohertz. This is shown in Figure 5.

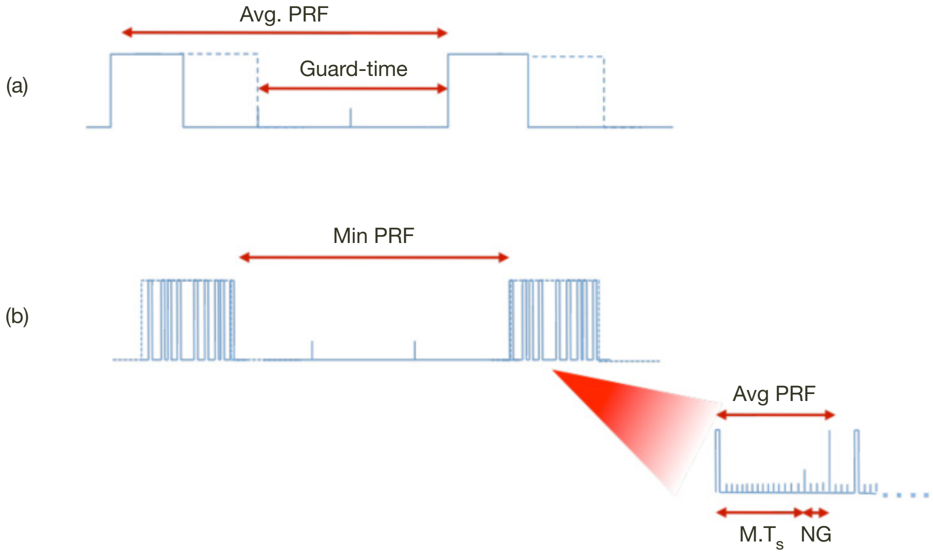

Figure 5. Nested modulation scheme showing (a) low-rate modulate with 2-slot guard-time enveloping a high-rate signal shown in (b) with a 4-slot guard-time.

The low-rate modulation envelops the high-rate modulation in a PPM-2 format with 100 percent guard slot time. The overall pulse envelope is 82 μs long with PRF from 2 to 4 kHz. Data commanding occurs with 128-ns pulses in PPM-16 with a 25 percent guard-time to give an average PRF from 4 to 500 kHz. The latter requirement is limited by the laser power-handling capability.

VII. Conclusion

Trade studies were performed to establish the most capable and cost-effective designs for a laser beacon transmitter for the DOT project. These studies concluded that, based primarily on cost and risk, implementation of a standard telescope-based transmitter design was most advantageous. A point design based on the 1-m OCTL telescope was conducted, demonstrating that this system is expected to meet all of the key and driving requirements.

Trade studies were simultaneously conducted to determine the type of laser best suited for implementation as the laser beacon. Two primary candidate laser systems resulted from this study: multiple lower-power fiber-based laser systems, and single or multiple high-power planar waveguide laser systems. Neither laser system has yet been demonstrated to meet all of the pulse requirements, but similar lasers in both configurations have been demonstrated. Development of the full laser system is not considered high risk in either category. Based on the vendor’s rough estimates, the fiber-based system currently appears to be significantly less costly to implement.

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