MLCD: Overview of NASA's Mars Laser Communications Demonstration System

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ABSTRACT

NASA is presently overseeing a project to create the world's first free-space laser communications system that can be operated over a range much larger than the near-earth ranges that have been demonstrated to date. To be flown on the Mars Telecom Orbiter, planned for launch by NASA in 2009, it will demonstrate high-rate laser communications from Mars orbit to one of several planned earth receiver sites. To support 1-10 Mbps over the up to 400 million kilometer link, the system will make use of a high peak-power doped-fiber transmitter, a hybrid pointing and tracking system, high efficiency modulation and coding techniques, photon-counting detectors, and novel optical collector architectures that can point near the sun. The project is being undertaken by the NASA Goddard Space Flight Center (GSFC), MIT Lincoln Laboratory (MIT/LL,) and the Jet Propulsion Laboratory (JPL.)

1. INTRODUCTION

In the near future the National Aeronautics and Space Administration anticipates a significant increase in demand for long-haul communications services from deep space to Earth. Distances will range from 0.1 to 40 AU (1 AU = 149.6 million kilometers,) with data rate requirements in the 1's to 1000's of Mbits/second. The near term demand is driven by NASA's Space Science Enterprise, which wishes to deploy more capable instruments onboard spacecraft and to increase the number of deep space missions. The long-term demand is driven by missions with extreme communications challenges such as very high data rates from the outer planets, support for sub-surface exploration, or support for NASA's Human Exploration and Development of Space Enterprise beyond Earth orbit.

NASA's Goddard Space Flight Center, the Jet Propulsion Laboratory, and MIT Lincoln Laboratory are working together to demonstrate optical communications on the 2009 Mars Telecom Orbiter (MTO). The Mars Laser Communications Demonstration Project (MLCD) will demonstrate one possible solution to meeting NASA's future long-haul communication needs. Near-Earth lasercom systems have already been

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demonstrated (GeoLITE and GOLD in the U.S. and SILEX in Europe), and the technology has the potential to revolutionize deep space communications. Lasercom will enable bandwidth-hungry instruments, such as hyper-spectral imagers, synthetic aperture radar (SAR) and instruments with high definition in spectral, spatial or temporal modes to be used in deep space exploration. It is even envisioned that high definition video will be used to support future manned missions to the planets.

The goal of the Mars Laser Communications Demonstration Project is to provide much needed engineering insight towards these goals by the end of this decade.

2. MLCD OVERVIEW

This past year, NASA sponsored the Mars Lasercom Study at MIT/LL ([1], [2]) to investigate deep space high-rate systems in general, to develop a demonstration concept for Mars, and to propose some strawman terminal designs. Aided by the deep-space knowledge base from the JPL team (see, e.g., [3], among many others) the study concluded that rates of between 10 and 100 Mbps from Mars to Earth, depending on the instantaneous distance and atmospheric conditions, are feasible with today's technology.

Based on these studies, as well as on the on-air experience of MIT/LL ([4]) and JPL ([5], [9]) NASA decided to proceed with a demonstration of the key concepts. To keep the risks and costs for a preliminary demonstration lower, however, the system is being designed to support between 1 and 10 Mbps, with a goal of several times that.

As directed by the Office of Space Science at NASA HQ, the MLCD Project is being run by the NASA GSFC under the Mars Exploration Program Offices at NASA HQ and JPL. The Mars Telecom Orbiter is being developed by JPL. The Flight Terminal for MLCD is being developed by MIT/LL, the Ground Terminals are being developed by JPL, and JPL will run the operations. JPL will lead the Principal Investigator Team, and MIT/LL will lead the System Engineering Team, although both teams include members from GSFC, MIT/LL, and JPL.

The scheduled launch of MTO is in the fall of 2009. The main function of MTO is to buffer and then relay data from near-Mars science-gathering missions. The present concept for MTO includes a 3-meter dish for both X-band and Ka-band communications. (See Figure 1.) Within the first few months after launch, during the cruise to Mars, the MLCD duplex lasercom link will be exercised for early system checkout and preparation for Mars orbit. Mars orbit insertion is scheduled to occur in early September 2010. Shortly after MTO has been established in its 6-hour Martian orbit, the lasercom link will be exercised. Demonstrations are planned for most passes over the Earth ground sites for an entire Earth year, with follow-on demonstrations a possibility.

The basic objectives and goals of MLCD include:

- Demonstration of a Mars to Earth downlink of 10-30 Mbps when conditions are favorable, and at least 1 Mbps in most conditions

- Transmission of both test and science data on the downlink
- Demonstration of an Earth to Mars uplink of at least 10 bps in most conditions
- Measurement and characterization of system performance in many Earth conditions including day and night, short and long range, as close to the sun as 3° (Sun-Earth-Probe angle, or SEP,) and various cloud-free weather conditions.

3. THE COMMUNICATIONS SYSTEM

The planet orbits are shown in Figure 2. It can be seen that the Mars to Earth range (shown in Figure 3) varies by 11 dB over the orbits. It can also be seen that the SEP angle (Figure 4) is less than 90° for most of the year, meaning that Mars is in the daytime Earth sky more of the time than in the nighttime sky. Furthermore, the most-stressing daytime case, for SEP near 0, occurs when the range is maximum. Thus, since there is a penalty in communications performance when background light levels are high (see, eg, [1],) we find that the most stressing part of the demonstration is to achieve the minimum 1 Mbps at this orbit position. We will see, in addition, that operating Earth telescopes at such a small SEP angle is also stressing. From Figure 4 we can see that, also at this time in the orbit, the small Sun-Probe-Earth angle (SPE) makes the Flight Terminal's near-sun viewing also a stressing parameter. Goals for the mission are to operate as close as 3° to the sun.

In Figures 5 and 6, we show the Point-Ahead and Doppler requirements for the mission. The Flight Terminal telescope is presently planned to be 30.5 cm in diameter, and the downlink wavelength is presently selected to be 1.06 μm, although both of these may change as the system design matures. With these parameters, the diffraction-limited beamwidth is 3.5 μrad. We can see that the Point-Ahead varies by well over 100 beamwidths, with orbital variations greater than 7 beamwidths once in the Martian orbit. These will need to be accounted for to a small fraction of the beamwidth. The Doppler shift for the whole mission covers over 30 Ghz, and so a proposed 1 Å width receiver filter, corresponding to 26.7 Ghz, will need to be tuned.

As discussed in [1], the communications system will used a pulsed format, most likely Pulse Position Modulation (PPM) at a high alphabet size, and thus, a low duty cycle. To achieve short (1-5 nsec) pulses, high average power (5 Watts,) and high peak power (>300 Watts,) with a path toward future systems demanding even more stressing parameters, the MLCD Lasercom Terminal (MLT) is planning to use a doped-fiber amplifier in a master oscillator power amplifier (MOPA) configuration.

A commercially available low-power distributed feedback (DFB) fiber laser based on Ytterbium-doped fiber is envisioned as the master laser. A $LiNbO_3$ Mach-Zehnder modulator, essentially the same as that used throughout the telecom industry, will provide the pulse modulation, with a tandem arrangement to achieve the high extinction ratio required by the low-duty cycle signal. Yb-doped power amplifiers of 5-20 Watts are available commercially, with peak power performance improving. Amplifiers have been acquired demonstrating 300-500 W peak powers at 5 W average power, with wallplug efficiency of 15%. It is expected that such a system could support 64-ary PPM, or perhaps as high as 256-ary.

Although every component to be used in space needs to be space-qualified and carefully packaged, it is felt that the fiber-based system will be straightforward to qualify, due to its insensitivity to most vibrations. Furthermore, it leads to a highly flexible modularity ([6],) useful for packaging, integration, and testing.

4. THE MLCD LASERCOM TERMINAL

A preliminary configuration for the MLT is shown in Figure 7. To keep the weight low, no larger than a 30.5-centimeter telescope is envisioned. It will use lightweight ULE mirrors with Invar metering struts. This telescope will be used for both transmit and receive. The entire optical module will be supported by a set of vibration isolators. Based on both springs and internal fluidics, their purpose is to lower the large vibration loads during launch, and to reject high-frequency spacecraft micromotions in space.

As is well known in near-earth lasercom systems, pointing, acquisition, and tracking are crucial for utilizing the extremely high gain possible with a diffraction-limited telescope. As mentioned earlier, the diffraction-limited beamwidth of the MLT telescope is about 3.5 μrad, although the transmit beam will be slightly wider due to the Gaussian profile presented by the fiber transmitter. In order to keep pointing losses small, the entire pointing error, from both DC pointing offsets and dynamic unrejected jitter, must be kept below about 0.1 beamwidth. Even with the vibration isolation struts, it is expected (thanks to measurements in a number of earlier satellites and systems) that the residual mechanical jitter, especially at low and medium frequencies, needs to be actively compensated. This is traditionally performed with a Fast Steering Mirror (FSM.) By using an incoming signal from an inertial source (such as the other terminal,) a servo system can create a pointing error signal that feeds the FSM.

As discussed in [1], there are a number of possibilities for this inertial source in deep space. In a symmetric duplex system, one can use the incoming communications signal itself. However, as we will see in the next section, transmitting a high-power beam up through and out of the atmosphere is difficult, because of turbulence. Uplink transmission can be as much as several 10's of dBs disadvantaged with respect to propagation in a vacuum channel. Thus, it would require on the order of 1 KW or more to be transmitted in order to provide enough light at the MLT at Mars to perform tracking out to several hundred hertz.

For this reason, the MLT will use a hybrid approach to pointing and tracking. It will depend on an uplink beacon for pointing, but only with approximately 1-second updates. All the medium frequencies for tracking will use as their reference an on-board Inertial Reference Unit called the Magneto-hydrodynamic stabilized reference Inertial Reference Unit (MIRU.) Based on the Inertial Pseudo Star Reference Unit (IPSRU, [8]) developed some years ago by Draper Laboratory for the Air Force Phillips Laboratory, the MIRU was recently developed by Applied Technology Associates of Albuquerque, NM under a Phase II SBIR for NASA. The device consists of a small, self-stabilizing platform from which is transmitted a low-power laser. The platform is capable enough to reject the remaining mechanical motions in the MLT optical module. Thus, the device provides a stable optical reference. By using a simple retro-reflector outside the telescope, it can be tracked in a high-speed quadrant detector. Since the stabilized beam then passes through all the MLT receive optics, it provides all the benefits of an on-board inertial reference, but actually senses changes in the optical path and not only at the mounting positions of the reference. The monitoring detector generates the error signal that is fed to the FSM.

With the incoming and outgoing beam paths now stabilized, it remains to point them correctly. The uplink beacon, now stabilized by the MIRU/FSM system, is viewed on a focal plane array. As shown in Figure 8, a small amount of light from the transmitter is picked off and fed, via a retro-reflector, to the same array. With a detailed off-line calculation of the desired Point-Ahead, and a careful calibration of the array itself, the exact angular relationship between the transmit and receive beams can be measured. By placing another steering mirror, the Point Ahead Mirror, in the transmit path, this point-ahead angle can be varied until it is correct.

Thus, the hybrid tracking system uses vibration isolators at high frequencies, the inertially-stabilized laser at medium frequencies, and the uplink beacon at low frequencies.

By placing a mirror on the inside of the telescope cover (to be opened after launch) and by including a flip-in mirror in the outgoing path, the MLT is provided with a number of Built-In Test features. These will make spacecraft integration and testing much simpler, and post-launch checkout much more capable. The mirrors allow the alignment of all steering mirrors and beam paths to be exercised and calibrated with the cover closed. The MIRU also includes a laser that, when provided with modulation, can be used to check the uplink beacon (and comm) receiver array as well as the received signal processors. In fact, it is felt that, with very few exceptions, the entire MLT can be exercised and monitored without opening the cover. As mentioned above, this allows integration and test to proceed without the need for a complex test set and without the problems associated with live beams propagating with people nearby.

5. THE GROUND TERMINALS

As discussed in [1], if the Earth receiver cannot be placed in space or in a high-flying balloon, then it must contend with the effects of turbulence. The simplest means for dealing with this is to open up the field of view to capture the blurred signal. This leads to a great increase in sky background captured by the detector. Increasing the size of the collection aperture can make up for this loss in efficiency. For our transmitter and data rate needs, this approach requires a collector with effective aperture between 3 and 5 meters in diameter.

In [1] it was discussed that inexpensive custom collector options include photon buckets and arrays. However, an existing telescope of adequate size is a highly cost-effective alternative for a demonstration. Thus, MLCD is planning to use both a large telescope – the famous 5-meter Hale Telescope at Mt. Palomar in California – and a custom telescope array based on the LDORA concept ([8].)

At Palomar, where arrangements are being made for extended usage of the facility by MLCD, an Avalanche Photo Diode (APD) receiver will be installed. With ongoing developments being pursued by the program, it is planned that a photon-counting capability with low noise (10 Khz) and high quantum efficiency (0.5) will be available by the time of launch. As a fall-back, there are already a number of presently-available APDs with communications performance only a few dB lower than the planned device.

Pointing an existing large telescope near the sun is a difficult task. In addition to extra background light scattered off the primary into the field of view, there is the larger problem of the sun's image being focused onto the telescope's structure. A study has calculated that over 1 KW of power would be focused onto the Hale Telescope structure without some means being taken.

To this end, a solar filter is being proposed to cover the large aperture. Either a mosaic of glass-based filters, or a coated polymer membrane filter will be used. Analysis predicts that such a filter could cut the 1 KW down to 20 Watts or so, well within the safety limits of the structure. With this alteration, the plan is to use Palomar as an MLCD receiver as close as 3° from the sun. With such performance, the MLCD link would suffer an outage of only about 25 days.

The beacon uplink, which will include low rate modulation to carry a few 10s of bits per second, will be generated by a 100-W-class Nd:YAG laser at the 1-meter Optical Communications Telescope Laboratory (OCTL) located at JPL's Table Mountain Facility. The optical beam will be sent through multiple smaller subapertures to help defeat the dynamic effects of turbulence.

The second ground terminal will be an array of small telescopes. As described in [8], by incorporating a small array of Geiger-mode photon-counting APDs behind each telescope, and carefully synchronizing their measurements, a scalable, flexible virtual aperture can be constructed. Since the Geiger-mode outputs are essentially digital, a digital network is used to collect the various measurements. Lincoln is presently developing custom readout integrated circuits to optimize the APD array performance.

The present plan is to build 16 telescopes, each of 0.8 meter diameter, with a gimbal for each pair. The design will be first developed by MIT/LL as a 4 telescope pathfinder, to be called the Link Development and Evaluation System (LDES) and to be mounted on a mobile platform, shown in Figure 9. It will also include an array of small telescopes for transmitting the uplink beacon laser.

The concept will be enlarged and made operational by JPL, who will fill out the larger array, and site it far enough away from Palomar that both receivers will not fall in the same downlink beam footprint, which ranges from 350 to 1250 kilometers. With this placement, a realistic ground-site-to-ground-site handover will be demonstrated. This would be required by any future operational ground-based global optical receiving system.

6. DEMONSTRATION

The system has been sized to achieve 1 Mbps with 3-5 dB of margin at the maximum range and in nominal atmospheric conditions (See [2] for a description of such conditions.) It is felt that unplanned link re-optimization, to deal with the varying atmospheric conditions, can be done on times scales of a few hours via command-based reconfiguration. Since uplink MLT configuration commands can also be carried on the low-rate optical uplink, the reconfiguration time can potentially be even shorter, perhaps as short as just the round-trip time, which varies from 11 to 40 minutes.

As the range gets shorter, and as the MLT stays longer and longer in the night sky, analyses predict that well over 25-40 Mbps will be achievable, even including 3 dB or more of margin. At such rates, the onboard buffer can potentially be read out well over an order of magnitude faster than the present RF system. The lasercom downlink will be filled with a combination of real buffered science data, MLT health and performance telemetry, and test patterns.

The ground sites will be instrumented with monitors of weather and turbulence conditions, so that link quality can be correlated with these conditions to validate performance models.

The demonstration is presently planned to last approximately one Earth year starting at orbit insertion in September, 2010.

7. SUMMARY

An exciting new era in deep space communications will be initiated by the Mars Lasercom Communications Demonstration, to be launched in 2009 on the Mars Telecom Orbiter. With the flight terminal being built by MIT Lincoln Laboratory and the ground terminals being built and operated by JPL, the NASA-run program hopes to gain knowledge and experience useful for designing, procuring, and operating cost-effective future deep space optical communication systems. Such systems are predicted to be able to provide the 1-3 orders of magnitude higher data rates required by future science and exploration missions.

ACKNOWLEDGEMENTS

Dedicated teams at MIT/LL and JPL have performed this preliminary engineering for MLCD, and a tireless group at NASA Goddard has provided program management. In addition, the JPL MTO team has given important inputs to the overall concept. The authors wish to acknowledge all of these contributions.

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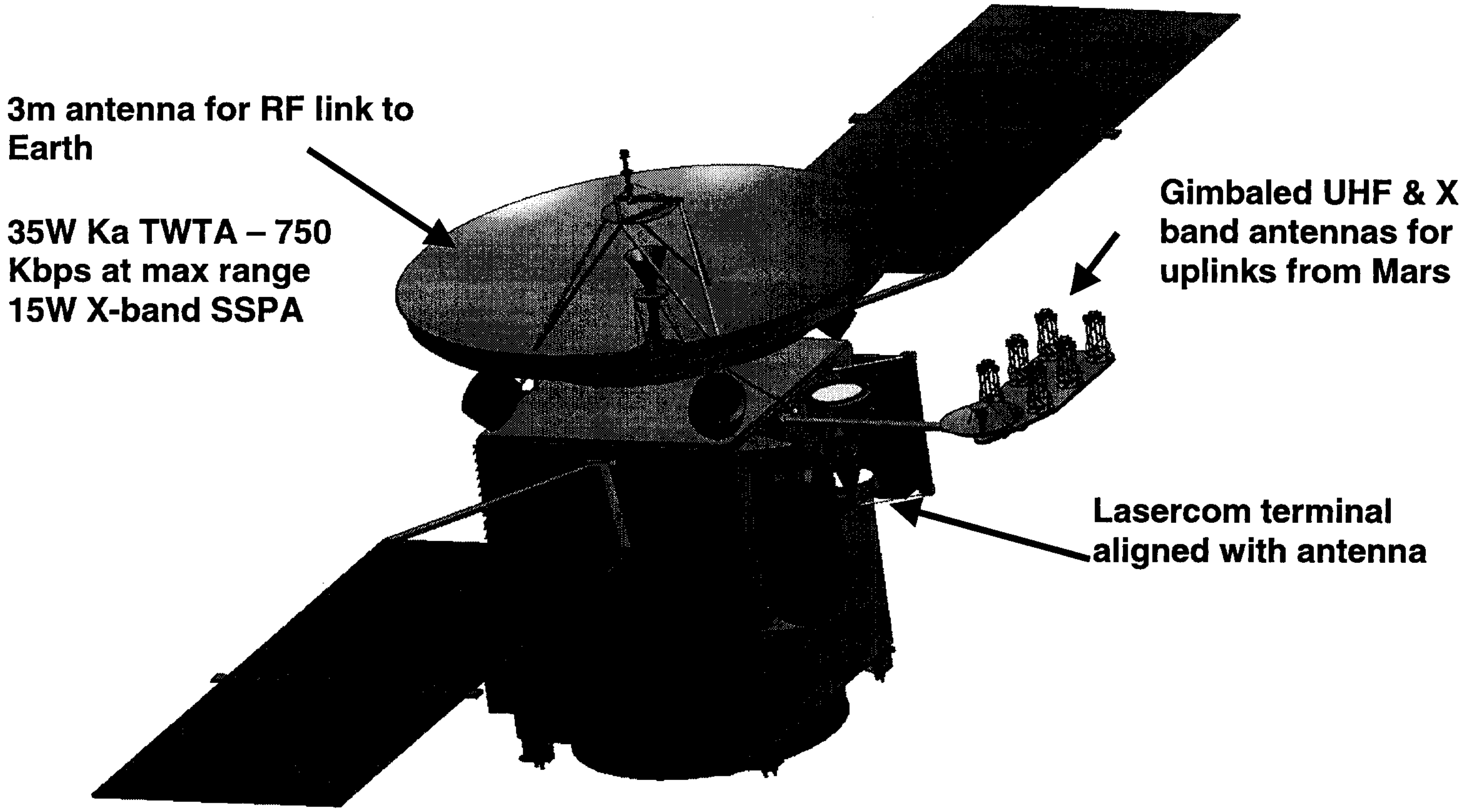

Figure 1
Mars Telecom Orbiter configuration

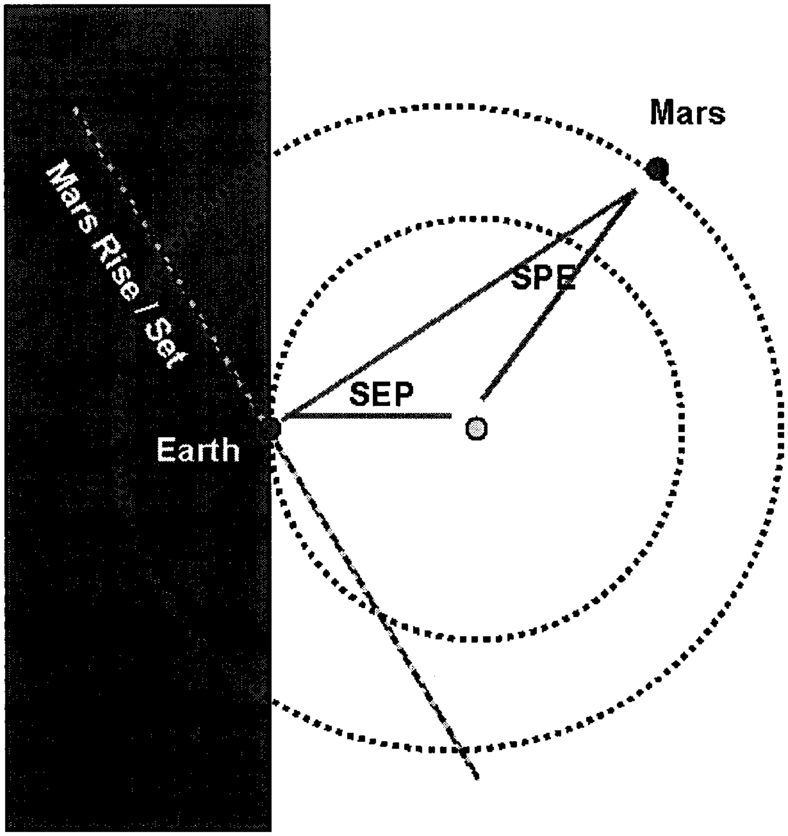

Figure 2
The geometry of the mission.

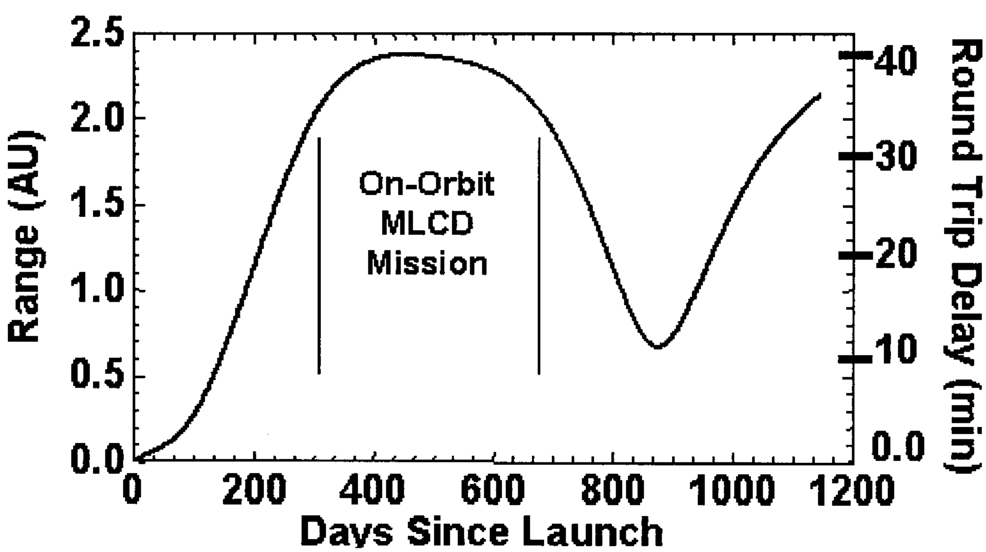

Figure 3
MLCD range.

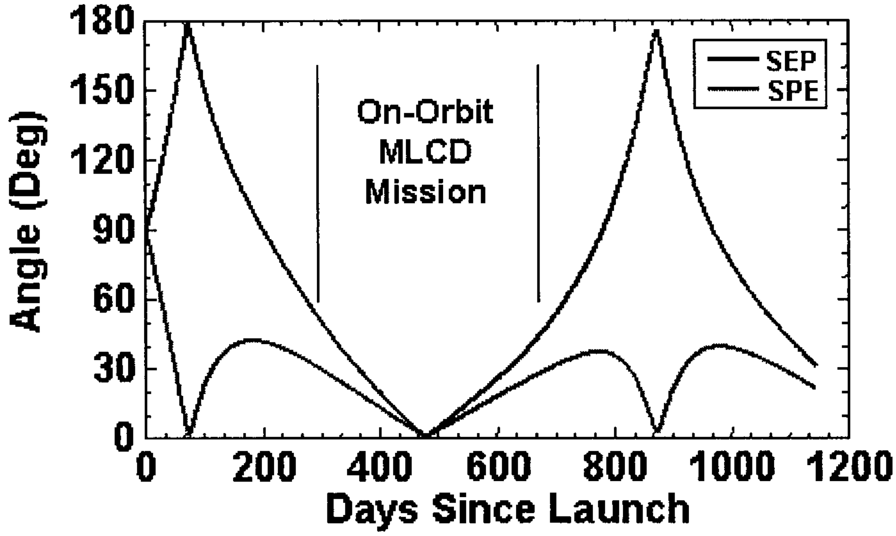

Figure 4
Sun angles: Sun-Earth-Probe and Sun-Probe-Earth.

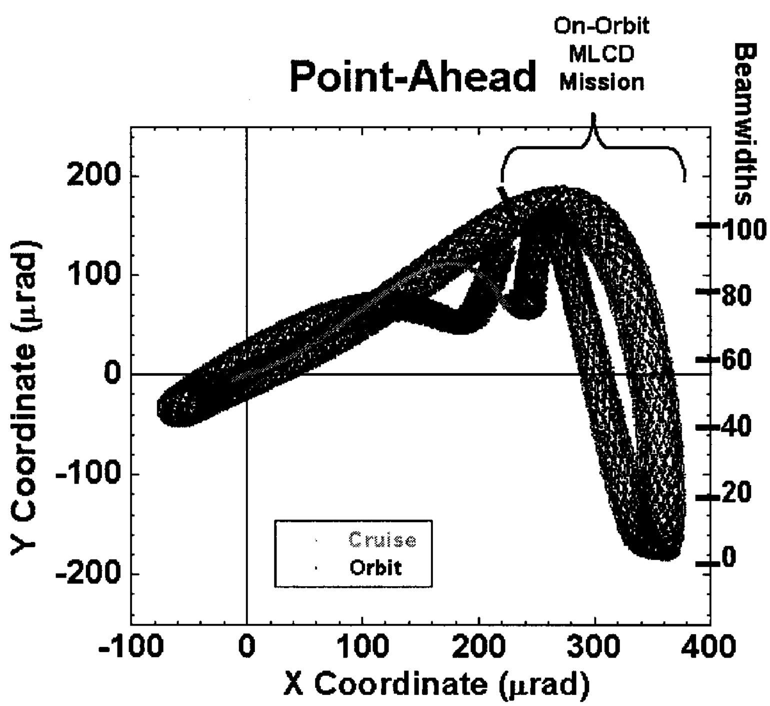

Figure 5
Point-ahead, with respect to an arbitrary axis.

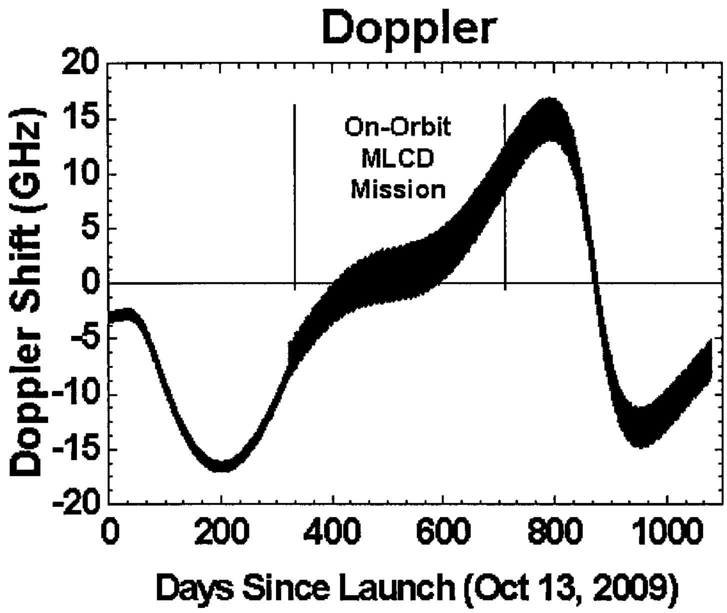

Figure 6
Doppler during the mission.

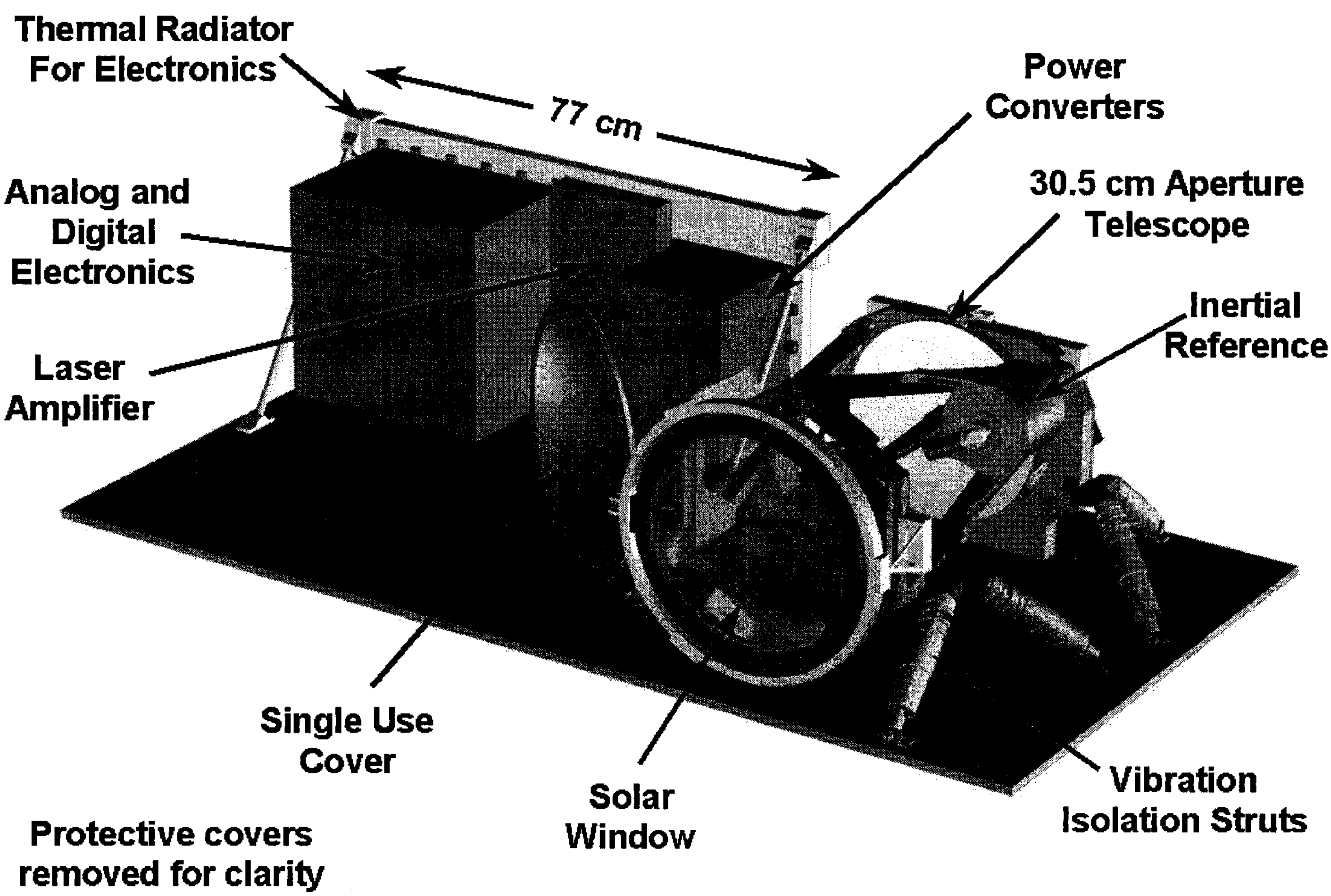

Figure 7
Preliminary configuration for the MLCD Lasercom Terminal

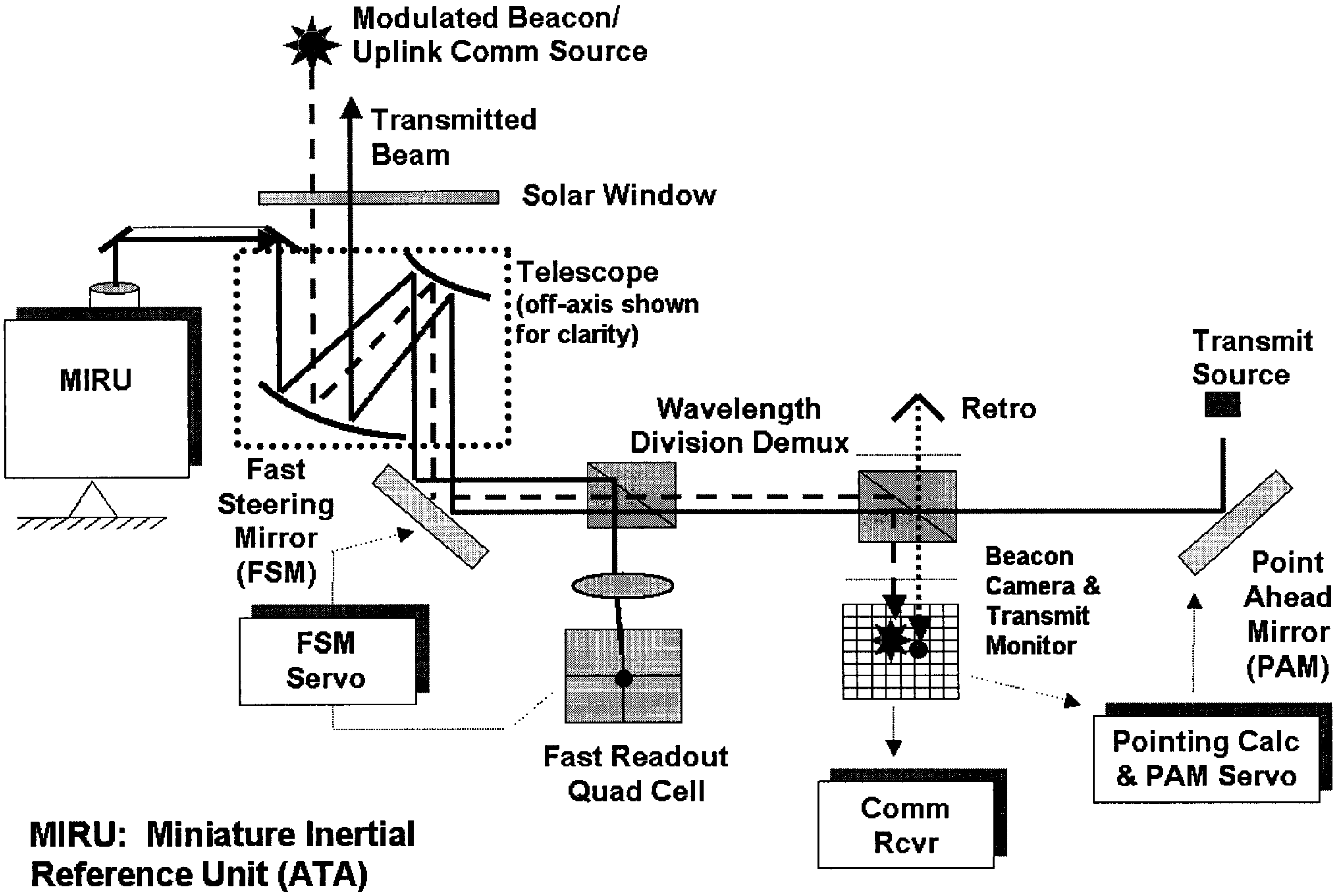

Figure 8
Optical layout of MLCD Lasercom Terminal

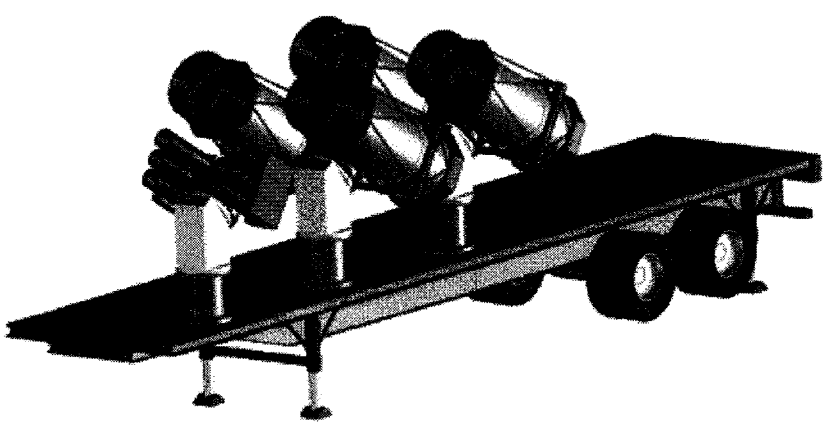

Figure 9
LDES: Link Development and Evaluation System