PROGRESS ON THE DEVELOPMENT OF THE OPTICAL COMMUNICATIONS DEMONSTRATOR

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ABSTRACT

The Optical Communications Demonstrator (OCD) is a laboratory-based lasercom demonstration terminal designed to validate several key technologies, including beacon acquisition, high bandwidth tracking, precision beam pointing, and point-ahead compensation functions. It has been under active development over the past few years. The instrument uses a CCD array detector for both spatial acquisition and high-bandwidth tracking, and a fiber coupled laser transmitter. The array detector tracking concept provides wide field-of-view acquisition and permits effective platform jitter compensation and point-ahead control using only one steering mirror. The use of a fiber-coupled transmitter modularizes the transmitter design and de-couples its thermal management problems from the main system optics. The reduction in design complexity can lead to a reduced system cost and an improved system reliability. This paper describes recent progress on the development of the OCD terminal.

1. INTRODUCTION

The purpose of the Optical Communications Demonstrator (OCD) program is to develop a laboratory-qualified lasercom demonstration terminal that can realize the potential performance advantages of space-ground laser communications. The approach is to employ a reduced complexity architecture using a CCD-based acquisition and tracking concept, and to employ fiber optics to simplify the transmit laser thermal management. This paper describes recent progress on the development of the OCD instrument.

The program was created to develop technology for spacecraft telecommunications terminals needed for NASA's future missions. The unit being developed is a spacecraft terminal engineering model for both earth-orbit-to-ground links at hundreds of Mbps to multiple Gbps data rates, as well as for deep space-to-earth missions at data rates in the kbps -Mbps range. Since the primary function of NASA missions is to return space-acquired data to the earth, the terminal is primarily a simplex (transmit) terminal, although a lower-rate command link can also be supported.

There are several technical challenges that hinder the development of laser communications. First, the smaller transmit bearnwidth imposes stringent demands on the pointing accuracy of the beam. Inaccurate beam pointing can result in significant signal fades at the receiving site and a severely degraded system performance. As a result, the lasercom transmit terminal must be capable of tracking the receiving station to maintain a residual pointing error that is small compared with the transmit beamwidth. For typical Earth-orbit applications, this requires a pointing-error budget that is on the order of microradians. Second, traditional lasercom system designs generally utilize two high-bandwidth steering mirrors, one to stabilize the detector line-of-sight along the beacon direction [1,2,3], and the second is a point-ahead mirror in the transmit beam to provide the required pointing offset between the transmit and receive directions. These multiple component architectures often require larger optical bench structures with precise thermal control tolerances to maintain optical system alignments.

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The OCD terminal uses a "minimum complexity" architecture [4] (see Figure 1) which uses only one steering mirror and one detector array for the beam control functions of acquisition, tracking, transmit/receive co-alignment, point-ahead control and point-ahead monitoring. A large format CCD array is used for initial beam acquisition as well as sub-frame fast tracking to deduce the position of the transmit optical axis of the system relative to the receiver beam. The array detector design also permits direct optical tracking of the point-ahead angle without additional sensors. The reduction in the number of detectors and steering elements leads to further simplification of the optical design and can potentially ease system reliability engineering problems.

In this paper, progress in the development of the OCD terminal will be described.

2. OCD DEVELOPMENT

The concept of the OCD has been developed and described in detail previously [4]. Although the instrument is designed to demonstrate technologies in the laboratory, it is expected that the same model can satisfy acquisition and tracking, as well as communications link requirements similar to those of a low Earth orbit-to-ground link. The design is compatible with high-data-rate communications from Earth-orbit, or at much more modest data rates from deep space.

Figure 2 shows the Telescope Optics Assembly (TOA) of the OCD Instrument, which constitutes the heart of the system. It consists of a telescope, the acquisition and tracking detector, and the opto-mechanical components needed for steering and collimation. The design uses a single aperture to maintain tight pointing alignment between the transmit and receive paths. The combined primary and secondary mirror produces better than one-half wave quality after alignment. The transmit laser is located away from the telescope, and is coupled to the main optical assembly using a single mode optical fiber.

The initial prototype large format detector array utilized the lowest 100x1OO pixel area of a Thomson TH7863 288x384 format CCD chip. A "windowed" read operation was performed by clocking the vertical transfer lines of the CCD such that only the lines containing the areas of interest would be read on a pixel-by-pixel basis; whereas other lines would be skipped without being read. Even with a combination of a window-read and a 40 Mhz DSP processing system, the maximum achievable frame update rate with this detector was less than the desired 2kHz rate. A decision was made to customize a commercial Dalsa 128 by 128 camera using the same window-read philosophy. The original Tracking Preprocessor Assembly (TPA), which provides the supporting signal processing, was redesigned to accommodate the change. The resulting camera meets the 2-kHz tracking update rate requirement for the prototype design.

In a laboratory demonstration of the tracking concept, the tracking array and steering mirror are mounted on a Sagebrush gimbal received as surplus equipment from the Air Force ROME Laboratory. The gimbal provides coarse pointing of the detector and steering mirror to orient its line-of-sight during initial acquisition. This gimbal does not provide adequate pointing accuracy for the developmental terminal. Accordingly, a worm drive gimbal has been procured from Automated Precision Inc.

The OCD has been calibrated and aligned in the laboratory using a Zygo interferometer. The interferometer produces the beacon signal to be imaged onto the detector array. A small portion of the OCD's transmit laser signal is also imaged onto the focal plane. By reading out the areas of the detector containing the focused beacon signal and transmit signal, and by calculating the image centroid, the angular difference between the beacon and transmit signals is accurately deduced. This is then compared against the desired point-ahead angle to derive the steering mirror control signals. This tracking behavior has been successfully demonstrated in the laboratory using the detector array and the steering mirror, and the resulting equipment has now been integrated into the OCD Telescope Optical Assembly housing

3. OPTICAL AND OPTO-MECHANICAL DESIGN

In order to provide effective signal delivery, the lasercom optical design must provide a high Strehl ratio for the transmit signal. The design must also provide sufficiently good image quality for both the received beacon signal and the boresight signal such that position determination based on the focal plane image can be effectively accomplished. Additionally, the design must provide high throughput, good background rejection, and sufficiently wide beam steering range.

Shown in Fig. 3 is a diagram of the optical setup [5]. The optical assembly provides three optical paths for the signals: a transmit signal path to relay the signal from the laser input to the output aperture and perform the beam steering function; a receive optical channel to relay the incident beacon signal from the input aperture to the tracking detector; and a boresight channel to relay the transmit signal to the receiver focal plane for both boresight tracking and point-ahead calibration purposes. The receive data detector is not implemented, although it is relatively straightforward to include it in the system. Note that the acquisition path is not steered by the beam steering mirror. An alternative design in which the steering mirror controls both the transmit and received optical paths was also evaluated. It was felt that a system which steers only the transmit optics beam can have less stringent relative alignment requirements between the transmit and receive paths as the boresight error can be calibrated in real time.

The three optical paths in the telescope optics assembly are described as follows:

1. Transmit Optical Path: The transmit optical path originates from the transmit fiber coupler and ends at the exit aperture of the main telescope, and includes the beam collimation / beam steering optics and the output telescope. The purposes of the transmit path are (1) to expand the modulated optical signal from the fiber output into a collimated beam covering the transmit aperture, and (2) provide high bandwidth steering control of the transmit signal line-of-sight relative to the beacon incident direction. The transmit path includes collimator optics to collimate the signal delivered from a single mode optical fiber, a beam steering optical element to provide tip-tilt control of the transmit line-of-sight, a dichroic element to combine the transmit and receive paths, and an output beam expander / telescope for final beam collimation.

2. Receive Optical Path: The receive path includes the common telescope to collect the beacon uplink signal, the dichroic element to separate the receive path from the transmit signal path, a narrowband optical filter to reject the out-of-band background noise, and focusing / imaging element(s) to image the beacon signal onto the focal plane detector array. The purpose of the receive path is to image the beacon source onto the tracking detector assembly. The receive optical path is not controlled by the fast steering mirror element.

3. Boresight Path: The boresight path couples the transmit and receive channels to provide a real-time reference signal for the point-ahead angle. The Boresight Path originates from the input fiber coupler and terminates at the tracking detector focal plane, and include the transmit collimator, relay elements, dichroic beam splitter, a retro mirror, and the receive imaging lenses. There is a need to distinguish the beacon signal and the boresight signal when the beacon and transmit signals are co-aligned. This is accomplished by introducing an angular offset in the boresight path such that the angular separation between the boresight and beacon signals is a fixed amount,

4. ACQUISITION AND TRACKING CONTROL

The large format array detector required for high bandwidth tracking can be implemented using either the charge coupled device (CCD), which provides serially addressable pixels, or randomly addressable devices such as the CIDs or Active Pixel sensors (APSs) [6]. Random access devices have shorter access time and hence have the potential of achieving higher tracking bandwidth. However, the technology is less mature and the devices are not as readily available. At the same time, recent advances in CCD fabrication technology have resulted in high readout rate devices with high quantum efficiency and essentially no dead zones. For these reasons, the CCD was chosen for implementation.

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In order to effectively acquire the remote beacon in the presence of initial attitude uncertainty of the host spacecraft, the acquisition detector array must possess a sufficiently large field-of-view to cover the uncertainty zone. For modern spacecraft, this is typically on the order of 1 mrad. At the same time, the pixel resolution of the CCD must be sufficiently fine such that the error in position information derived from the CCD is small compared to the desired pointing accuracy. For a 10 cm transmit aperture system operating with a near diffraction limited beam, the required pointing accuracy is on the order of 2 urad.

Pointing error for a lasercom system can result from (a) error in position determination, (b) boresight calibration error not detectable by the tracking detector, and (c) residual errors not compensated by the pointing control loop. A simple pointing budget which divides the pointing error into component contributions is shown in Table 1. Errors in position determination are due to detector noise and algorithm error. The detector noise includes contributions from (1) detector read noise, (2) non uniformity of the detector responsivit y, (3) dead zone and other lossy effects, and (4) signal shot noise. The algorithm error is due to the fact that, for bandwidth considerations, a simple centroiding algorithm is used rather than a more accurate maximum likelihood algorithm. This simpler algorithm introduces residual bias in the centroid estimate. For a CCD operating with a 10 μrad pixel field-of-view, it is estimated that under the expected link environment, the error due to position determination can be controlled to within 0.75 μrad. The boresight alignment error is estimated to be another 0.75 μrad.

The residual tracking error of the pointing control loop is the platform jitter not properly compensated for by the pointing control subsystem. Generally, a higher bandwidth control loop can more effectively compensate for the platform jitter and hence has a lower residual pointing error. For tracking a ground-based station from a space-based laser transmitter, the required image centroid update rate should be on the order of 2 kHz. The main factors limiting the control loop bandwidth are the loop delay (sampling rate) and the fine steering mirror frequency response. In normal operation, the CCD must integrate over a certain period of time. The image is then read out sequentially and processed to derived the pointing control. Conventional CCD imaging systems read out every pixel in the detector. Because of the large number of individual pixels in an array detector, a detector with the required field-of-view and pixel resolution will generally have a relatively slow frame read speed. To achieve the desired update rate, either a smaller format device [3,7] or a large format device with multiple-readout channels [8] is required. However, a small format detector cannot provide the large field-of-view desired for initial acquisition, and the multiple readout channel devices require complex electronics arrangements.

A third alternative is to read out only the portions of the device that contain the tracking images. At the beginning of the read cycle, the image zone is transferred into the storage zone such that integration can be conducted independent of the subsequent image readout. A "windowed" read operation can then be performed by clocking the vertical transfer lines of the CCD such that only the lines containing the areas of interest will be read on a pixel-by-pixel basis; whereas other lines will be skipped without being read. With a combination of a window-read and a fast processing system, the desired 2kHz update rate can be achieved using a single readout port device. The minimum frame integration time is equal to the sum of frame transfer time and readout/data processing time. Since the CCD integration effectively introduces a delay which is 1/2 of the frame integration period, the overall average loop delay is approximately 1.5 times the frame integration time.

Instead of using the entire array for tracking, only the lowest 10x1O pixel areas around the located beacon and transmit signal regions are used for tracking because of readout speed considerations. A novel interface circuit is used to provide access synchronization between the CCD camera and the main control processor. The main processor is responsible for computing the image centroids and control law implementation. Actual pointing control is accomplished by outputting the control voltages via a pair of D/A converters to a two axis beam steering mirror (TABS-II) from General Scanning. The mirror has a 17 Hz first resonance frequency, and is located at a conjugate surface to the exit pupil of the telescope such that tilting the mirror effectively controls the output beam direction. Analysis of the pointing control loop indicates that with a loop delay of 500 μs and a centroid update rate of 2 kHz, an rrns pointing error of less than 1.2 μrad can be achieved. Furthermore, the control loop will have a gain margin greater than 4 dB and a phase margin greater than 53 degrees [9].

5. LASER TRANSMITTER IMPLEMENTATION

As mentioned earlier, the laser transmitter module used in the OCD is decoupled from the main telescope optics assembly, and is connected to it by a single mode optical fiber which delivers the modulated optical signal. The de-coupling of the laser transmitter from main optical assembly permits a modular design of the laser transmitter, which can be carried out independent of the main optical assembly design. Furthermore, by locating the laser transmitter away from the main optical assembly, thermal control problems associated with the laser can be considerably simplified.

6. INSTRUMENT CONTROL AND PROCESSING

External control of the OCD Instrument is provided via a user control terminal. The control terminal simulates the data interface expected between the lasercom instrument and the host spacecraft. The Control Terminal interfaces between the operator and the instrument, and translates all user input to control commands that are sent to the instrument. Likewise, it interprets the status data sent by the instrument into numerical values that are displayed on the status screen. The Control Terminal is implemented using an IBM-compatible PC and a frame grabber to display the CCD image.

The internal instrument control of the OCD is accomplished using a single board Digital Signal Processor (DSP) based on the Texas Instrument TMS320C40 and an associated interface circuit board. The function of the control system is to perform the following functions:

a. Control directly the horizontal and vertical transfers of the CCD,
b. Monitor the detector output data to acquire and track a remote beacon signal
c. Compute necessary pointing coordinates based on point-ahead ephemerides and current attitude input,
d. Close a steering mirror control loop at 2k Hz update rate,
e. Close a coarse-pointing gimbal (if used) control loop at 200 Hz update rate,
f. Provide asynchronous command reception and acknowledgment,
g. Provide status return on demand,
h. Monitor the status of the instrument and flag the control terminal of any anomaly.

The DSP has parallel pipelines and can support a maximum processing throughput of 50 MFLOPS. Furthermore, it has built-in timers (frame time tracking) and direct memory access (DMA) circuitry (for CCD control) [10]. The detector and the interfacing circuit designs are greatly simplified by requiring the processor to provide direct control of the horizontal and vertical shift clocks. This can be accomplished by using a DMA write to the circuit which control the CCD timing. The DMA can be executed in the background and hence does not burden the processor. The processing budget is determined by the frame rate, which is based on the CCD integration time of 500 μs to produce the required 2 KHz update rate.

At the beginning of every frame interrupt, the CCD is set to transfer the image from the image plane to the storage plane. During that period of time, the processor will poll the communications port to monitor any command update, and compute the desired point-ahead angle based on the following information: (a) point-ahead angle supplied by the ephemerides, (b) current orientation of the host platform relative to the standard reference frame, and (c) current position of the gimbal (if one is used). At the end of the frame transfer operation, the centroiding process will be initiated. This is accomplished by first rapidly shifting (vertically) to the line of interest. Pixels that are in the tracking window are then processed to compute the following quantities: (a) number of pixels above tracking threshold, (b) integrated intensity, (c) centroid position, (d) average intensity along the window boarder, and (e) new window coordinate based on the current centroid position, The new window coordinate is computed such that the centroid is always near the center of the window. This ensures accurate tracking of the window. The number of pixels above threshold and total integrated intensity values serve as auxiliary information that can be used for clutter rejection and lost track detection. Finally, the average intensity along the window boarder provides an indication of the background intensity which can be subtracted from the current pixel value. For the OCD implementation, this background intensity value is assumed to be uniform throughout the window, and is subtracted off in the subsequent frame processing.

At the end of centroid computation, the control signals are calculated based on the current point-ahead value and the desired point-ahead value. The control signal calculations, which are performed via three concatenated second order IIR filters, are accomplished within 20 µs. These signals are then fed into the digital-to-analog converts to drive the mirror.

6. CURRENT DEVELOPMENT STATUS

The OCD Telescope Optical Assembly has been fully integrated and aligned. Additionally, a test and evaluation station, capable of providing a plane-wave beacon signal, and measuring the OCD's performance parameters, has been designed, built and aligned. The acquisition and tracking electronics and preliminary software have been integrated together in a table-top demonstration environment and are ready for integration with the TOA. Testing of the TOA is ready to begin. Tests to be performed include the transmit beam divergence, pointing direction, point-ahead angle implementation and accuracy, acquisition and reacquisition times, total power output, and overall communications modulation performance.

7. SUMMARY

The architecture of the OCD Instrument represents a significant reduction in system complexity compared to previous lasercom system implementations. A single array detector is used for both initial pointing acquisition and fine tracking. The array detector also permits direct optical feedback of the point-ahead angle. By operating the CCD in a "windowed" read mode, the instrument can achieve the desired tracking bandwidth without requiring complex signal processing circuits. Furthermore, because the detector measures the point-ahead angle directly, only one steering mirror is required for both transmit signal point-ahead and platform jitter compensation. Finally, the use of fiber optics permits modulator design of the transmit laser and simplifies the thermal management design of the main optical assembly. The reduction in design complexity can lead to a reduced system cost and an improved system reliability. Furthermore, it can permit the implementation of a new generation of lasercom instruments capable of realizing the inherent advantages of optical frequency communication systems.

The high bandwidth CCD-based tracker concept has been validated separately in a laboratory demonstration. Preliminary versions of the required software for pointing acquisition and tracking, as well as instrument control, have been completed and integrated with the laboratory demonstration. At the same time, implementation of the laser transmitter has been completed. **The optical design, fabrication, and alignment of** the telescope optics has been completed. The optical design requires only 12 spherical refractive elements and two aspheric mirrors. The design of the OCD Instrument is currently being experimentally validated.

7. ACKNOWLEDGMENTS

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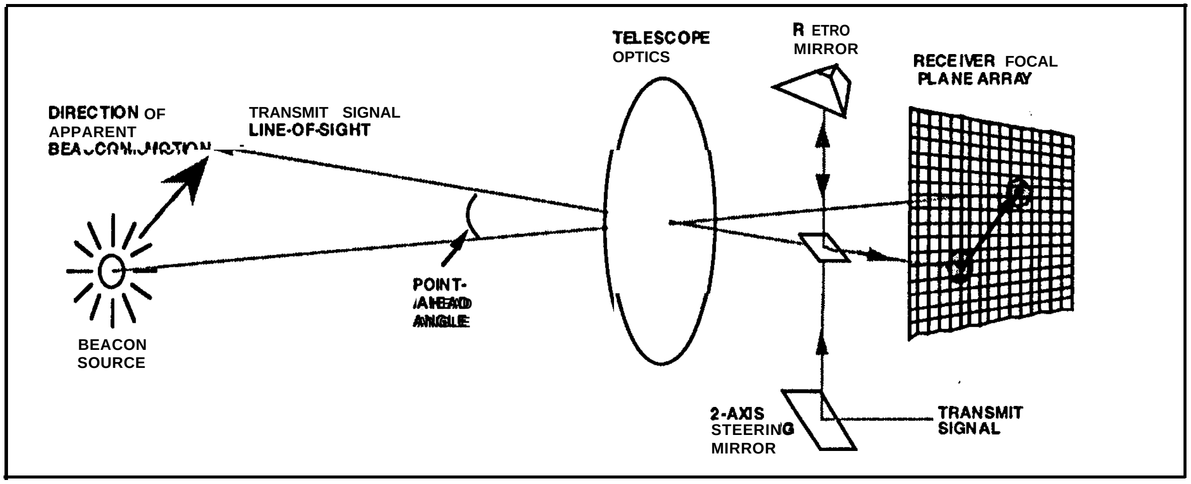

Figure 1. Concept of an Optical Communication Demonstrator Instrument

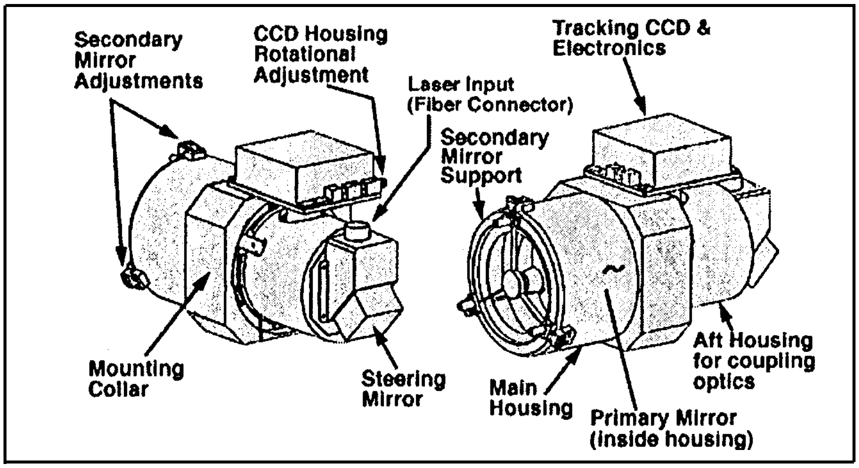

Figure 2. OCD's Telescope Optical Assembly

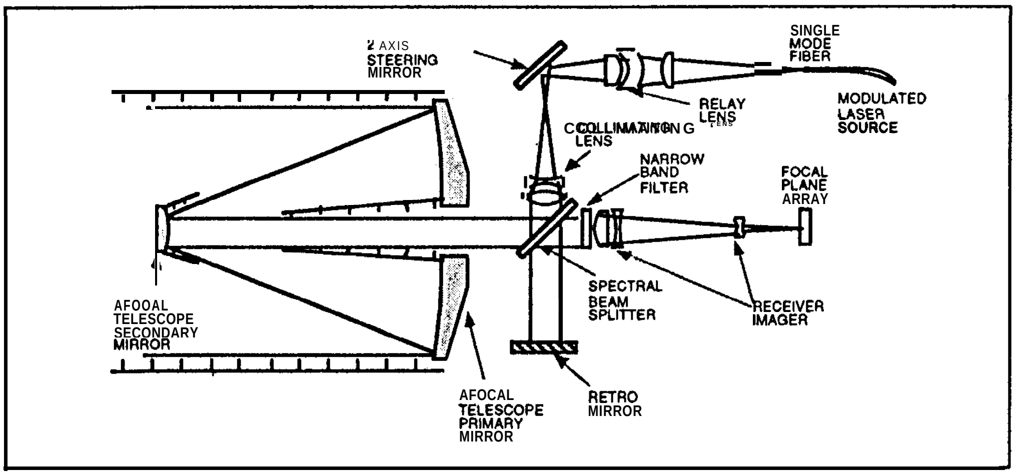

Figure 3. OCD Optical Diagram

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RMS POINTING BUDGET	
CCD and Electronic Noise	0.75µrad
Centroiding Algorithm Bias	0.75µrad
Transmit/Receive Alignment Error	0.75µrad
RMS Residual Jitter	1.50µrad
RSS Total	2.0 µrad

Table 1. Pointing error budget for the tracking control subsystem