Overview of the Optical Communications Demonstrator

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ABSTRACT

The Optical Communications Demonstrator is a laboratory-based lasercom demonstration instrument designed to validate effective beacon acquisition, high bandwidth tracking, precision beam pointing, and point ahead compensation functions. The instrument is designed using an 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 as well as high update rate using a single output channel device. At the same time, it permits effective platform jitter compensation and point ahead control using only one steering mirror. The use of fiber coupled transmitter further modularizes transmitter design and de-couples the thermal management problem. 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.

1. INTRODUCTION

Laser communication technology has been under active development over the past two decades. By virtue of a shorter operating wavelength, a lasercom system has a significantly smaller beam divergence compared to conventional microwave systems. For spaceborne systems, the smaller aperture requirement can lead to reduction in size and mass of the communication system, and hence the overall system cost.

Although the smaller transmit beamwidth permits effective reduction of the transmit antenna size, the narrow beam can impose stringent demands on the pointing control accuracy of the instrument. Inaccurate beam pointing can result in large signal fades at the receiving site and a severely degraded system performance. In order to effectively deliver the signal, the lasercom transmitter must be capable of tracking the receiving station such that the residual pointing error is less than ≈20% of the transmit beamwidth. For typical Earth orbit applications, this required pointing budget is on the order of microradians. This tight pointing control problem is further compounded by the fact that the angular motions presented in the spacecraft platform due to deadband cycle and random vibration are typically much larger than the transmit beamwidth. As a result, a dedicated pointing control subsystem to maintain accurate beam pointing must be an integral part of the lasercom system design. Unfortunately, the complexity of the beam pointing control subsystem can quickly erode the inherent mass advantage of the lasercom system, as more complex hardware is required to maintain accurate beam pointing. Furthermore, the complexity introduced adds to the cost of reliability engineering and overall system cost.

In the past, designs of lasercom systems generally achieved the desired pointing accuracy by using a directionally sensitive detector such as a quadrant avalanche photodiode (QAPD) to measure the angular error between the detector line-of-sight and the beacon direction. The error was then fed back to a high band width steering mirror to stabilize the detector line-of-sight along the beacon direction [1,2,3]. A second point-ahead mirror in the transmit beam path was then used to provide the required pointing offset between the transmit and receive signals. Since the quadrant detector has a limited field-of-view, a separate, larger format detector was usually required to provide the wide field of view coverage during the acquisition process. Alternatively, quadrant detector can be used for acquisition with complex scanning sequence and acquisition algorithm. Furthermore, additional optical relay elements were required to channel the optical signals between steering mirrors and detectors.

Recently, advances in array detector technology has permitted the implementation of a new generation of acquisition and tracking subsystem. In an array-based tracking system, a remote beacon laser is imaged by the telescope optics onto the focal plane array. By reading out the area of the detector containing the beacon signal and calculating the image centroid, the angular direction of the beacon can be accurately deduced relative to the optical axis of the system, This information can then be fed into the pointing control subsystem for pointing stabilization. In practice, a small amount of the transmit signal can also be imaged onto the acquisition detector, and the distance between the two image spots in the focal plane is a direct measure of the relative angular offset between the transmit and beacon signals. By sensing any difference between this measured, instantaneous point-ahead angle and the desired point-ahead value, the instrument can derive a real time control signal to maintain the pointing of the transmit signal on target, Instead of stabilizing receive and transmit lines-of-sights individually, the array detector-based tracking concept described above requires only the relative angle between the transmit and receive beams to be stabilized. As a result, only one detector and one steering mirror are required to close the pointing control loop. A single detector array can also permit direct optical tracking of the point-ahead angle without additional sensors. The reduction in the number of detector and the steering element can lead to further simplification of optical design and can potentially ease the system reliability engineering problem.

The purpose of the Optical Communications Demonstrator (oCD) is to develop a laboratory lasercom demonstration instrument that can realize the potential performance advantages of the lasercom system. 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 problem. This paper will describe the conceptual design and considerations leading toward the OCD system' architecture, as well as an overview of the system development status.

2. OCD CONCEPT

The objective of OCD is to design a lasercom instrument to validate effective beacon acquisition, high bandwidth tracking, precision beam pointing, and point ahead compensation functions in a laboratory qualified structure. The instrument is designed to satisfy acquisition and tracking, as well as communications link requirements similar to those of a low Earth orbit to ground link [4]. Even though the 200-300km distance typical for a shuttle to ground link does not demand stringent pointing, as the laser beam can easily be expanded to cover the attitude uncertainty of the spacecraft, the pointing control design of the OCD will be required to provide accurate pointing of a diffraction-limited beam, as would be required for a longer range link (e.g. geosynchronous crosslink). The rationale for a near-Earth performance requirements being that early applications of the lasercom technology will most likely be between earth orbiting satellites, or between satellites in the Earth orbit and ground,

It was decided early in the development that the OCD instrument design will not be constrained by the requirements of flight validation and environmental qualification. State-of-the-art commercial components technologies are incorporated into the design, provided there are sufficient confidence that the process or components can be eventually fielded. However, novel technologies that are still in the laboratory stage, such as phased-array emitter and active pixel sensors, will not be used.

Shown in Figure 1 is a mock up of the OCD instrument. It consists of a gimbaled telescope and the associated laser and opto-electronics units. The acquisition and tracking detector, as well as the opto-mechanical components needed for transmit signal beam steering and collimation, are housed within the gimbaled telescope unit. A single aperture design with multiplexed beam path was selected because of the difficulty in maintaining tight pointing alignment between the transmit and receive paths for a multiple aperture system. The gimbal provides coarse pointing of the telescope to orient the instrument line of sight during initial acquisition. The gimbal also removes large amplitude disturbances, such as the dead band cycle of the spacecraft, that cannot be accurately compensated by the fine steering mechanism built into the telescope optics assembly. The transmit laser is located away from the telescope, and is coupled to the main optical assembly using a single mode optical fiber.

Spatial acquisition and tracking for the OCD Instrument is accomplished using a large format CCD array. A conceptual block diagram of the array-based tracking system is shown in Figure 2. The beacon signal from a remote receiver is received and imaged onto the array. A small portion of the transmit signal is also re-imaged onto the focal plane. By reading out the area of the detector containing the beacon signal and calculating the image centroid, the angular direction of the beacon and transmit signals can be accurately deduced relative to the optical axis of the system. The instantaneous point ahead angle can be measured simply by measuring the distance between the transmit and receive signals on the focal plane. This pointing offset can then be compared with the desired point ahead angle and the error is corrected using a fast steering mirror in the transmit optical path. The coarse pointing gimbal then removes the bias and maintains the steering mirror at the middle of its dynamic range.

3. OPTICAL AND OPTO-MECHANICAL DESIGNS

In order to provide effective signal delivery, the lasercom optical design must provide a high Strehl ratio of 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 block 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 at a later date. It was felt that a system which steers only the transmit optics beam can have a 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 arc 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 a common telescope to collect the beacon uplink signal, a 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 this by introducing an angular offset in the boresight path such that the angular separation between the boresight and beacon signals is deviated from the beacon - transmit signals separation by a fixed amount.

4. ACQUISITION AND TRACKING CONTROL

The large format array detector required for high band width 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 (AI%) [61. Random access devices have shorter access time and hence has 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 no dark zones. For these reasons, the CCD is chosen for implementation.

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 10cm 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 error 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 include contributions from (1) detector read noise, (2) non uniformity of the detector responsivity, (3) dead zone and other lossy effects, and (4) signal shot noise. The algorithm error is due to the fact that, for bandwidth consideration, 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 10μrad pixel field of view, it is estimated that under the expected link environment, the error due to position determination can be controlled to within 0.75μrad. The boresight alignment error is estimated to be another 0.75μrad.

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 readout 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 mad 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 arrangement.

A third alternative is to readout only portions of the device that contains the tracking image. 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. Shown in Fig. 4 is an illustration of the high speed clocking concept. 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 introduce a delay which is 1/2 of the frame integration period, the overall loop delay is approximately 1.5 times the frame integration time.

Shown in Figure 5 is a block diagram of the OCD pointing control subsystem. The system employs a Thomson TH7863 CCD with 288x384 format. Instead of using the entire array for tracking, only the lowest 100x100 pixel area is 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 output the control voltage, via a pair of D/A converter, to a two axis beam steering mirror (TABS-II) from General Scanning. The mirror has a 17Hz 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 indicated that, with a loop delay of 500 µs and a centroid update rate of 2 kHz, a rms 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” [91.

5. LASER TRANSMITTER IMPLEMENTATION

As mentioned earlier, the laser transmitter module in OCD is decoupled from the main telescope optics assembly, and is connected to it only by a single mode optical fiber which delivers a 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. Furthermore, by locating the laser transmitter away from the main optical assembly, the thermal control problem 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 actual 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 output data to acquire and track a remote beacon signal
c. computes necessary pointing coordinates based on point ahead ephemera and current attitude input,
d. close a steering mirror control loop at 2k Hz update rate,
e. close a gimbal control loop at 200Hz 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) circuit (for CCD control) [10]. The detector and the interfacing circuit design is 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 to 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 relative to the standard frame, and (c) current position of the gimbal. 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 serves 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 signal is calculated based on the current point ahead value and the desired point ahead value. The control signal calculation, which is performed via three concatenated second order IIR filter, is accomplished within 20μs. This signal is then fed into the digital-to-analog convert to drive the mirror.

6. 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 design of the OCD instrument is currently being pursued. The high bandwidth CCD-based tracker concept has been validated separately in a laboratory demonstration. The required software for pointing acquisition and tracking, as well as instrument control has been completed and integrated with the laboratory demonstration [11]. At the same time, implementation of the laser transmitter has been completed [121. The optical designs of the telescope optics has been completed, and opto-mechanical design of the structure is currently being conducted. The optical design requires only 12 spherical refractive elements and two aspheric mirrors. The optical design has been athermalized and checked with a finite element thermal analysis. The opto-mechanical design has been considerably simplified by borrowing previous designs. For example, the primary telescope concept is near identical to the relay telescope of the wide-field-planetary camera, Detailed drawings of the opto-mechanical elements, as well as the fabrication of the telescope, is scheduled for completion during FY94.

7. ACKNOWLEDGMENTS

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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

Figure 1. Concept of an Optical Communications Demonstrator

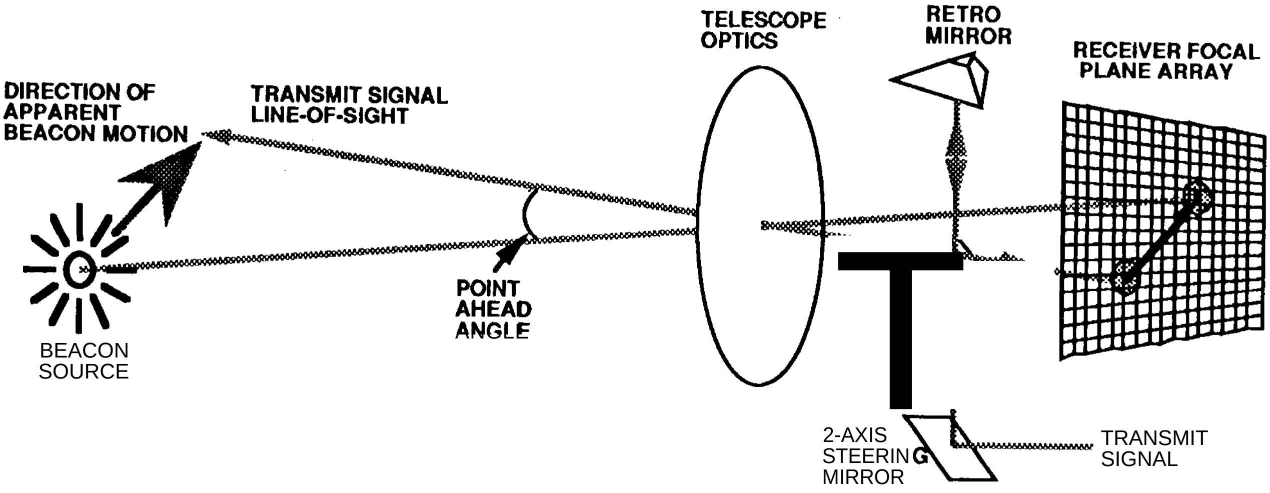
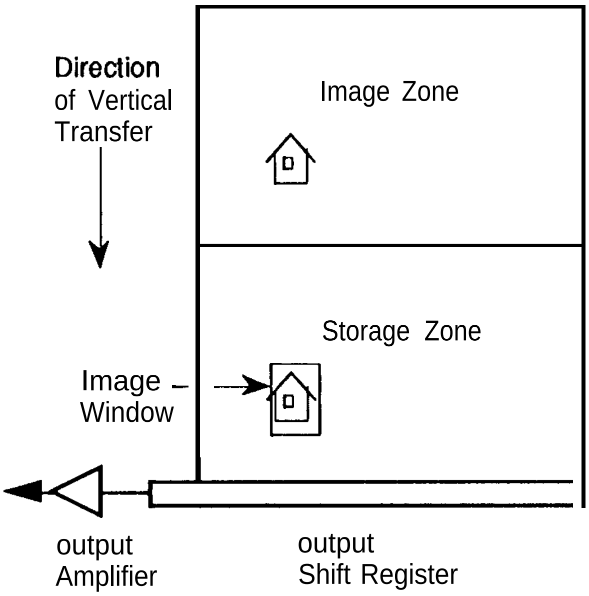


Figure 2. Spatial tracking using a single array detector.

Figure 3. Optical Block Diagram



1. Transfer image into storage zone
2. Rapid vertical transfer until the first line of the window is in the horizontal shift register
3. Rapid horizontal transfer until the first pixel to be read is at the output gate
4. Read out the desired number of pixels in the line
5. Vertical shift when last pixel of the window is read
6. Repeat 3-5 for every lines in the window

Figure 4. Windowed read algorithm for an image transfer CCD.

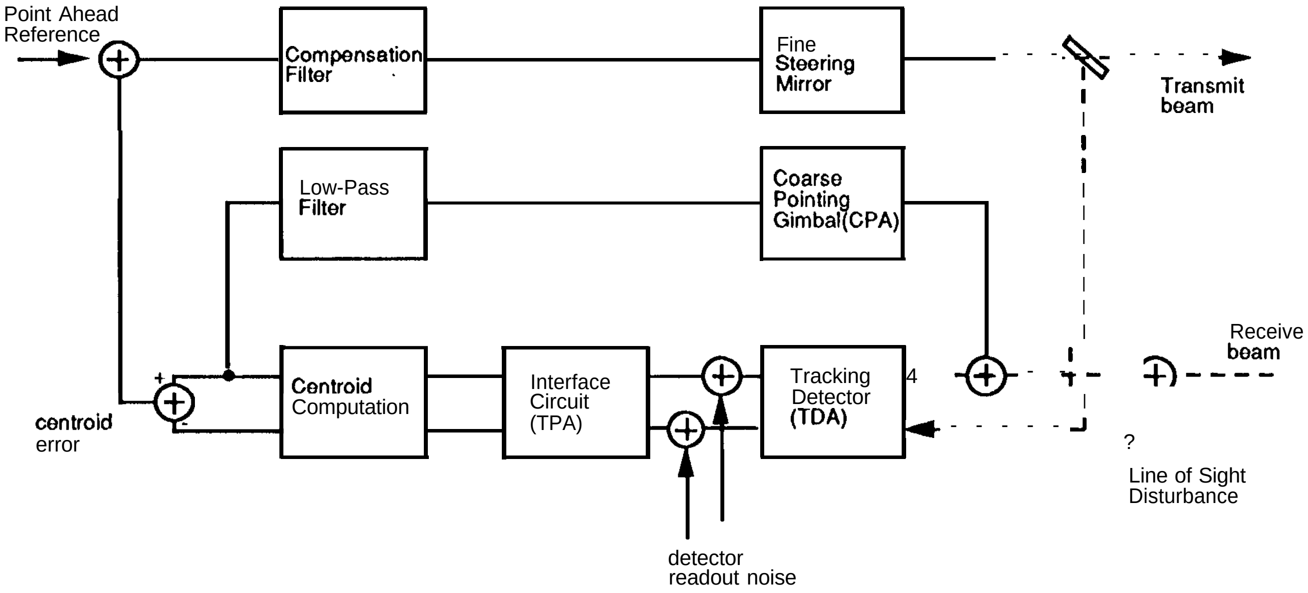


Figure 5. A conceptual block diagram of a OCD pointing control subsystem.