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Citation: Murphy, Robert J. et al. "A conical scan free space optical tracking system for fading channels." Free-Space Laser Communications IX. Ed. Arun K. Majumdar & Christopher C. Davis. San Diego, CA, USA: SPIE, 2009. 74640P-7. © 2009 SPIE--The International Society for Optical Engineering

As Published: <http://dx.doi.org/10.1117/12.826299>

Publisher: The International Society for Optical Engineering

Persistent URL: <http://hdl.handle.net/1721.1/52719>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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A Conical Scan Free Space Optical Tracking System for Fading Channels

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ABSTRACT

Free space optical communication systems require robust pointing and tracking to establish and maintain line-of-sight (LOS). Atmospheric scintillation can present a challenge to the LOS tracking systems located at each end of the link. This paper describes a pointing, acquisition, and tracking (PAT) approach for single-mode fiber coupling, which was successfully demonstrated over a 5.4 km lasercom link that was subject to severe turbulence conditions. One of the primary advantages of the scheme described is its compensation for thermo-mechanical drift, which simplifies opto-mechanical design and allows use of simple COTS hardware. An overview of the PAT system and performance data are presented.

Keywords: Pointing, Acquisition, and Tracking (PAT), Line Of Sight (LOS), Nutation, Scintillation

2. INTRODUCTION

Optical nutation serves as the primary means of spatial tracking on many free space optical communication systems. The nutation tracker is used to couple the optical power received at the terminal's aperture into a single mode fiber for further processing by the communications and tracking receivers [2]. The advantage of this scheme is that incoming power delivered to the fiber is optimized by virtue of the fact that the comm and tracking detectors are co-located. This narrow field of view tracker typically relies on an auxiliary Wide Field Of View (WFOV) sensor to accomplish the initial acquisition and coarse tracking functions necessary to align the fiber to the incoming beam. Once the LOS has been handed over to the nutation tracker the auxiliary or coarse tracking sensor is often disengaged.

The approach described here, assumes that the nutator is not the primary tracking sensor but rather a mechanism for maintaining co-alignment between the fiber and the WFOV sensor. The WFOV sensor performs the primary tracking functions necessary to reduce LOS errors due to platform jitter. The nutator maintains fiber alignment with the WFOV sensor in a low bandwidth fashion. Thermo-mechanical drift appearing on the differential path between sensors occurs on time scales suitable for low bandwidth co-alignment updates. Low bandwidth tracking is suitable for applications where the link is subjected to atmospheric scintillation which can hinder the performance of wide bandwidth, nutation trackers [3].

An experiment was conducted over the summer of 2008 involving a 5.4 km stationary link utilizing two laser communications terminals of similar design [6]. The purpose of the experiment was to demonstrate communications at OTU1 rate using a combination of FEC and interleaving as well as spatial diversity on the receiver to overcome the effects of atmospheric scintillation [5]. A secondary purpose was to gather channel data during link operation in support of a future aircraft flight program.

The air to ground link being emulated was designed to deliver high bandwidth optical data from a low Size, Weight, and Power (SWAP) terminal on an aircraft to a very capable ground receiver. To achieve this goal, the technique of optical diversity was used on the receiver in order to mitigate fading due to atmospheric turbulence. To realize optical diversity, a system of 4 independent receivers (each individually tracked) was used to collect the optical signal. The photocurrents from the four receivers were then summed (with proper time alignment) and delivered to the clock and data recovery subsystems.

This work was sponsored by the Department of Defense, RRCO DDR&E, under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government.

The purpose of this paper is to highlight the Pointing, Acquisition, and Tracking (PAT) approach used by both ends of the link in support of this initial experiment. In particular, the four trackers comprising the receiver had to be continuously optimized to take full advantage of the optical diversity design.

3. PAT Free-Space Optical Hardware

The objective link will be aircraft to ground, exercising low elevation angles. The atmospheric measurements conducted in this experiment are pertinent to the aircraft link. The terminal configuration for this experiment consisted of a single aperture representing the aircraft side of the link and four similarly constructed apertures representing the ground side of the link. The acquisition and tracking system described next would likely be augmented by an Inertial Reference Unit (IRU) to aid in the high bandwidth mechanical jitter suppression required on the aircraft side of the link.

A block diagram of the free space optical terminal design common to all transceivers used in the experiment is shown in Fig. 1 and a photograph of the terminal is shown in Fig. 2. The terminal consists of a transmit/receive single mode fiber collimator (Col), a fast steering mirror (FSM), a coarse steering flat on the output (OFLAT), a hollow retro reflector (HRR), a high speed IR camera or Wide Field Of View (WFOV) sensor, and associated optics.

Figure 1: Block diagram of the free space optical terminal design. Diagram represents a design which is common to all transceivers used in the experiment.

Figure 2: Photo of one representative channel of the free space optical terminal.

The collimator is a Lightpath 10265900, which is a self contained one piece Commercial Off The Shelf (COTS) item. It has an 11mm $1/e^2$ beam-width which effectively sets the terminal's aperture size. This functions as both the terminal's transmitter as well as its communications receiver. Tx / Rx are combined using a fiber based WDM add drop multiplexer. The IR camera is a Sensors Unlimited SU320K used for acquisition and high speed centroid tracking. The camera is preceded by a band pass filter in the optical path to reduce the influence of background and increase Tx / Rx

isolation. The FSM is a Newport FSM-300-02 which features a 1 inch diameter mirror, $\pm 3^\circ$ optical stroke, and >500 Hz pointing bandwidth. The beam-splitter serves to pass most ($>95\%$) of the received optical power to the fiber collimator and pass the rest ($<5\%$) of the optical power to the WFOV sensor. The beam-splitter is an angular co-alignment mechanism between these two sensors. The steering flat serves as a gimbal surrogate as well as a static alignment aid for the diversity receiver. The beam-splitter and steering flat are driven by piezo electric motors on each axis. The hollow retro reflector is inserted to facilitate fiber to camera bore-sighting.

4. Initial Alignment

Since Tx and Rx are inherently aligned in the fiber collimator, the remaining alignment to be performed is between the collimator and the camera. This is done by inserting the hollow retro reflector (HRR) in the optical path leading to the FSM. A Tx beam from the collimator is reflected off of the retro and observed on the IR camera. The beam-splitter between the collimator and the camera is adjusted to null the centroid tracking errors observed on the camera. Once this task has been performed on the terminals at each end of the link, the HRR can be removed and the acquisition phase of a terminal session can begin.

Figure 3: Tracking System Loops

5. Tracking System Operation

The tracking system contains three inter-dependant loops as shown in Fig. 3. The primary tracking loop (Loop#1) can be described as follows: LOS errors are sensed on the IR camera at a rate of 1kFPS and applied to the FSM to achieve a 50 Hz closed loop tracking bandwidth. The 1/20 closed loop to sampling frequency ratio is used in order to achieve a stable loop operation. (Rate 2x has also been demonstrated) This loop serves as the primary means of acquiring and correcting LOS error.

A coarse steering loop (Loop#2) is nested around the primary tracking loop, as is often done to extend the equivalent angular stroke of the terminal and track a target over a broad field of regard. This is done by adjusting the output steering flat (OFLAT) to null the position sensors on the FSM at a low (0.2 Hz) update rate. A major benefit of this loop, is that it holds the last known position of the target during link outages. It also maintains co-alignment among the 4 ground apertures during link operation. This loop forms the first fine tuning loop.

The fiber collimator is aligned to the camera per the initial bore-sighting operation previously mentioned. The bore-sight between the camera and the fiber is however free to drift. This will eventually bring about a reduction in delivered power as well as an apparent magnification of atmospheric scintillation. This drift is mitigated through a second fine tuning loop (Loop#3) which is the primary topic of this paper, and is described as follows.

6. Nutation

A circular nutation pattern is superimposed onto the FSM at a rate which exceeds the rejection bandwidth of the primary tracking loop. The nutation signal is observed by a Newfocus 2103 log power meter contained within the fiber receiver. This signal is subsequently demodulated into azimuth and elevation error components. These error signals are then averaged for a period of 5 seconds and passed to a window comparator. The window comparator generates a "no update" signal when the error is within some threshold about zero and generates a "+step" or "-step" signal outside that threshold. The window comparator signal is passed to the piezo drive elements (pico-motors) of the beam-splitter. The beam-splitter therefore helps to optimize power in fiber as well as power delivered to the remote terminal. The update rate was adequate to combat the effects of thermo-mechanical drift in the optical module over the course of our experiment.

A circular nutation pattern similar to that shown in Fig. 4 was chosen since it leaves minimal residual dither at the local and remote terminals once the loop has fully optimized the LOS. The tracking signal scales with nutation depth while the comm signal power penalty increases as one minus the square of the nutation depth. A 10% nominal depth was chosen, resulting in a <0.5 (TBR) dB comm penalty.

It is important to re-iterate that the nutation applied to the FSM appears not only on the local receive fiber but also on the remote terminal. This occurs primarily when the pointing is off center, since the pattern produces close to a circular constant power contour when on center as shown in Fig. 4. A different nutation frequency was applied to the remote terminal to avoid ambiguities in detection. The nutation frequencies were selected so that they and their beat notes, lie near or outside the edge of the tracking rejection bandwidth of the primary loop as shown in Fig. 5. The nutation frequencies were also chosen to be adequately sampled at 1kHz, set by the camera frame rate and real-time control loop.

Figure 4: Nutation applied to optical beam and resulting tracking discriminant

7. Terminal Control

The PAT systems were controlled via a computer running Labview real-time as shown in Fig. 6. Real-time PAT processes ran in a 1 KHz high priority thread. Timing of the loop was driven by generating a pulse which triggered camera frame acquisition. The width of the pulse / duty cycle determined the integration time used by the camera. The maximum loop rate was largely dictated by data acquisition from the tracking camera & various A/D & DAC processes. Each camera frame was processed with a centroid algorithm to provide beam location for Loop#1.

The centroid position was combined with the computed nutation pattern to create the FSM drive signal. The FSM position required to track the beam was used to provide feedback to null the position of the output mirror for Loop#2. This was accomplished in a slow, low priority loop. The log power in fiber meter was sampled and a discriminant calculated at rate which allowed for a slow low priority correction of the tracker/fiber alignment via the beam splitter mount for Loop#3.

Real time telemetry on the position of the beam, FSM positions, and power in fiber was sent to the telemetry archiver at 1 KHz rate via UDP and a lower priority thread.

Figure 5: Tracking Systems frequency map

Figure 6: Tracking System computer control diagram.

8. Performance

Fig. 7 shows the pull-in action or acquisition of the nutator. The nutation tracking errors Az and El, are displayed as 16 bit signed values. When these error signals lie outside the thresholds Wthresh+/-, a +step or -step of the beam-splitter is applied in an effort to co-align the WFOV sensor with the fiber. Once the error signals lie inside the thresholds, no step of the beam-splitter is required.

Figure 7: Pull in of the nutation tracker

The nutation tracking errors reveal that the initial fiber bore-sight is sub-optimum. The average power in fiber increases by ~2dB as the nutation errors decrease during nutation track operation.

Figure 8a). Power in fiber relative to the power on the WFOV 8b.) Corresponding correlation

Fig. 8a shows the power in fiber relative to the power on a 2x2 pixel (~ 1 beam-width) segment of the WFOV while the nutation errors fall within steady state. These traces are well correlated (95%) as shown in Fig. 8b indicating that the power in fiber is close to optimum.

Figure 9. Power in fiber under a.) Low, b.) Moderate, c.) High atmospheric fading conditions d.) Average power under all three conditions.

Fig. 9a. shows operation for a 4 minute period under non stressing atmospheric conditions. The variance is 7.2% of the mean sq power in this case. Nutation errors are evaluated every 5 secs. The errors are very small and no correction is necessary during this period. Fig. 9b. shows operation for a 4 minute period under moderately stressing atmospheric conditions. The variance is 64% of the mean sq power in this case, with nominal 25-30dB class fades. The nutation variance is larger but the errors have zero mean. Fig. 9c. shows operation for a 4 minute period under stressing atmospheric conditions. The variance is 175% of the mean sq power in this case with nominal 35-40dB class fades. The nutation errors primarily lie within the adjustment thresholds and have zero mean.

Figs 9a through 9c each show a two minute sample of low, moderate, and high fading conditions, taken from a larger data set summarized in Fig 9d. Fig. 9d. is a plot of the mean power received under atmospheric conditions for a period of 1 hour. The mean power level changes observed in the earlier portion of the plot for Sept. 18 were manually applied for communications performance measurements not discussed here.

9. Summary

The experiment conducted over the summer of 2008 demonstrated communications over a link exhibiting challenging atmospheric scintillation. A tracking system immune to scintillation was required to maintain line of sight in support of this experiment. The nutation tracker implemented, facilitated the use of COTS components for the free space portion of the optical hardware. No explicit sensor bore-sighting was required beyond that executed during daily experiment startup. The link ran daily for 3 months. Operation occurred for over 150 hrs including three 24hr non-stop measurement

periods. This tracking system supported communications measurements performed over the last month of the experiment's lifetime.

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