Acousto-optic pointing and tracking systems for free-space laser communications

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ABSTRACT

Implementation of long-range laser communication systems holds great promise for high-bandwidth applications. They are viewed as a technology that in the nearest future will handle most of the "last mile" communication traffic for the individual subscribers, corporate offices, military, and possibly deep space probes. Indeed, lasers allow for concentration of energy within tightly focused beams and narrow spectral interval, thus offering high throughput, information security, weight and size of components and power requirements that could not be matched by RF systems. However, the advantages of optical communication systems come in the same package with several major challenges. In particular, high data rates should be complemented by high-precision wide-bandwidth position control of a laser beam. In many applications the ability to maintain a link is affected by the complex maneuvers performed by mobile communication platforms, resident vibrations, and atmospheric effects. The search for the most effective and reliable way to shape and steer the laser beam is an on-going effort. This paper is focused on the application of acousto-optic technology as an alternative to electro-mechanical devices. With realization that an acousto-optic Bragg cell is only a component of the entire communication system, which should perform complex tasks of acquisition, pointing, and tracking of the remote terminal, we present an attempt to consider this problem from the “systems” point of view.

Keywords: tracking, Bragg cell, adaptive control, quadrant detector

1. INTRODUCTION

While RF and fiber optics still dominate global communications, free-space laser-based systems are viewed as the technology that in the nearest future could handle most of the information transit throughout the world [1], including the last-mile links. Laser communication employs highly directional laser beams, thus affording intrinsically high bandwidth with small antennas and at low power, low probability of interception and detection and high resistance to jamming [2]-[4]. However, these advantages do not come without a price: due to low divergence, laser beams must be very accurately positioned on the target or the receiving station. In many aerospace applications when the transmitting optical platform is placed on board of an airplane the ability to track the target is affected by the complex maneuvers performed by the airplane, often at supersonic speed, the resident vibration of the airframe, and atmospheric effects.

A laser-positioning task must comply with the bandwidth, accuracy and the steering range requirements prompted by a particular application. The main challenge of this task is that it must address several specific problems: initial pointing of the laser beam, target acquisition, tracking a moving communication transmitter/receiver, stabilization of the optical platform and/or compensation of resident vibrations and other effects. Consequently, a laser positioning system is likely to feature a combination of several devices, a high-precision high-bandwidth mechanical or non-mechanical device performing target acquisition, tracking and compensation of resident vibrations, and a gimbal system responsible for the initial pointing and retargeting of the laser beam.

The search for the most effective and reliable way to form and steer the laser beam is an on-going effort. Non-mechanical devices such as acousto-optic Bragg cells are virtually inertia-free and; therefore, have a great potential for agile beam steering [5], [6]. They offer a solution to overcoming the speed limitations encountered with many mechanical steering devices. This paper features the synthesis of an advanced control system to facilitate fast and accurate tracking and presents the results of an experimental study.

Free-Space Laser Communications V, edited by David G. Voelz, Jennifer C. Ricklin, Proc. of SPIE Vol. 5892
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.617498

2. ACOUSTO-OPTIC BEAM STEERING

An acousto-optic cell, when used as a beam deflector, utilizes the effect of Bragg diffraction of the laser beam incident upon a volume grating (see Fig. 1). An ultrasonic wave is used to create regions of expansion and compression inside the Bragg cell, causing changes in density.

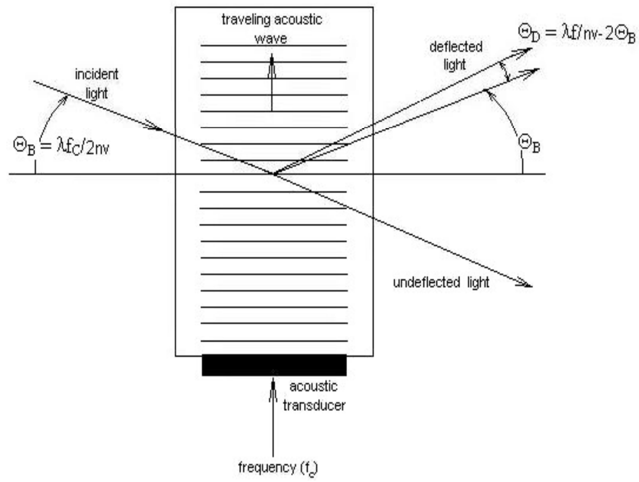

Figure 1. Bragg cell operation

The index of refraction is then periodically modulated and the medium becomes equivalent to a moving phase grating, where a change in the index of refraction of the Bragg cell follows the equation [7]

$$\Delta n(z,t) = \Delta n \sin(w_s t - \mathrm{K}z), \tag{1}$$

where z - position in the Bragg cell,

w_s - acoustic frequency,

K - acoustic wave vector.

The angle of incidence is selected in such fashion that the conservation of energy and the principle of momentum conservation between the acoustic and optical wave vectors during light-sound interaction is preserved [8]. It leads to a mathematical expression commonly known as the Bragg angle

$$\Theta_B = \sin^{-1}(\lambda f_c / 2nv), \tag{2}$$

where λ - optical wavelenght,

f_c – central frequency of the acoustic signal,

v - acoustic velocity in the interaction medium.

When the acoustic frequency applied to the Bragg cell is varied from f_c to $(f_c+\Delta f_s)$, there is a change in the magnitude of the sound vector equal to $\Delta K=2\pi(\Delta f_s)/v$ [1]. As a result, the diffracted beam will propagate along the direction that least violates the momentum conservation principle. This change in the sound vector results in a small angular motion of the deflected beam and is found to be proportional to the frequency of the input acoustic signal via

$$\Delta\Theta = (\lambda * \Delta f_s)/(n * v), \tag{3}$$

hence the direction of the diffracted beam could be controlled by the frequency of the acoustic signal as follows

$$\Theta_D = \lambda/(nv) * (f - f_c) \tag{4}$$

It should be noted that (4) represents static properties of a Bragg cell as a steering device. It relates the frequency of the RF signal to the steady-state value of the deflection angle without reflecting any transient characteristics. Designing a control system for agile beam steering requires the knowledge of the dynamic properties of a steering device.

The direction of the diffracted beam changes as the acoustic wave with an updated frequency traverses the aperture of the Bragg cell. Experimental studies show that an acousto-optic device does not exhibit overshoot [9], [10]; therefore, its dynamics could be approximated by that of a first-order system. Response time, also known as access time, is related to the aperture size of the Bragg cell w and also to the properties of the interaction media (acoustic velocity) via the following equation

$$T_{resp}=w/v, \tag{5}$$

then, the associated open-loop bandwidth is found as

$$w_b = \frac{4}{T_{resp}} \tag{6}$$

As a result, the steering model of the Bragg cell can be established in the form of the following transfer function

$$G(s) = \Theta_D/(f-f_c) = [\,\lambda/(nv)\,] \ * [\, w_b / (s+ w_b)\,] \tag{7}$$

Definition of the parameters of the above model and extensive study of the acousto-optic phenomena suggests no cross-coupling between two sequentially mounted Bragg cells, when two-dimensional steering is required.

3. TRACKING SYSTEM AND ITS MAIN COMPONENTS

A generic configuration of an acousto-optic tracking system is shown in Fig. 2. It includes two Bragg cells required to perform 2-dimensional beam steering and a quadrant detector, which provides beam position feedback to the controller that regulates frequencies of the RF signals.

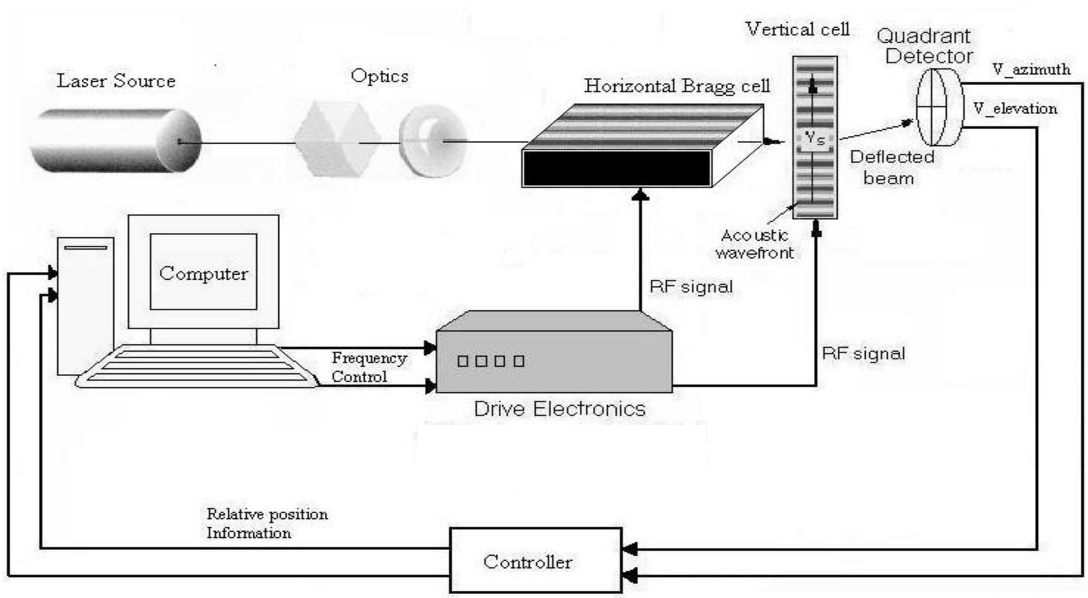

Figure 2. Acousto-optic tracking system

The Bragg cells used in this study are made from tellurium dioxide (TeO_2 or paratellurite) and are driven by ultrasonic signals with a center frequency at 24MHz and the acoustic bandwidth of 12 MHz. The electronic subsystem uses direct-digital-synthesis (DDS) and consists of a control interface card, two DDS cards, and an RF section, all self-contained in one box. The electronic subsystem is interfaced to a PC, which generates control and frequency information via a digital input-output card. FIFOs in the Control Interface Card buffer and then latch two channels of frequency information to the DDS cards upon command from the PC. The position-sensing detector is an avalanche photodiode with a quadrant structure connected to four trans-impedance amplifiers (TIAs), whose outputs are used to generate the azimuth and elevation feedback signals.

4. CONTROL SYNTHESIS

The dynamics of a Bragg cell is characterized by a first-order transfer function of (7), which is also supported by the results of our step response experiments [9], [11]. Considering that the access time of these devices could easily be on the order of tens of microseconds or less, their steering bandwidth is typically very large (usually on the order of tens of kHz). Therefore, a simple gain controller in the feedback appears to be sufficient to reject most of the distortions, and an equation for the control effort applied to a Bragg cell could be written as follows

$$f=f_c+H^*v_{az,el}\ , \tag{8}$$

where $v_{az,el}$ – azimuth or elevation feedback signal from the quadrant detector.
This approach, however, does not work in practice. Our quadrant photodiode will be a source of several types of noise, including signal shot noise, background noise, and dark current noise; while thermal noise will be generated in the electronic circuitry. System performance will be affected by all noise frequencies within the passband of the tracking system, which will pose a significant problem. Indeed, a device as agile as a Bragg cell would respond to almost any signal coming from a quadrant detector, regardless of whether the signal represents an actual displacement of the laser beam or just the additive noise. Therefore, a constant gain controller in the feedback needs to be complemented by intelligent filtering of the position measurement signal. A block diagram of the proposed control system, per channel, either azimuth or elevation, is presented in Fig. 3.

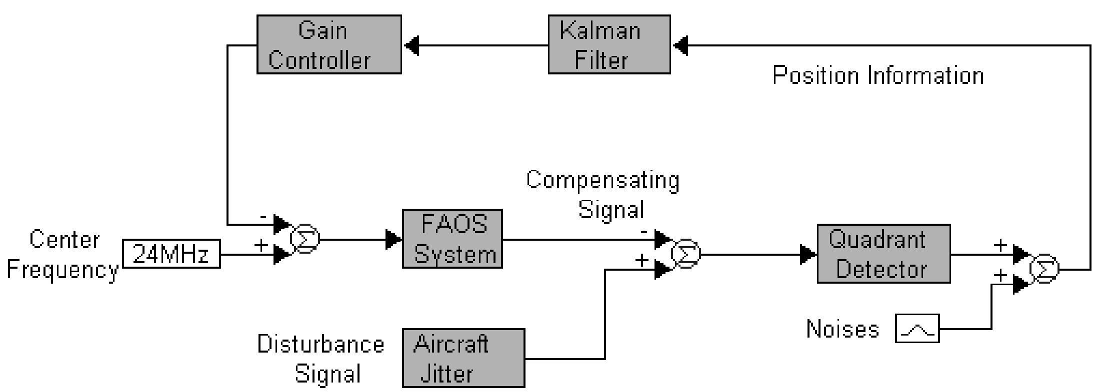

Figure 3. Control system configuration

A disturbance signal with a specific spectrum, e.g. representing aircraft jitter, continuously affects the pointing direction of our transmitter. If this disturbance is not completely compensated by a fast acousto-optic steering (FAOS) device, the resultant pointing angle error causes response in the quadrant detector. Since a signal from the detector is contaminated with noise, it is first filtered, and then used by a constant-gain controller to adjust the frequency of AOSD around f_c=24MHz. The purpose of a Kalman filter is to estimate the state of a system from measurements, which contain random errors due to the noises in the tracking system.

Since the controlled plant (acousto-optic device) in this case is a first-order system, the implementation of a first-order Kalman filter would probably be sufficient for rejecting measurement noise. Generally, a first-order system could be expressed in the discrete-time domain as follows:

$$y_n = x_n + a \cdot y_{n-1}, \tag{9}$$

where x – filter input;
y – filter output;
a – parameter of the model.
Then an equation for a first-order Kalman filter is

$$y_n = \frac{M_{n|n-1}}{s + M_{n|n-1}} \cdot \left(x_n - a \cdot y_{n-1}\right) + a \cdot y_{n-1}, \tag{10}$$

where s is the noise variance and

$$\begin{aligned} M_{n|n-1} &= M_{n-1} \cdot a^2 + \left(x_n - a \cdot y_{n-1}\right) \\ M_n &= M_{n|n-1} \cdot \frac{1 - M_{n|n-1}}{s + M_{n|n-1}} \end{aligned} \tag{11}$$

The above control and adaptive filtering algorithms are iterative and could be programmed in software. The frequency at which the control outputs to the AOS system are updated could be very high (tens of kHz or more) and is simply a function of the hardware characteristics and the latency in software-hardware interaction.

5. LABORATORY SYSTEM CONFIGURATION

An experimental tracking system was assembled on an optical table as the schematic in Fig. 4 shows. The parts on the right-hand-side are installed in the transmitter, while L, M3, M4, and QD could represent receiver components.

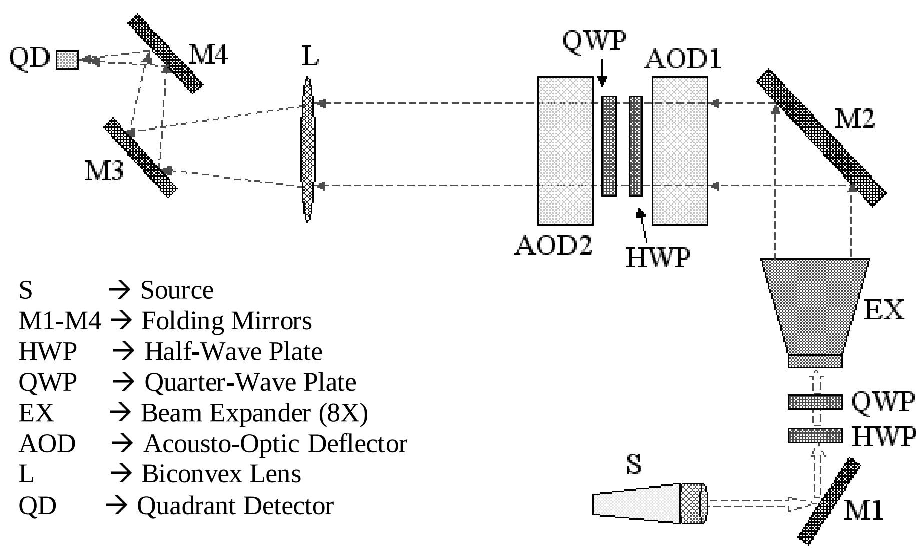

Figure 4. Acousto-optic tracking testbed

A beam from a HeNe laser source with λ=633nm is sent through an optical path which includes two orthogonal-mounted acousto-optic deflectors for horizontal and vertical steering. The beam is expanded to approximately 12mm in diameter to fill the apertures of the AODs. Since the Bragg cells are designed to work with circularly polarized incident beams, two sets of half-wave plates and quarter-wave plates are used for this purpose. Lens L, representing the receiver aperture is used to focus the beam on the quadrant detector. A number of folding mirrors are also used in the setup.

Tracking experiments require some disturbance to be applied to alter the pointing direction from the transmitter to the receiver. In our original approach, a Physik Instrumente piezo-electric mirror was installed in place of M4 to introduce tip/tilt fluctuations of the arriving beam, which would be compensated by the tracking action of the Bragg cells. However, the bandwidth of the mirror, which was roughly 500Hz, did not allow higher frequency pointing distortions to be introduced and made it very difficult to test the acousto-optic devices in that spectral range. An alternative to using a mechanical mirror is another set of Bragg cells, capable of much faster operation. However, these devices are linear, and proportional increments/decrements of the acoustic frequency result in linear increase/decrease of the pointing angles. We were able to take advantage of this property by using the same cells for both pointing angle disturbance and compensation. Details of this approach as well as the electronics setup are presented in Fig. 5.

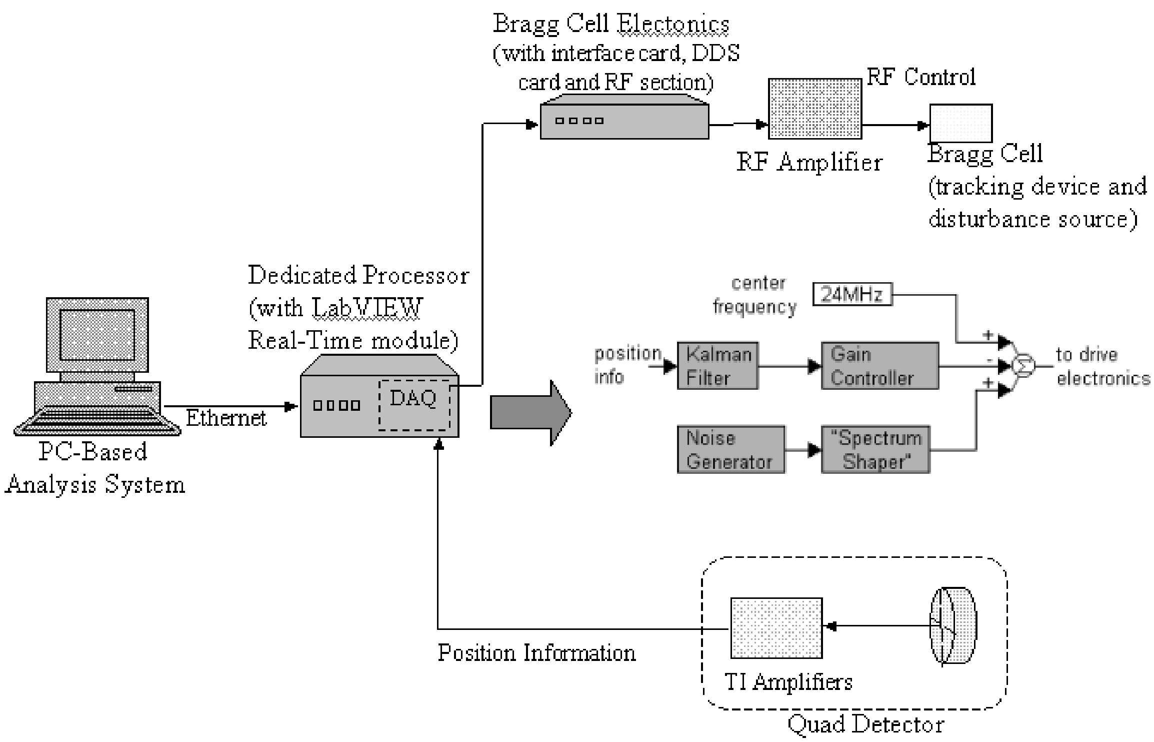

Figure 5. Electronic system setup

As can be seen in the above figure, both the compensating signal from the feedback gain controller and the noise are combined to give a cumulative effect of the pointing errors and the tracking action. The noise is initially generated with an infinite spectrum, but then it is changed by a “spectrum shaper.” The latter represents a single filter or a combination of filters capable of producing a signal whose spectrum could be similar to a practical communication scenario, e.g. vibrations of an aircraft, spacecraft, or the effects of turbulence.

The control system is built using National Instruments data acquisition (DAQ) boards and LabVIEW Real-Time software [11]. A Pentium-IV class desktop computer was converted into a real-time dedicated hardware target that runs a single-kernel real-time operating system. Experimental algorithms were first developed on a Windows host computer and then downloaded onto the real-time hardware target via an Ethernet link. Upon completion of each experimental run the same host computer was used for temporal and spectral data analysis.

6. EXPERIMENTAL RESULTS

The designed tracking system has been tested under pointing disturbance conditions, which could represent mechanical vibrations of the communication platform or the effects of optical turbulence, resulting in the change of beam direction. The results of this experimental study are summarized below. First, the baseline noise characteristic was obtained. For this purpose, the beam was centered on the quadrant detector by moving the latter manually with precision mount knobs. This resulted in zero mean signals representing the azimuth and elevation displacements, but due to the noises generated in the system, mostly through the shot noise mechanism and the thermal noise mechanism, we always had nonzero signals from the position sensing circuitry. A spectral characteristic of the radial displacement signal, representing our noise floor, is featured in Fig. 6.

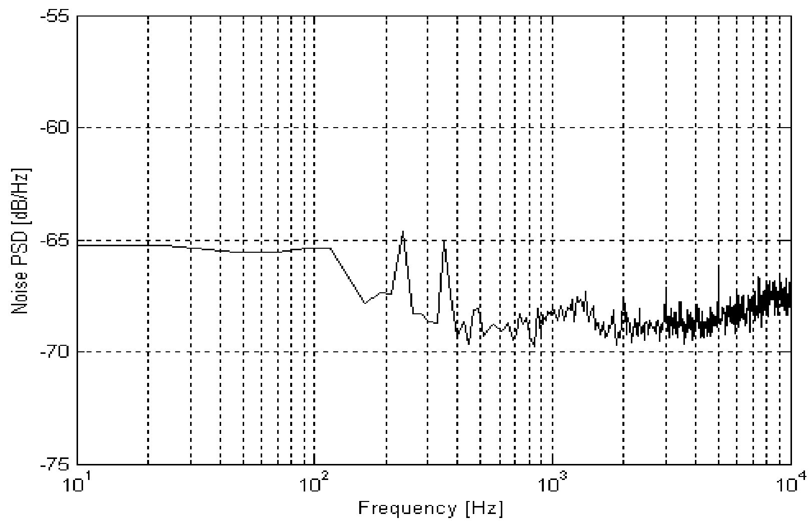

Figure 6. Spectral characteristic of the electronic noise

An important aspect of a tracking experiment is the choice of a disturbance signal, whose spectral characteristics are supposed to represent a specific communication environment. These could be, for example, recorded vibration spectra from satellites, aircraft, ground vehicles, etc. All these characteristics have very particular shapes, possibly with resonant peaks, representing operation of specific subsystems onboard the communication platform as well as its motion patterns. In principle any of these spectral characteristics representing motion, vibrations or turbulence effects could be implementing in our experimental setup by tuning the “spectrum shaper” module shown in Fig. 5.

However, for the purpose of this demonstration we chose a more generalized spectrum. A disturbance signal was formed by filtering random noise with a third-order low-pass filter with a bandwidth of 2kHz. This results in almost flat spectrum extending to 2kHz, which exceeds the effects of most of the realistic environments where precise pointing of a laser beam is adversely affected by vibrations and atmospheric effects. This signal was generated twice and applied to both horizontal and vertical channels of our system without activating tracking, while azimuth and elevation responses were recorded. The two outputs were combined into a radial signal, whose power spectral density is shown by a solid line (‘uncompensated’) in Fig. 7. It should be noted that this spectral response includes both, the actual beam motion across the quadrant detector, and the electronic noise, with a spectrum shown in Fig. 6. Sampling of the two outputs was performed at a rate of 24,000 samples/second; therefore, the highest frequency that could be detected by a frequency-domain analysis procedure is 12kHz. It can also be seen from Fig. 7 that at frequencies exceeding 8kHz only the electronic noise effects are observed.

The same disturbance signal was used to test the performance of the tracking system. The control loop, implementing the procedure given by (8)-(11), was designed to operate at a rate of 24kHz, same as the sampling rate. The spectral response of the tracking system is shown by a dotted line in Fig. 7. As can be seen from the results, 7 to 9 dB of noise rejection is assured at frequencies up to a few hundred Hz. The bandwidth of the tracking system, defined at the frequency where

3dB reduction of the disturbance is achieved, is equal to 2,203Hz. This is sufficient for rejecting most of the vibration effects and could, to a significant degree, compensate beam wander or wavefront tilt due to the atmospheric distortions.

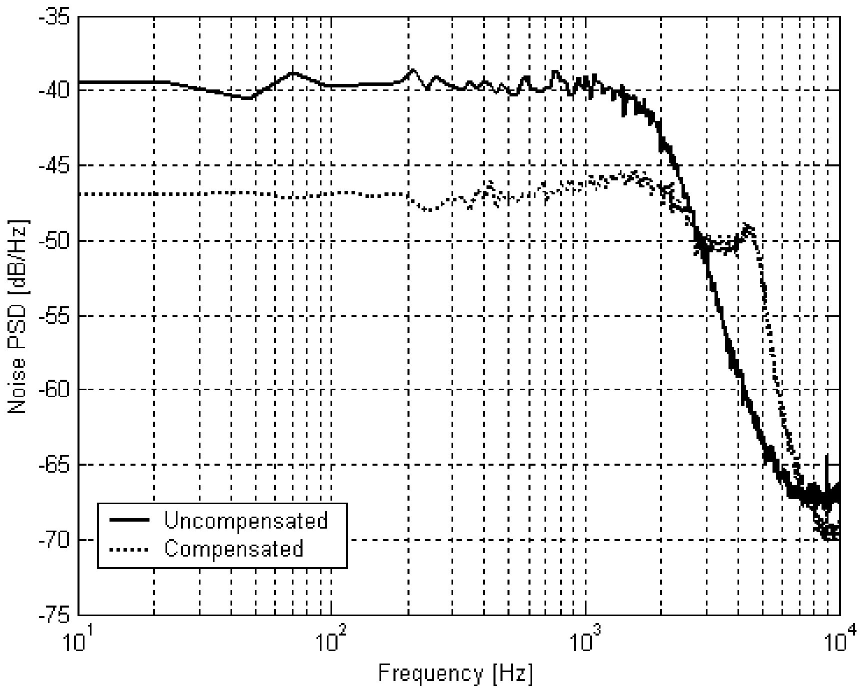

Figure 7. Spectral response of the acousto-optic tracking system

It could also be observed that fast steering action of the acouso-optic cells introduces additional noise at higher frequencies. However, this happens in the stopband of the tracking system, where the magnitude of the spectrum is already low. Performance of the designed system could be compared to the uncompensated case by calculating noise variances as follows

$$\sigma^2 = \int_0^\infty S(f)df, \tag{12}$$

where *S(f)* – power spectral density of the noise signal.

Numerical calculations using the spectral data presented in Fig. 7 give variance of the uncompensated radial displacement signal σ_u^2=0.2258V^2, and variance of the compensated radial signal σ_u^2=0.0831V^2. Another characteristic of the performance is the signal-to-noise ratio (SNR) in the tracking system, where the signal is calculated as a squared sum of mean voltages from the four quadrants, and the noise is a summation of the noise variances from the quadrants. Analysis of the measurement data shows that SNR=11.1 and SNR=30.02 for the uncompensated and compensated cases, respectively.

CONCLUSIONS

This paper presents a non-mechanical pointing and tracking system for free-space laser communications. It was implemented using acousto-optic Bragg cells to assure agile beam steering. Experimental results were obtained on a laboratory prototype, and the tracking bandwidth exceeding 2kHz was demonstrated with a rate of the control loop equal to 24kHz. The system is capable of compensating the effects of most practical vibration environments and could also provide partial mitigation of the atmospheric effects. Adaptive filtering was implemented to alleviate the effects of the electronic noise in the position sensing circuitry on the tracking performance. It is most likely that increasing the rate of the control loop would benefit both the filtering process and the control system, thus extending the tracking bandwidth, decreasing the additional noise introduced by the Bragg cells at higher frequencies, and reducing the noise in the received signal.

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