Near-Infrared (IR) Spectrometric Imaging Using a One-Meter Fresnel Telescope

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A near-infrared optical telescope with an aperture of approximately one-meter has been constructed to detect interstellar laser transmissions. The near-IR telescope (4760 to 25000 cm^{-1}) is being operated at the University of Kentucky in conjunction with a microwave radiotelescope for Project Argus. The telescope comprises a one meter visible / near-IR Fresnel lens, an aluminum compound parabolic concentrator, tilting interference filters, a robot for detector translation and star tracking, a liquid nitrogen Dewar and detectors (PbS, InSb, and InGaAs) and a 50 MHz preamplifier with 26 dB gain (max. data rate approximately 3 Gb per minute). Autocorrelation and cross-correlation are applied in screening the data collected. The telescope is currently used in targeted searches, in part because of the volume of data collected. In this initial experiment, a well-studied target was selected, and spectra were collected near the star Vega.

Introduction

The search for optical signals from civilizations on distant planets has been slowly growing, as in the early stages of an unseen epidemic, since its modern beginning nearly four decades ago (Schwartz 1961). As knowledge of the optical approach and its potential advantages has slowly spread, the number of sites conducting optical studies has begun to increase. The Columbus Optical SETI Observatory, Harvard / Smithsonian, Princeton University, Schaller Observatory, University of California Berkeley, SETI League and more now have programs aimed at detecting continuous, pulsed or otherwise modulated laser signals.

The birth of adaptive optical telescopes encouraged more scientists to search for interstellar laser communications. The application of bendable mirror technology and laser guide stars in telescopes allows most of the signal distortion produced by the atmosphere to be removed, resulting in near diffraction-limited performance of ground-based receiving telescopes. The same technology that permits distortion to be removed from received signals also permits atmospheric distortion to be removed from transmitted signals when the transmitting laser is directed toward the flexible mirror instead of directly into the sky.

Modulation schemes that permit high peak transmitting power to be employed increase S/N (Ross 1965, Kingsley 1995). Low duty cycle, brief-pulse laser modulation with high peak-power enables transmission of signals over immense distances with low average power and high efficiency. Meaningful data can be transmitted by each pulse in digital pulse-position modulation when the number of possible discrete delays is large. Because the signal energy in a short pulse can overcome the noise generated by the emission spectrum of the nearby star, precise discernment of optical frequency is not required. Frequency selectivity can still be employed if desired to reduce such background interferences. Nonimaging optical concentration systems permit the construction of large area collectors at low cost.

Given the distances involved and the size of the transmitters, any emitters can be considered as point sources of light. The ability to form an image is not strictly required in an optical communications receiver. Imaging limits the receiver design unnecessarily when only power concentration is required. Nonimaging solar power collectors have been built that exceed the concentration achievable with diffraction-limited focusing techniques by a factor of four or more, and approach the theoretical limit fixed by the second law of thermodynamics ([illegible]). Such a nonimaging concentrator, in combination with a traditional telescope mirror, has been used to concentrate sunlight by a factor of 56,000 and produce irradiance exceeding that of the solar surface. A Fresnel lens can be substituted for the parabolic mirror with some loss of efficiency due to lens absorption and lack of correction of spherical aberration and coma. However, some of this loss can be restored with proper design of compound parabolic concentrator (CPC) using edge-ray calculations (Welford 1978). A CPC is designed to concentrate skew rays on the detector(s). The earliest use of CPCs was in concentration of the diffuse blue glow of Cerenkov radiation. The concentration of light from a Fresnel lens is also possible using CPCs.

Near-infrared light rays may be among the best candidates for concentration, in part because near-IR light penetrates galactic dust better than visible light (Gemini North 1999). In addition, the intensity of Rayleigh scatter from the molecules of the atmosphere falls off as 1/wavelength^4. Reduced Rayleigh scatter means reduced interference from terrestrial background light. Good detectors with quantum efficiencies of 70% or more are available in the near-IR. Many bright laser sources are known in this spectral region. All of these factors combine to suggest that a near-infrared telescope using nonimaging optical components might be an effective receiver for laser communications over long distances.

Experimental

A near-IR telescope was constructed using an aluminum compound parabolic concentrator and a 0.914 m diameter visible / infrared Fresnel lens (Edmund Industrial Optics, Barrington, NJ). The CPC was machined and polished from a solid block of aluminum with a light entrance-port diameter of one cm and an exit port diameter of one mm.

Fig.1 demonstrates how a CPC is able to concentrate skew rays. In this 2-D representation of the 3-D reflector device, each side of the CPC is parabolic, with a focal point on the opposite edge of the light exit port. The focus in 3-D is therefore a circle. Skew rays entering from any angle between the representation on the left and the one on the right are directed onto a detector placed at the light exit port after a maximum of one reflection, minimizing losses. As light rays move from the angle at left to the angle at right, the focused rays move from the left to the right across the detector. The CPC concentrates light that cannot be focused sharply by the Fresnel lens, making it possible to place two small photodiode detectors at the exit port of the CPC. The use of two detectors can help to eliminate some noise sources. However, in this experiment only one InGaAs detector (Fermionics, Simi Valley, CA) was employed.

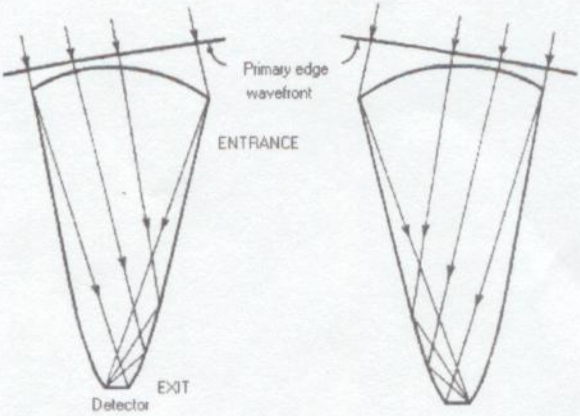

Figure 1. This CPC can concentrate skew rays arriving over the solid angle between the picture on the left and the picture on the right.

Thermodynamics places an upper limit on the concentration ratio of any optical device (Gleckman 1989). The limiting concentration ratio, C_{max}, is a function of the angular size (2 theta) of the target object:

$$C_{max} = 1 / \sin^2 \theta \qquad \text{eq 1}$$

Fig. 2 graphs the relationship between concentration ratio and angular size. Using the sun (theta=0.27°), Gleckman et al. calculated the thermodynamic concentration limit to be 45,032. A point source can theoretically be concentrated infinitely, while a source with an apparent size somewhere in between (e.g. a point source through a Fresnel lens) also has an intermediate maximum-concentration ratio.

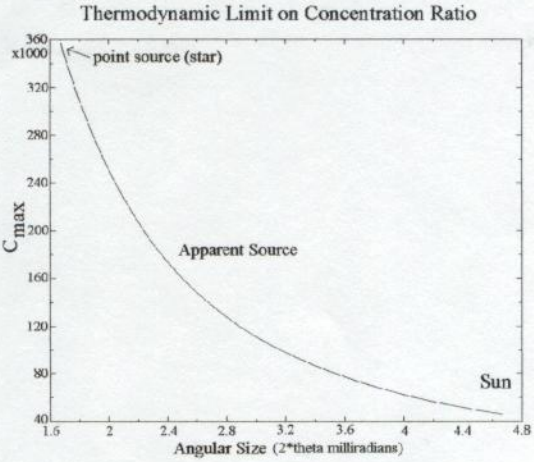

Figure 2. The thermodynamic limit on the optical concentration ratio is a function of the angular size of the target object.

The apparent size of a point source varies depending upon its location relative to the axis of the lens, but 2.2 mrad is a rational figure for this telescope.

A schematic drawing of the near-IR telescope is given in Fig. 3. The baffles are constructed from Foamcore. The optical chopper (Grainger), CCD array (Edmund), IR detector, cooler (Biorad) and interference filter (OCLI, Santa Rosa, CA Rosa) are mounted on a translation stage (Arrick Robotics, Hurst, TX). Filters are available from 4760 to 25000 cm^{-1}, and can be tuned to lower wavenumbers by tilting them in their mount. The use of interference-filter wavenumber selectivity reduces background light reaching the detector, it offers discrimination against distant broadband sources, and it should enhance measurements made during daylight. In typical use, the telescope is locked into an azimuth and elevation and the detector is translated to track a certain area of the sky using the robotic translation stage. The optical chopper is used for focusing and star tracking in the visible spectral region, and it can be pivoted over the detectors or away from the detectors as needed. The JFET preamplifier (26 dB gain) is configured as a high pass filter to amplify short pulses. An 8-bit A/D (Wittig, Boeblingen, Germany) is used to digitize the signals. The short pulsed light source for testing in the near-IR is a Mirage 3000 Nd:YAG-pumped optical parametric oscillator (Continuum, Santa Clara, CA) that produces 6 nanosecond pulses from 2440-7140 cm^{-1}. Collecting data with a high-

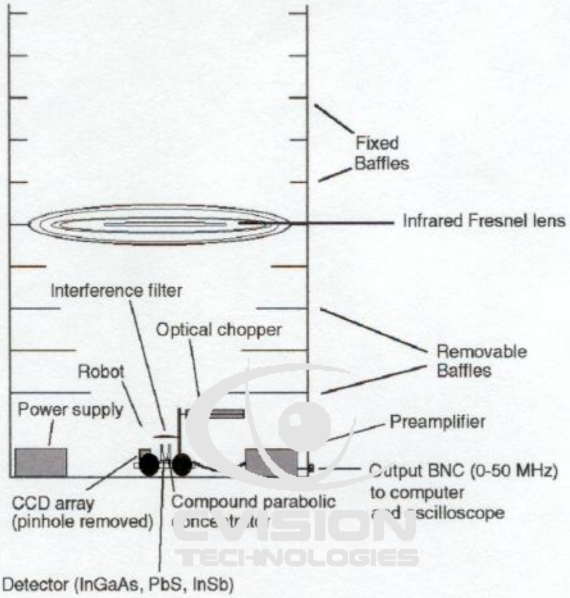

Figure 3. Diagram of the Fresnel / CPC near-IR telescope.

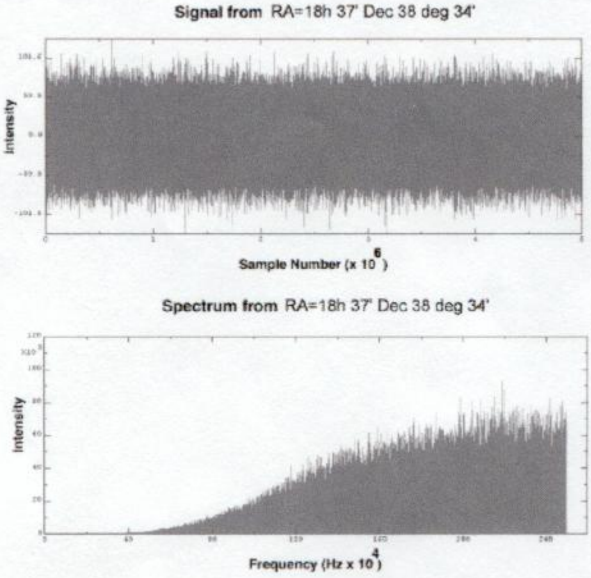

Figure 4. Signal intensity data in the time domain (top) and frequency domain (bottom). Filtering low modulation frequencies should reduce some sources of interference.

pass filter system eliminates many possible sources of interference, but does mean that a CW beacon might be missed. However, the amount of power required to operate such a beacon is likely to be too large to be practical.

Programs to collect data and perform autocorrelation and crosscorrelation analysis were written in Speakeasy IV Eta+ (Speakeasy Computing Corp., Chicago, IL). Imaging is accomplished with a nonimaging telescope system by translation of the telescope and detector to collect spatially resolved spectra.

Results and Discussion

The first spectra were collected near midnight at RA=18h 37', Dec=38° 34', in the direction of the star Vega. Data were collected every 200 nsec at 8-bit resolution, with one second of data shown in Figure 4. No interference filter was employed, and no unusual signals were detected. The Vega vicinity has been highly studied in the past, and so it provides a good test for interferences. The system has poor response at low frequencies, reducing interference from sources like atmospheric turbulence, airglow, scattered light and activities of humans. The telescope system is able to collect data every 20 nsec in bursts. At this rate, discrimination of interference pulses should be improved. The laboratory near-IR laser produces pulses with an average

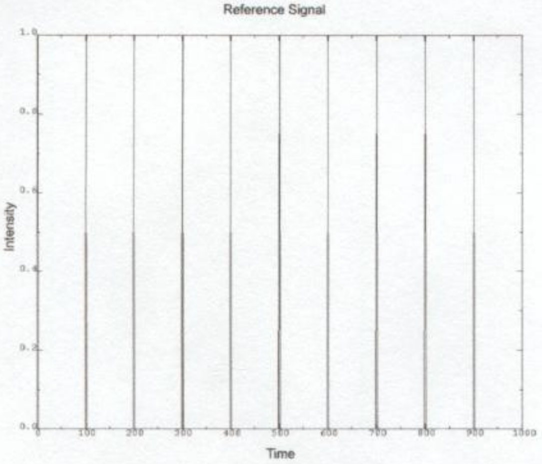

Figure 5a. The narrow pulsed signal added to the near-IR telescope noise in Fig. 5b.

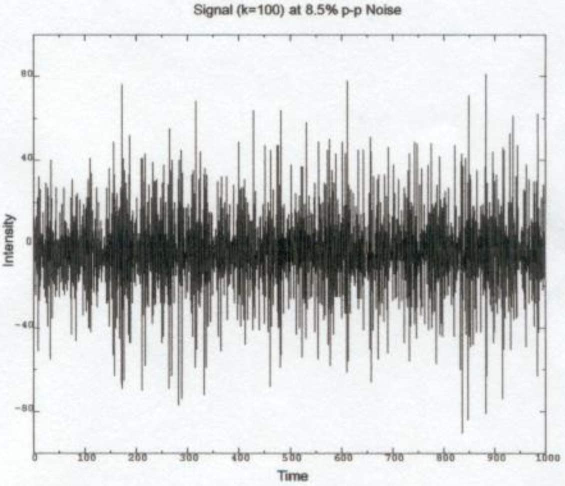

Figure 5b. Telescopic noise with a pulsed signal (at intensity=8.5% of noise p-p, shown in Fig. 5a) added.

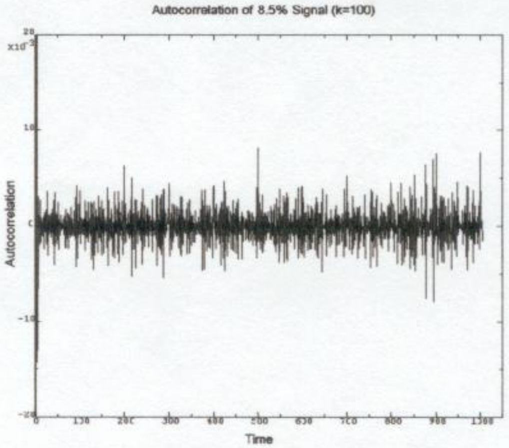

Figure 5c. The autocorrelation signal calculated from the signal in Fig. 5b.

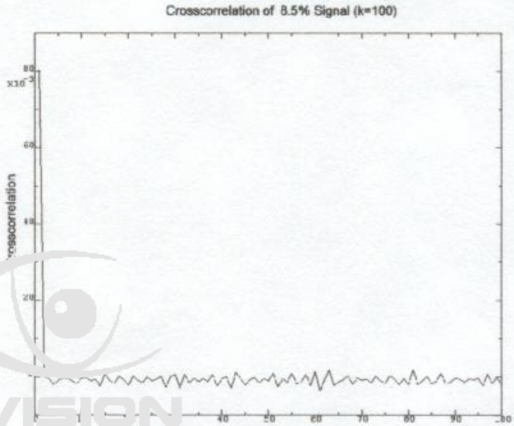

Figure 5d. The crosscorrelation signal calculated from the signals in Figs. 5a and 5b. The signal peak is at zero, and it compares very favorably to the noise.

duration of 6 nsec (FWHM). Each pulse undergoes 0.5-2 nsec broadening in the telescope, depending upon the geometry of the principal axis of the lens and the source of the pulse. (Stray light from the laser in the laboratory broadens the test pulses considerably more.)

Signal processing using autocorrelation and crosscorrelation might improve S/N on a pulsing beacon signal. In Figure 5, a small pulsed signal (Figure 5a, intensity = 8.5% of the peak-to-peak noise) was injected into telescope noise to test pulse detection using correlation techniques. The pulsed reference signal is not visible in the noise (Figure 5b). However, the autocorrelation shown in Figure 5c does reveal at least a hint of the original signal. (These data were obtained near the detection limit for the pulsed signal by autocorrelation.) Crosscorrelation outperforms autocorrelation by a wide margin (see Figure 5d), but requires knowledge of the waveform sought in the noise. The detection limit for the pulsed signal by crosscorrelation is less than 1% of the p-p noise in this experiment. In actual use, however, the efficiency with which crosscorrelation detects signals in noise depends upon the accuracy of the estimate of the original pulsed signal (e.g., pulse shape, duration, frequency and phase). The creation of such estimates remains a topic for future research

Conclusions

Computation and storage can be one of the biggest barriers to making near-IR measurements with high sensitivity. Post-collection data processing requires the near-IR telescope to collect 4.3 Tb of data per day. A full sky survey would require an "epidemic" spread of additional near-IR telescopes with similar coverage, and would produce on the order of 1000 petabytes (1 exabyte) of data each day. While instruments can certainly be designed to detect candidate signals in real time, [illegible] signal-averaging methods can be employed.

Some scientists still ask, "Why develop instrumentation for remote biosensing?" Our civilization is unlikely to experience an epidemic of near-IR telescope construction for optical SETI experiments. The simple answer is that every major scientific advance has been preceded by an advance in measurement science that made a significant observation possible. That measurement equipment must be in place before the observation can be made, and that is what current researchers in optical SETI are at least beginning to accomplish at this time.

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More information on the research underway at the University of Kentucky is available at [illegible] 94/argus.htm