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Optical SETI: The Next Search Frontier

Michael Lampton

Space Sciences Laboratory, U. C. Berkeley, Berkeley CA 94720, USA

Abstract. Just as the 20th century growth of radio technology spurred radio SETI, the advent of infrared and optical communications is now making IR/optical ETI searches feasible. I review the electromagnetic windows open for communications and discuss photon-limited observing. The rapid growth in IR/optical technology is outlined; these advances include lasers, optics, image sensors, and data processing, all of which bear on issues of detection and communication. Ongoing IR/optical search techniques are described, and prospects for future work are presented.

1. Introduction

The field of optical and infrared SETI is in its infancy, lagging far behind the scope and sensitivity of radio searches. The reasons for this disparity are largely historical: when Cocconi and Morrison (1959) proposed that the radio and microwave bands offer the prospect of searching for ETI signals, radio telecommunications had been well established for decades, yet Earth-bound optical communications did not exist. Since its invention in 1960, however, the laser has sparked an enormous growth in optical communication. Schwartz and Townes (1961) pointed out that because of the high directivity of optical links, interstellar signaling with good signal-to-noise ratio is feasible with modest transmitting power using lasers. For a more recent overview, see Townes (1992). Continuing advances in detectors, lasers, optics and data processing are currently motivated by ever-growing demands for data bandwidth. These market forces inevitably improve all aspects of optical communications technology, including the feasibility of space optical data links. These advances in turn are making possible a variety of Optical SETI (OSETI) searches.

Is the time ripe for large-scale optical and IR SETI? In this short review, I address some basic considerations: signalling range, photon statistics, and possible signal types. Within this framework I identify four kinds of O/IR searches that could be conducted. Then I explore some of the emerging detector technologies, and outline the kinds of searches that have been, or are being, conducted. I conclude with an outline for the future prospects for this field.

2. The Electromagnetic Windows

Just as we on Earth face growing bandwidth needs, so might ETIs. The optical/IR bands offer huge bandwidth for data links needing high information rate and efficient beam formation.

Within about 1000 light years of Earth, interstellar space is essentially transparent in all directions. Indeed, away from the plane of our Galaxy, intergalactic space is transparent out to cosmological distances. In the plane of our Galaxy, extinction becomes serious in the visible band beyond 1000 light years but at closer distances, or in the infrared, optical communication is practical and efficient. For space based ETIs, the only spectrum blockages encountered are at very low radio frequencies, where the interstellar plasma imposes a cutoff, and the blockage from UV/EUV (3 to 30 PHz) extinction due to atomic absorption and scattering by interstellar dust. There are then two broad windows: the combined radio/IR/optical band, and the combined X-ray/gamma-ray band.

The situation is different for ETIs communicating from beneath Earth-like atmospheres. The transmission wavebands are narrower: the ionosphere LF cutoff is higher, and the 0.1 to 100 THz band is largely blocked by atmospheric water vapor and other molecular species. The UV, X-ray, and gamma-ray bands are entirely blocked by photoabsorption. So for ground based ETIs, the natural division in communications regimes divides into the radio/microwave band and the NIR/optical band.

We conclude from these contrasting situations that the choice that ETIs might make for establishing communications links or beacons are influenced by their habitats. Spacefarers and ground dwellers have different electromagnetic windows. The human race is presently just beginning its venture into space, and as such is situated between these two regimes: we have a few (expensive!) space observatories orbiting Earth, while terrestrial communications is managed by radio and fiber links. SETI is presently low-budget and hence Earth-bound, restricting it to the radio and optical bands, which I will contrast further below. However, in the not too distant future, SETI could be pursued from spaceborne platforms, opening up much broader windows.

3. Is Interstellar Optical Communication Feasible?

Given that we have the bandwidth motive for optical, are optical links practical? Since nothing is known about ETI transmitter capabilities, a feasibility question like this is usually addressed by adopting current Earth technology at both ends of a link, and calculating communications ranges for feasible energy levels, antenna sizes, and signal-to-noise ratios.

For an omnidirectional transmitting beacon, the amount of transmitted energy needed is

$$E_{trans} = \frac{4\pi R^2}{A_{rec}} E_{rec}\,, \tag{1}$$

where R is the range, A_{rec} is the area of the receiving antenna, and E_{rec} is the minimum detectable received energy. This expression is independent of frequency except for the explicit factors A_{rec} and E_{rec}.

In the optical, our biggest receivers are the ten meter telescopes, for which $A_{rec} = 100\,\mathrm{m}^2$. A signal has to have at least (say) ten photons to be detected, so $E_{rec} = 10^{-18}$ J. At a range of 1000 ly, the minimum transmitted energy is then 10^{19} J.

In the radio, two savings accrue: receiving antennas are larger, and the minimum detectable energy is lower – ten kT, or 10^{-21} J. So the minimum transmitted energy at 1000 ly is only 10^{14} J, a savings of 50 dB. We conclude that omnidirectional beacons are substantially less expensive in the radio than in the optical.

How about directed beams? Here, optical links excel because optical energy is far more easily directed than low frequency radio energy. Specifically, the transmitting gain G_{trans}, offered by a diffraction limited dish of area A_{trans} is

$$G_{trans} = \frac{4\pi f^2 A_{trans}}{c^2}, \tag{2}$$

which increases as the square of the frequency, f. Although optical dishes have merely 1/100 the area of the larger radio dishes, the ten orders of magnitude benefit from the f^2 factor brings an 80 dB improvement. Then for a directed 1000 ly link the needed transmitted energy is 10^4 J in the optical, compared with 10^7 J in the radio. Since existing inertial-confinement lasers are already at this energy level, there are no fundamental obstacles to such links. Seen from this standpoint, the optical band appears highly efficient for directed communications. Thus, our Galaxy, and others, may already be woven by vast networks of such links, and OSETI searches could discover evidence of these.

4. Why Photons?

Radio astronomers and optical people tend to have trouble communicating. Part of the problem is units, but a bigger problem is the nature of radiation itself. In an isothermal enclosure at temperature T there are two frequency regimes. At frequencies below the blackbody peak at $f_{peak} = kT/h$ there are many photons in every electromagnetic mode and their Bose-Einstein fluctuations set the system noise level. But at $f > f_{peak}$ photons are few and the electromagnetic modes are mostly empty. Because independent modes give statistically independent detections, in this high frequency regime photon arrivals are independent of each other. Photons can be individually counted, and their accumulation is governed by Poisson statistics.

4.1. The Sky Spectrum

The night sky spectrum has several important components. Galactic radio emission dominates up to 1 GHz, above which the cosmic microwave background (CMB), which contains the bulk of the electromagnetic energy in the Universe, dominates up to about 1 THz. Above that, in our Galaxy, diffuse infrared and visible starlight dominate, extending to a few PHz. Beyond that, at much lower intensity levels, the X-ray and gamma-ray bands extend to the highest observable photon energies.

For observers there is an important dividing line that crosses this broad spectrum. It is the intensity equal to $2\,h\,f^3/c^2$, along which there is an average of just one sky photon per electromagnetic mode. To the left and above this line there are many photons contributing to each sample of the EM field. To the right and below, there is on the average less than one photon per mode. Photon counting becomes a natural way to observe in this high-frequency regime.

4.2. Are Stars a Problem?

The optical sky is extremely inhomogeneous – there are stars, and there are spaces between them. A source ETI would likely be located within a few AU of a star where energy is plentiful. Then, from Earth, atmospheric seeing would blur it with that star at any reasonable distance (e.g., at 1000 ly, one arc second = 330 AU). If the optical ETI signal were a star-like steady continuum it would certainly take an astronomical power level to become evident. However if it had a strong narrowband character, or took the form of brief pulses, or both, it could easily stand out against the steady stellar continuum. Table 1 shows the number of photons accumulated looking at a one square arc second patch of sky, with or without a star present, using a broadband or narrowband detector. In this example the star is a typical sun-like star at 1000 ly, hence $m_V = 12.0$ delivering a photon flux of 10^3 photons $\mathrm{s}^{-1}\,\mathrm{m}^{-2}\,\mathrm{nm}^{-1}$. The wideband example has $\Delta\lambda = 1\,\mu$m and the narrowband example has $\Delta\lambda = 0.01$ nm. The count accumulations are for a perfectly efficient detector.

Table 1. Examples of mean photon count accumulations
Receiver: one 10 meter telescope
Field of view: 1 sq arcsec

		Wideband	Narrowband
Dark sky			
	1 second	25000	0.25
	1 millisec	25	-0-
	1 microsec	-0-	-0-
	1 nanosec	-0-	-0-
	1 picosec	-0-	-0-
One m_v=12 star			
	1 second	1E8	1000
	1 millisec	1E5	1
	1 microsec	100	-0-
	1 nanosec	0.1	-0-
	1 picosec	-0-	-0-

We conclude from this short example that starlight essentially disappears when examined on very short time scales appropriate for searching for brief optical pulses, or on very narrow bandwidths appropriate for searches for unusual line emissions, possibly modulated in some way.

5. What Search Methods Might we Use?

This question raises issues of transmission modalities, alternative search strategies, and cost. Four kinds of searches might be envisioned in the optical/IR:

- *Targetted Pulse*: The nearest thousand (or million) candidate stars could be observed on a regular basis for the presence of unusual optical pulses.

Whereas natural flaring has a time scale of minutes, and atmospheric twinkling has a time scale of milliseconds, pulses in the microsecond regime and below cannot arise from known natural causes, and their detection would constitute a major new discovery, possibly an ETI signature.

- *Targetted Line*: The nearest thousand (or million) candidate stars would be surveyed for extremely narrow emission lines, possibly being modulated or otherwise time variable. Although natural masers are known, an inexplicable wavelength or modulation pattern would constitute a major new discovery, possibly an ETI signature.
- *Untargetted Pulse*: A wide field of view pulse detector, possibly with imaging capability, could remain exposed to a patch of sky for long time periods each night. The target field might include galaxies, star clusters, portions of the Milky Way, etc. Brief pulses on the nanosecond or picosecond time scale would be sought. Cosmic ray Cerenkov atmospheric fluorescence could be rejected by using two separated sites in coincidence. Because of the similarities to the existing fly's-eye cosmic ray observatories, collaboration with cosmic ray groups could be productive.
- *Untargetted Line*: Wide field objective prism surveys have already covered the sky many times, although with rather low spectral resolution. The search would be archival, examining existing plate material for monochromatic stars, which automatic stellar-type classifiers would probably regard as plate defects. Follow-up spectroscopy would be needed to ascertain the nature of each candidate.

6. Visible/Near-IR Detectors

A remarkable variety of sensors suited to the detection tasks outlined above are now available. In Table 2, I have summarized their salient properties.

7. Searches to Date

A number of workers over the past 25 years have reported carrying out optical and infrared searches for ETI signatures, usually employing astronomical equipment or archival material developed as part of other programs. A few projects however are long term, and the interested reader should consult the current literature for their latest status. Although space does not allow a listing of these efforts, they divide into four kinds: dedicated facilities, facilities shared with other ongoing astronomical work, piggyback instruments, and data mining. We can reasonably expect the current large-scale surveys (SDSS, 2MASS) to provide even greater opportunities to conduct specialized searches of many kinds.

8. Conclusions

Rapid developments in the fields of optical signal detection, adaptive optics, high-speed image analysis are converging in such a way as to open new kinds of experiments and observations for OSETI. Novel observing instruments and

Table 2. Visible and near-infrared detectors

Device	Photon-counting?	QE	Gain	Time-resol	Pixels
Video CCD	No	0.8	1	10 ms	few 10^6
Photomultiplier	Yes	0.2	10^7	1 μs	1
APD-linear	Yes	0.8	10^3	1 ns	1
APD-Geiger	Yes	0.8	10^6	10 μs	1
SSPM (cryo)	Yes	0.8	10^5	1 μs	1
MicrochannelPlate	Yes	0.2	10^7	1 ns	10^6
STJ(cryo)	Yes	0.9	10^4	1 μs	few
Intensified CCD	Yes	0.2	10^4	10 ms	few 10^6
Photodiode-SiDiode	Yes	0.4	10^4	1 ns	1

strategies will discover how best to pursue these searches. At present, the OSETI community is exploring a large number of low-cost small-scale ideas to find out which are the most productive. As evidence of this, during the Optical Working Group's 18 month lifetime, three new projects have been started: P. Horowitz (Harvard) has begun campaigning an optical pulse piggyback instrument, D. Werthimer (Berkeley) has begun using a coincidence optical pulse detector, and G. Marcy (Berkeley) has begun mining existing high resolution spectra of nearby stars. Other new developments are described at this conference. Future work will certainly benefit from today's exploratory efforts.

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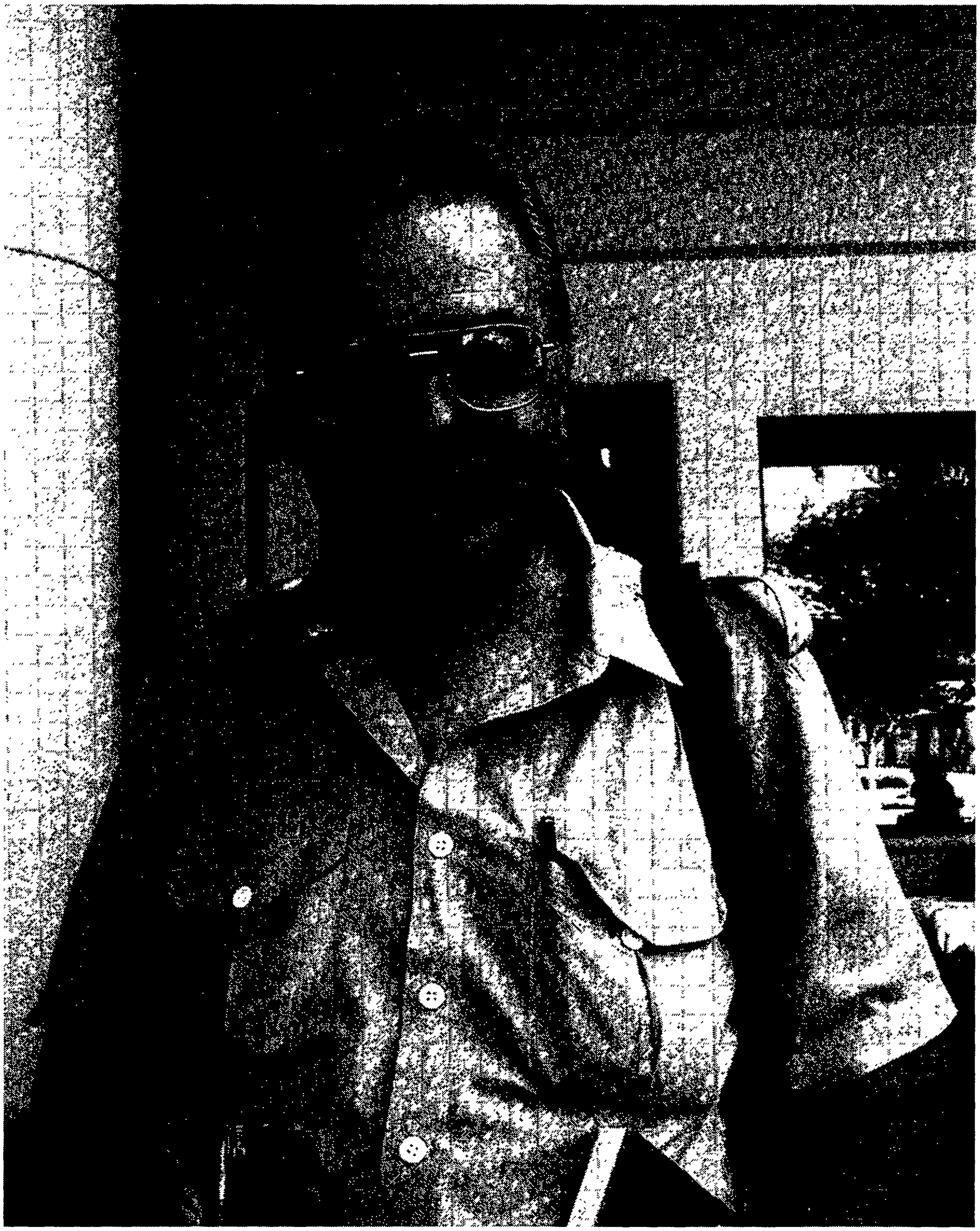

David Morrison

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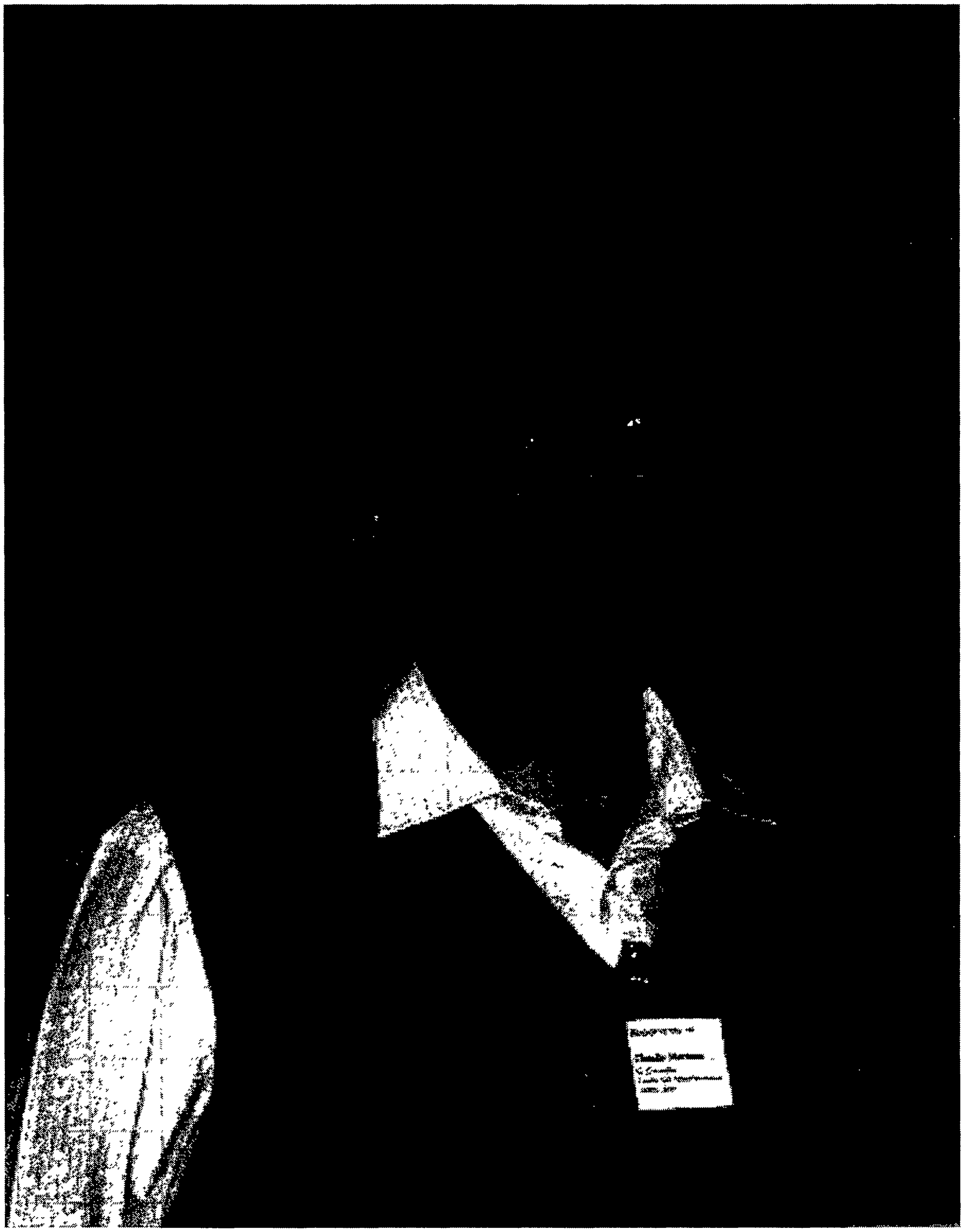

Claudio Maccone