Icarus **150**, 163–167 (2001)
doi:10.1006/icar.2000.6579, available online at http://www.idealibrary.com on IDEAL®

Optical SETI with NASA's Terrestrial Planet Finder

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Received May 24, 2000; revised September 13, 2000

NASA's space-borne nulling interferometer (the Terrestrial Planet Finder—TPF) will look for the traces of early life in the infrared spectra of extrasolar planets, beginning in roughly 2010. We point out that this instrument, as currently envisioned, will also be sensitive to deliberate laser transmissions from a technologically advanced civilization. A kilowatt-class infrared laser with a 10-m beam director would produce a signal visible to TPF at a range of 15 pc that is distinguishable from astrophysical phenomena and noise.

Key Words: **interstellar communication; SETI; extrasolar planets.**

1. INTRODUCTION

Slated for construction in roughly a decade, NASA's Terrestrial Planet Finder (TPF) will be a set of infrared (3–30 μm) telescopes whose combined light forms a nulling interferometer. Although details have yet to be worked out,[1] its high angular resolution (up to a maximum resolution of 0.75 mas at 3 μm for general imaging) will allow it to examine extrasolar planetary systems while nulling the light from the parent star. TPF will hunt for planets and will examine their structure, formation, and evolution. It will also search for the chemical signatures of life on these planets, in the form of CO_2, H_2O, CH_4, and O_3 absorption bands. We argue below that the features of this spacecraft also allow it to receive and identify intentional laser transmissions of modest power from extraterrestrial civilizations.

Historically, the Cocconi and Morrison (1959) suggestion that SETI be carried out at the 21-cm line of neutral hydrogen came at a time when no other astronomical lines were known in the microwave spectrum. In the following two years, the laser was invented, and Schwartz and Townes (1961) noted that these relatively low power "optical masers" could be used for interstellar communication. The suggestion has received increasing attention as lasers have continued to show an annual Moore's Law doubling in power over the past 40 years (during which time radio technology has remained relatively static). Today, there are optical SETI[2] programs at Harvard (Howard *et al.* 2000), Berkeley (Lampton 2000), Columbus (Kingsley 1996), and elsewhere.

The merits of optical SETI are well documented in other articles (Townes 1983, Kingsley 1993, Ross 1965), but we highlight a few advantages here. Given the high gain of optical telescopes, optical beacons can be narrowly focused on target systems. The bandwidth-limiting dispersive broadening observed in radio pulses is negligible in the optical regime. The computational power and sophistication required for broadband microwave SETI searches is unnecessary in optical SETI. Finally, the pace of laser development on this planet has made possible optical interstellar communication *from* Earth; shouldn't we be looking for such communication *to* Earth?

TPF will be one of a handful of instruments in the Solar System sensitive to optical interstellar communication. Clearly, such instruments have to mitigate the background light from stars. One approach in optical SETI is to build instruments capable of detecting optical pulses on a very fast timescale, where the received optical pulse manifests itself as many photons arriving at the detector in an unresolved ($\sim$ns) time interval, against a background patter of single, Poisson-distributed photon arrivals from the host star. A simple calculation shows that the signal from a transmitter capable of delivering nanosecond speed, megajoule optical pulses at a 10-Hz repetition rate attached to a Keck-class telescope ("Earth 2000" technology), would outshine our Sun by a factor of more than 1000 in broadband visible light and could be easily detected by another Keck-class telescope at distances of up to 300 pc (Howard *et al.* 2000).[3] Several optical SETI programs monitor nearby stars for optical pulses of this type in roughly the 300–600 nm band. Our group is now developing a pixelated wide-field camera to search the Northern sky for such high-intensity pulsed signals.

An alternative approach in optical SETI is to reduce the stellar background by high-resolution spectroscopy and/or nulling

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[1] Both 5-AU and 1-AU orbits have been considered, but the 1-AU orbit seems to be the present scientific consensus.

[2] "Optical" SETI is to be interpreted in the broad electromagnetic sense—including the near IR and UV—and is characterized by photon counting, as contrasted with the heterodyne techniques of microwave SETI.

[3] Note that extinction limits optical SETI to a range of $\sim$1 kpc in the visible part of the spectrum and $\sim$10 kpc in the infrared. These distances correspond to roughly the thickness and radius of the galactic disk and volumes enclosing $\sim 10^7$ and $\sim 10^{10}$ sunlike stars, respectively.

0019-1035/01 $35.00

interferometry. In such a strategy, one looks for unexplained lines in the spectra of stars and their planetary disks. Such lines would be produced from either continuous-wave (CW) lasers (possibly modulated) or pulsed lasers. These would be detectable at considerably lower transmitted power levels than is possible without interferometry and spectroscopy, as we will demonstrate below. TPF is the first interferometer with the angular resolution capable of separating starlight from planetlight and has a modest spectral resolution. Thus it can probe the entire zodiacal disk of a nearby star for planets and life.

The purpose of this paper is not to suggest changes to the design of TPF, but rather to point out that, as currently envisioned, it has a serendipitous sensitivity to extraterrestrial lasers. In addition to other desirable characteristics of mid-IR signaling (Townes 1983), one might expect a SETI signal in the IR band precisely because TPF, and instruments like it, are sensitive to the atmospheric signs of basic life there. It seems reasonable to posit that extraterrestrials may place a beacon at frequencies where they expect scientifically curious emergent civilizations to look. This is closely analogous to the microwave argument that since young civilizations survey the sky at 21 cm, it is a good transmission beacon choice.

The discovery of extraterrestrial communication from a nearby planetary system using TPF might proceed along the following lines. A planet candidate is discovered after several hours of observation at minimal spectral resolution (R of order unity). Follow-up observations at modest spectral resolution ($R \sim 20$) reveal a rich absorption spectrum with a large spectral peak in a particular wavelength bin.[4] The spectral purity is then probed at TPF's highest resolution, revealing an unresolved narrow emission line.[5] Ground-based telescopes then look for modulation in the signal, down to the scale of nanoseconds; they also examine the full range of wavelengths accessible to terrestrial telescopes.

2. LASER POWER REQUIRED

Extraterrestrial lasers would have to compete with at least four backgrounds in potential TPF searches: (1) incompletely nulled stellar photons, (2) reflected photons from the extrasolar planet, (3) photons from the extrasolar planet's blackbody spectrum, and (4) light scattered by zodiacal dust in both the target solar system and in ours. We will examine these backgrounds in greater detail below, but first note that they are all isotropic (roughly) and spectrally broad. Therefore, as Marcy (1997) pointed out, the laser power necessary for interstellar communication is reduced by the following factors:

Directionality. Even at the maximum range of 15 pc envisioned for TPF observations, a beam director of just 10 m in diameter produces a 3-AU-wide beam (which allows for small aiming errors or incorrect proper motion compensation when aimed at our Sun), with $\theta_b \approx \lambda/D = 1 \times 10^{-6}$ radian beam width at $\lambda = 10\ \mu$m (and an antenna gain of $g_t = \pi^2 D^2/\lambda^2 \approx 10^{13}$, or 130 dB—a factor of 10^6 greater than the gain of the 305-m Arecibo dish at $\lambda = 21$ cm). Civilizations targeting our Solar System from a closer range would presumably use a smaller mirror (or illuminate a smaller portion of the larger mirror). It is interesting to note that such a scheme requires constant transmitter power *independent of the range to the target solar system*, for a given delivered photon flux.

Spectral resolution. The spectrometer onboard TPF will sort the incoming radiation into frequency "bins" (of width $\Delta\nu$) thereby reducing the background in any given bin by approximately $\Delta\nu/\nu = 1/R$ (assuming a flat spectrum). Because lasers are spectrally narrow, all of their photons will fall into one bin. The spectral resolution R of TPF varies widely, from $R = 3$–20 for "planet detection and spectroscopy," to $R = 3$–300 for "continuum and spectral line imaging," and extending to $R \sim 10^5$ for "specific lines" (Beichman *et al.* 1999). Let us assume that extraterrestrial lasers would be discovered in TPF's "planet detection mode," and take $R = 20$ for this calculation.

Fluctuations. We must not forget that the laser signal competes only with the *fluctuations* in the background, and not the background signal itself. Pixel-to-pixel fluctuations in the spatial image will inhibit TPF's planet detection power. These include physical processes such as emission from the incompletely nulled star and dust, as well as instrumental effects such as telescope jitter, intrinsic detector noise, and emission from the cooled telescope. Diffractive intensity scintillations should be insignificant at TPF's high frequency (compared to radio) and long integration times (Cordes and Lazio 1991). Spectral fluctuations will limit the spacecraft's ability to identify atmospheric gas absorption bands and extraterrestrial laser emission lines. Noise sources of this type include spectrometer noise and noise in the reflected and blackbody light from the planet. Note that since TPF's planned spectrometer is Fourier-based, and not dispersive, the photon noise of all frequencies appears in each spectral bin. On large spectral or spatial scales, these fluctuations are characterized by a signal-to-noise ratio; Appendix A of Beichman *et al.* (1999) finds SNR ≈ 7 during a typical run of TPF.[6] However, for the purpose of detecting extraterrestrial lasers—which deposit all of their light into one spectral

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[4] The time requirements to detect microscopic *or* intelligent life on an extrasolar planet are lengthy. NASA estimates that planet detection will require observations with 2.0-hour integration times (with $R = 3$, $S/N = 5$). Detection of atmospheric gases such as CO_2 and H_2O would require integrations of 2.3 days ($R = 20$, $S/N = 10$), and for detection of life-indicating O_3 or CH_4 the corresponding figure is 14.7 days ($R = 20$, $S/N = 25$).

[5] Deep nulling and high-resolution spectroscopy are incompatible measurements since each require precise pathlength adjustment. At best, TPF may achieve $R \sim 100$ with nulling, and $R \sim 10^5$ without nulling.

[6] This calculation is for either 2-m mirrors at 5 AU or 3.5-m mirrors at 1 AU imaging a planet at 10 pc and integrating for 10^5 s (roughly a day) at 12 μm with $R = 20$. It includes (i) the effects of zodiacal and exo-zodiacal emission, (ii) the galactic cirrus, (iii) leakage signal and jitter from the target star, (iv) the telescope properties, (v) and detector noise.

bin—the figure of merit is the bin-to-bin variation in the spectrum, that is, the deviation from a smooth spectrum. Note that fluctuations of this type include not only the above noise sources, but also spectral *features* (such as absorptions lines) whose width is comparable to the bin size. For the purpose of the calculations in the paper, let us assume that the "signal-to-fluctuation ratio" is the same as the signal-to-noise ratio; in practice they may differ by perhaps a factor of two.

Taking account of these factors, the laser power sufficient for detection by TPF is

$$P_L \geq \frac{\lambda^2}{\pi^2 D^2} \cdot \frac{\Delta\nu}{\nu} \cdot \frac{5}{\mathrm{SNR}} \cdot L_T \equiv \alpha \cdot L_T, \tag{1}$$

where L_T is the total isotropic radiated power of background sources seen in a spatial TPF pixel, and where we have assumed that a 5-σ signal is required for detection.

To get a sense of the order of magnitude of α, let us assume that the transmitting device is simply a CO_2 laser ($\lambda = 10$ μm) coupled to a Keck-class telescope ($D = 10$ m). Combining this with the above results, we find $\alpha = 4 \times 10^{-15}$. This means, for example, that a laser of $\approx 10^{11}$ W average power would be visible over the background of its G2V host star, *without the use of interferometry.*[7] In other words, the high transmitting aperture gain at IR wavelengths, combined with only modest wavelength specificity, already reduces the required transmitting power (relative to solar luminosity) by some 14 orders of magnitude. Moreover, as we shall now demonstrate, TPF's exquisite interferometric nulling capability greatly reduces this figure, bringing it within the range even of modest contemporary lasers.

3. BACKGROUNDS

As discussed above, the background for extraterrestrial lasers can be broken down into several distinct sources. Incompletely nulled stellar photons, as well as inhomogeneities in the zodiacal and exo-zodiacal dust, are important during spatial imaging, while reflected and blackbody photons from the planet are important during spectroscopic integrations. In the discussion that follows, we calculate these backgrounds using Earth/Sun values for the physical parameters of planets and stars in units of broadband visible equivalent isotropic radiated power (EIRP).

Incompletely nulled stellar photons. The most technically challenging aspect of TPF is nulling light from the parent star. Although a nascent field today, astronomical nulling is being developed at various observatories on Earth and will soon be developed on the Space Interferometry Mission in orbit. After this decade of research, TPF is projected to achieve a null depth of $N = 10^{-5}$–10^{-6}. Taking the more conservative estimate of $N = 10^{-5}$, we get a nulled stellar luminosity of

$$\begin{aligned} L_N &= N \cdot L_\odot \\ &= 4 \times 10^{21}\ \mathrm{W}. \end{aligned} \tag{2}$$

Note that L_N is only important for spatial imaging near the parent star (assuming that L_N does not saturate TPF's spectrometer). During spectroscopic integrations on a planet separated from its parent star by many pixels on the TPF image, L_N is unimportant.

Reflected photons. Light reflected off of the extrasolar planet will be a background for discovering a planetary atmosphere and detecting extraterrestrial lasers. Assuming an albedo of unity, the power reflected from a planet of radius $R_\oplus$ at a distance $r_\oplus$ from its sun is approximately

$$\begin{aligned} L_R &= \frac{\pi R_\oplus^2}{4\pi r_\oplus^2} \cdot L_\odot \\ &= 5 \times 10^{-10} \cdot L_\odot \\ &= 5 \times 10^{-5} \cdot L_N. \end{aligned} \tag{3}$$

This estimate may be high by perhaps an order of magnitude since the hot star's blackbody peak is in the visible part of the spectrum, rather than at TPF's infrared wavelength. We have also not taken account of the variations in apparent planetary brightness as the result of orbital phase as seen from Earth.

The planet's blackbody spectrum. Although cooler and smaller than its parent star, the planet emits a blackbody spectrum of its own, which peaks in the infrared. This will be spatially resolved from the parent star, as well as from other planets in the system, and will be seen as a bump on the zodiacal background. In total power, the planet emits far less than its nulled parent star,

$$\begin{aligned} L_B &= \left(\frac{T_\oplus}{T_\odot}\right)^4 \cdot \left(\frac{R_\oplus}{R_\odot}\right)^2 \cdot L_\odot \\ &= 4 \times 10^{-10} \cdot L_\odot \\ &= 4 \times 10^{-5} \cdot L_N. \end{aligned} \tag{4}$$

However, in the infrared, where TPF is sensitive, the nulled stellar and planetary blackbody power per unit frequency are more nearly comparable. For example, at $\lambda = 10$ μm ($\nu = 3 \times 10^{13}$ Hz),

$$\begin{aligned} \frac{L_B}{\Delta\nu} &= N \cdot 4\pi R^2 \cdot \frac{2h\nu^3}{c^2} \cdot \frac{1}{e^{h\nu/kT} - 1} \\ &= 8 \times 10^4\ \mathrm{W\ Hz^{-1}}\ \text{(star)} \\ &= 1 \times 10^3\ \mathrm{W\ Hz^{-1}}\ \text{(planet)}, \end{aligned} \tag{5}$$

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[7] We assume that the transmitting civilization would arrange unity duty cycle transmission by, for example, using a single transmitter in a planet-trailing orbit or a fleet of such transmitters orbiting the host planet with one transmitter always aimed at the Earth.

where we take the null depth to be $N = 10^{-5}$ for the star and $N = 1$ for the planet. These signals should be within the dynamic range of the spectrometer on board TPF. Such results should not surprise us, given that TPF is being designed to resolve and identify extrasolar planets.

Zodiacal and exo-zodiacal dust. Dust in the Solar System will create a diffuse infrared glow that will cloud, but not block, TPF's view.[8] Exo-zodiacal dust also presents a significant challenge. A "1 Zodi" cloud of Solar-System-like dust is only 0.3 AU in diameter, yet it emits and scatters roughly the same amount of infrared and optical radiation as the Earth. This dust is warm (275 K with temperature decreasing with distance as $r^{-0.4}$), small ($\sim$40 μm grains), and smoothly distributed over the ecliptic, except for wakes and rings attributed to gravitational effects from planets and bands caused by recent asteroid or comet collisions (Backman *et al.* 1998). TPF's high angular resolution is therefore essential to subtract out this largely uniform exo-zodiacal background from the image of extrasolar planets (and their possible inhabitants' lasers).[9]

With detail on a scale down to roughly 0.1 AU,[10] the TPF image will be a central bright star surrounded by a diffuse zodiacal disk. Within this shroud of dust we will see the reflection and emission from a planet. An extraterrestrial laser affixed to or orbiting the planet will therefore only have to overcome the background from the planet itself. Any techniques used to spatially resolve the planet from the zodiacal disk and the parent star will also resolve the extraterrestrial laser. Taking the total background to be the sum of the reflected and blackbody backgrounds, $L_T = L_R + L_B = 9 \times 10^{-5} \cdot L_N \approx 4 \times 10^{17}$ W, we estimate that the laser power sufficient for interstellar communication, is $P_L = \alpha \cdot L_T \approx 1$ kW.[11] In just 40 years of development on Earth, we have managed already to produce *mega*watt infrared CW lasers (Slusher 1999). Taking "Earth 2000" technology as a lower bound on extraterrestrial technological sophistication, we conclude that infrared CW lasers are an altogether reasonable way to achieve interstellar contact.

4. ALTERNATIVE PLANETARY SYSTEMS

In this rather simple treatment, we have calculated various quantities for detecting laser transmissions from the vicinity of an Earth–Sun system with TPF. Although it will not dramatically change the above results, the bodies of extrasolar systems studied by TPF will almost certainly differ in size, temperature, and relative separation. For example, suppose that the extraterrestrial civilization lives on the moon of a Jupiter-like planet in an Earth-like orbit, where its lasers would have to compete with a larger planetary background. Substituting $R_\oplus \rightarrow R_J$, we find that the required laser power, $P_L \approx 100$ kW, is still well within our present capability. Table I shows that P_L is at most a few kW for Solar System planets in their natural orbits as viewed by TPF from 15 pc (its specified maximum range for planet detection). Moreover, as our arbitrary choice of "Earth 2000" technology for the transmitting device suggests, this discussion was intended not as a blueprint for Earthly transmission, but rather as a sanity check for optical SETI with TPF.

TABLE I

Alternative Planetary Systems

Planet	Minimum P_L (kW)	$L_R/L_\odot$	$L_B/L_\odot$	$r/r_\oplus$	$R/R_\oplus$	$T/T_\oplus$
Mercury	1	4×10^{-10}	4×10^{-10}	0.39	0.38	1.61
Venus	2	8×10^{-10}	7×10^{-10}	0.72	0.95	1.17
Earth	1	5×10^{-10}	4×10^{-10}	1	1	1
Mars	0.2	6×10^{-11}	5×10^{-11}	1.5	0.53	0.81
Jupiter	6	2×10^{-9}	2×10^{-9}	5.2	11	0.44
Saturn	1	4×10^{-10}	4×10^{-10}	9.5	9.4	0.32
Uranus	0.1	2×10^{-11}	1×10^{-11}	19	4.0	0.21
Neptune	0.1	8×10^{-12}	1×10^{-11}	30	3.9	0.20
Pluto	0.1	1×10^{-14}	9×10^{-15}	39	0.18	0.16

Note. Here we tabulate the minimum power P_L of a 10-μm laser with a 10-m diffraction limited beam director on a Solar System model planet at a range of 15 pc for detection by TPF under the assumptions of Section 2. This power is calculated using Eq. (1) with $L_T = L_R + L_B$ (L_N is unimportant when doing spectroscopy on a planet well separated from its sun). Physical data in the three rightmost columns were taken from Zeilik and Gregory (1998) (T was taken to be the equilibrium blackbody temperature). $L_R/L_\odot$ and $L_B/L_\odot$ were calculated using Eqs. (3) and (4), respectively. Note that many of the outer Solar System planets—Mars, Uranus, Neptune, and Pluto—might not be detected by TPF since they emit less power than a background 0.1×0.1 AU patch (roughly TPF's minimum pixel size) of a 1 Zodi cloud. Extraterrestrial lasers on such planets would have to exceed the radiated power of the local zodiacal dust (this directed laser power is roughly 100 W).

We also note that the extraterrestrial laser could be on a satellite in a wide (say 5-AU) orbit and therefore spatially uncorrelated with planets in the system. In this case, the signal would be a narrow spectral peak on the exo-zodiacal background. Such signals might be missed if planetary systems are first scanned in low spectral resolution and only followed up with higher resolution spectroscopy if planets are discovered.

5. CONCLUSIONS

Although not designed for optical SETI, TPF is uniquely sensitive to infrared extraterrestrial signals originating from extrasolar planets. This sensitivity in an unexplored corner of

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[8] This is the primary motivation to reduce TPF's mirror size and place it in a 5-AU orbit.

[9] Note that the above quantities were calculated assuming that the ecliptic plane of the imaged planetary system is perpendicular to TPF's line of sight. As this angle varies to an edge-on view, the background from exo-zodiacal dust will increase by a factor whose maximum value is roughly the ratio of the diameter to the thickness of the exo-zodiacal disk. In a beautiful measurement using COBE, Reach *et al.* (1995) found this factor to be $\sim$3 in the Solar System.

[10] The angular resolution in the nulling mode is bounded by a need to extend the null to the limb of the star; i.e., the null must not be narrower than the star's disk.

[11] Even if the transmitting device is reduced in size to 3 m so that it irradiates a 5-AU orbit with the same photon flux, the power requirement is only $\approx$10 kW.

frequency/location space is particularly important in the logic of SETI where we have no *a priori* knowledge of the signal. TPF scientists should be aware of the possibility that their experiments may serendipitously extend the reach of humanity far beyond the Solar System.

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