Looking for the Optical SETI "Sweet Spot"

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Background. For several years, I have developed and employed a number of optical SETI receiver/detector methods. These were mostly pulse coincidence detectors using up to 4 photomultipliers and based upon the published work of a number of institutions and individuals. (This work eventually led to a detector design using a single photomultiplier.) However, several logical disconnects left me wondering if anyone had put the problem together into one piece. Few of the papers addressed laser transmission in terms of pulse power rather than pulse energy. Trying to sort it out was made more difficult because some of the published papers were not plainly written.

To go forward it was necessary to reduce all of the elements of the problem to their simplest approximations and attempt to tie them together. The scope of the analysis that follows includes the:

- range of transmission system peak power,
- range of transmission wavelengths,
- range of laser pulse durations,
- range of laser pulse repetition rates,
- laser signal photon flux for detection at the receiver,
- receiving telescope and detector characteristics,
- free space signal to background ratio given the range of stellar visual magnitudes and stellar background Poisson distribution,
- detected/processed signal to background ratio for Poisson N=2,3,4.

At first, the scope of the effort seemed too great. But, it was found useful to define regions of each element that were, from my perspective, viable, marginal or unreasonable. By discarding the extremes and focusing on what was thought to be the most reasonable, the work took form and direction.

Transmitting Laser and the Collimating Telescope. The analysis begins with calculating the total photon flux emitted by a device such as a laser.

$$\Phi_t = E_o/E_p \quad \text{(photons per pulse)} \qquad (1)$$

E_o = single pulse energy output of a laser (J)

E_p = $h \cdot c/\lambda$ energy per photon (e.g., 3.6×10^{-19} Joules/photon @ λ = 550nm)

h = Planck's constant ($6.626 \cdot 10^{-34}$ m^2kg/s)

c = speed of light ($3 \cdot 10^8$ m/s)

λ = laser output wavelength (m)

It is common to describe cw laser output in terms of average power and to refer to pulsed laser output in terms of energy. However, as will be seen, the later ignores an important characteristic necessary in the investigation. The output photon flux from a laser's single pulse is therefore presented in terms of energy, power and pulse duration as

$$\Phi_L = E_0 / E_p = P \cdot t_p / E_p \qquad (2)$$

P = laser peak power (Watts)

t_p = pulse length (sec.)

And for a uniformly illuminated disk at a distance z, the flux from the source is

$$\Phi = (E_0 \cdot \lambda / \pi \cdot \omega_z^2 \cdot h \cdot c) \quad \text{(photons m}^{-2}\text{)} \qquad (3)$$

ω_z is the radius of the illuminated disk

Next, it is useful to examine the elements that characterize laser beam divergence. The parameters needed are the beam waist and Raleigh length. The beam waist (ω_0) is the radius of the beam where it is at a minimum. The Raleigh length is the distance from the beam waist to where the beam radius has increased by a factor of the square root of two. A laser can be coupled to a telescope via a weak negative lens to match the telescope optical characteristics. Where a transmitting telescope is used for beam collimation, the beam waist becomes the diffraction limited telescope aperture radius (ω_0) and the Raleigh length is

$$Z_r = \pi \cdot \omega_0^2/\lambda$$

From this it is a simple matter to calculate the radius of a beam (ω_z) at any distance (z) from the diffraction limited transmitting telescope (waist).

$$\omega_z = z \cdot \omega_0/z_r \qquad (\omega_z \gg \omega_0)$$

and

$$z = \pi \cdot \omega_0 \cdot \omega_z/\lambda$$

For example, using a 10 m diameter transmitting telescope with a transmission wavelength of 550 nm, the distance (z) from the source to a 1 AU illuminated diameter disk is ~227 light years or ~2270 light years to a 10 AU disk.

In a manner different from Eq. (3), one can calculate the flux of a laser signal at any distance as

$$\Phi = \pi \cdot \omega_0^2 \cdot E_0 / z^2 \cdot \lambda \cdot h \cdot c \qquad \text{(photons m}^{-2}\text{)} \qquad (4)$$

Note that equations (3) and (4) are equivalent statements.

The radius of an illuminated area (disk) at z can be calculated as

$$\omega_z \approx z \cdot \lambda / \pi \omega_0 \qquad \text{(m)} \qquad (5)$$

Assuming a wavelength of 550 nm we can boil down equations (4) and (5) to convenient mixed units forms for quick calculations.

$$\Phi \approx 0.32 \cdot \omega_0^2 \cdot E_0 / z^2 \qquad \text{(photons m}^{-2}\text{)} \qquad \text{for } z \text{ (ly), } \omega_0 \text{ (m) and } E_0 \text{ in (J)}$$

and

$$\omega_z \approx 0.011 \cdot z / \omega_0 \qquad \text{(AU)} \qquad \text{for } z \text{ (ly) and } \omega_0 \text{ (m)}$$

Of course the equations above model an ideal laser beam and transmission system.

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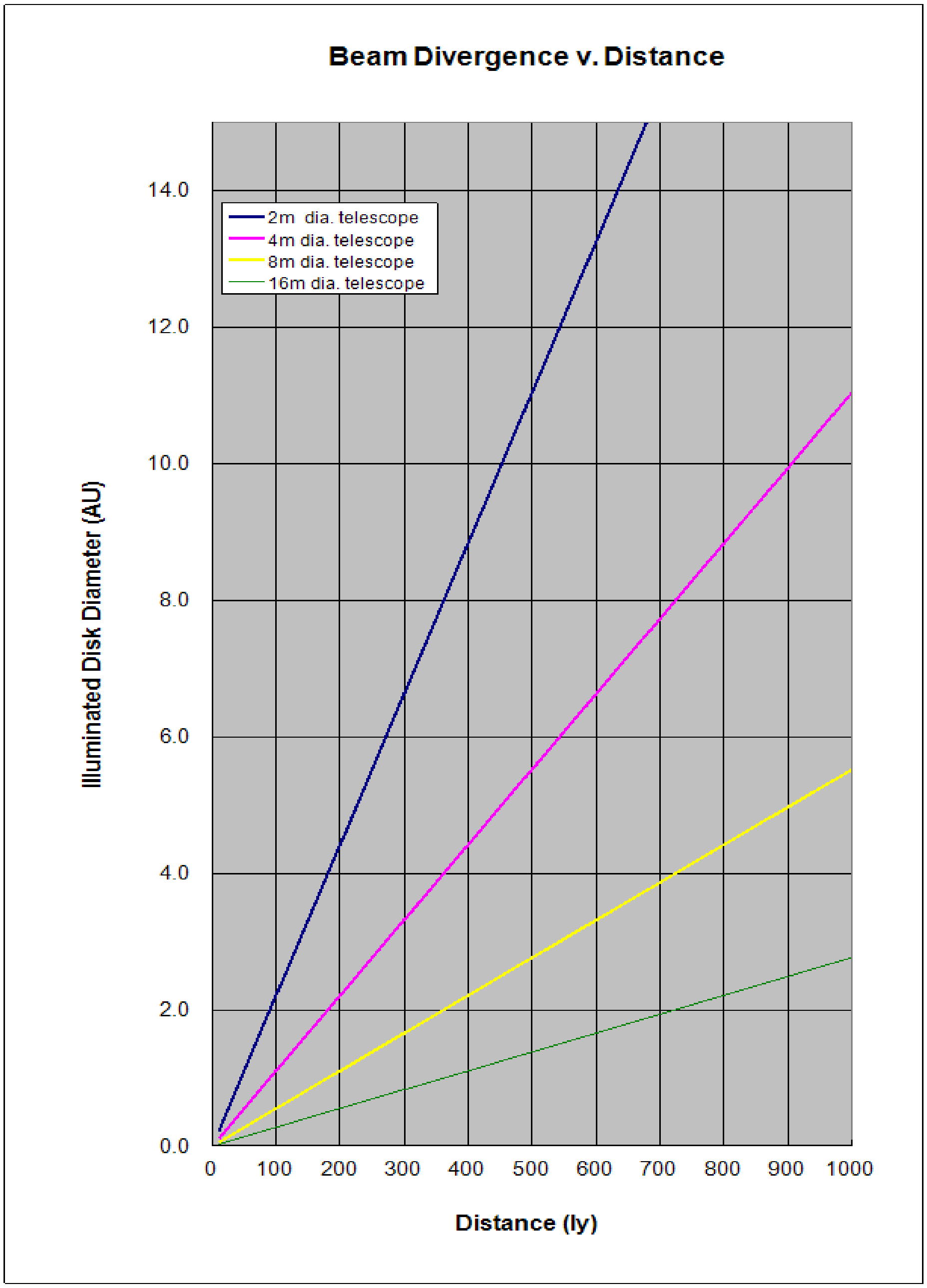
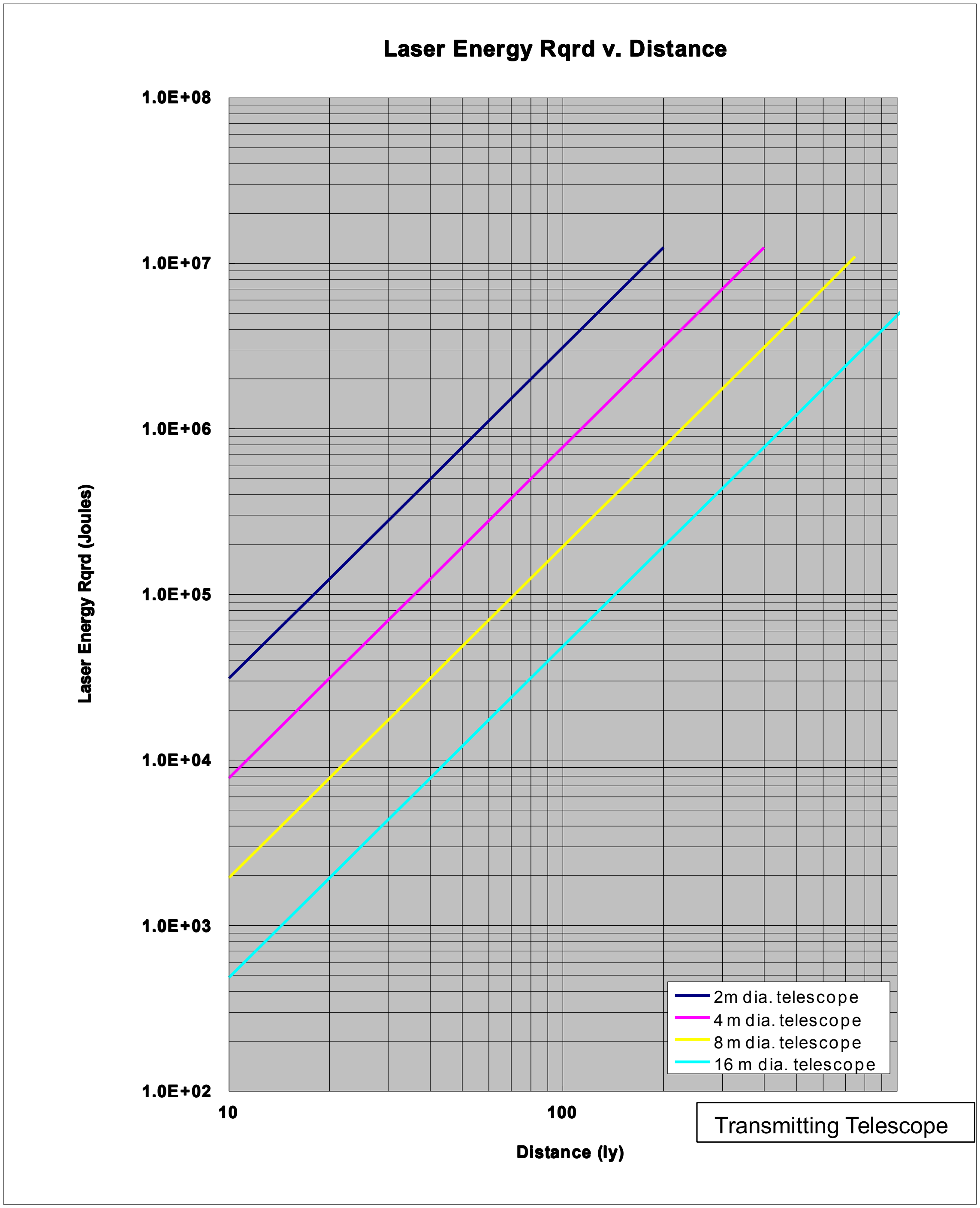
The adjacent graph is helpful for a quick appreciation of beam divergence versus the transmitting telescope aperture diameter.



Laser Energy Requirements. We can make a basic assumption regarding the minimum detectable signal at great distances and from that calculate the transmitting telescope and laser energy requirements. The figure below uses 100 photons m^{-2} as the minimum detectable signal level at distances out to 1000 light years. Although 100 photons/meter sq. would be the minimum required signal level for small telescopes, that would be a whopping large signal for a 10 meter receiving telescope. The four plot lines are for different transmitting telescope diameters, i.e. larger diameter telescopes have less beam divergence. From this it seems reasonable for small telescopes to search for ETI out to at least 300 light years.



Transmission pointing accuracy. The Hubble Space Telescope is capable of tracking objects to an accuracy of about 7 milliarcseconds. This James Webb Space Telescope is expected to do a bit better. Combining that capability with the ~10 microarcsecond stellar parallax measurement accuracy expected of the ESA GAIA spacecraft and we are on the verge of having the laser targeting capability expected of ETI for targeting earth.

The half angle of divergence for an ideal laser beam is:

$$\Theta = \lambda / \pi \cdot \omega_0 \quad \text{(rad)}$$

As an example, at 550 nm and with ω_0 = 5 meters, $\theta = 2 \times 10^{-6}$ degrees or about 7 milliarcseconds.

From equation (4) it might appear that the biggest bang for the buck would come from using the largest possible telescope for transmission. However, with a 10 meter telescope the beam divergence is so small that targeting precision may be an overriding difficulty. It may be that a lesser sized transmitting telescope, i.e., 4 to 8 meter diameter aperture, would be a better match for transmission/reception out to 500 ly. The devil is in the details.

Transmission wavelengths. It can be argued that ETI might opt for wavelengths in the near infra-red (NIR). Over great distances, >1000 ly for example, NIR signals are much less attenuated by the interstellar medium (extinction). But, while the number of NIR photons emitted per unit of energy is greater than for visible light, for a given transmitting telescope, beam divergence is also greater and the overall result is less flux per unit area at any distance.

Yet another argument suggests that one-way communications over many hundreds or thousands of light years is nearly pointless, especially for those making beacon signal transmissions with no hope of receiving a return signal – perhaps in the lifetime of their civilization, (all bets are off for artificial intelligence). At those distances efforts toward chance interception of signals using radio astronomy may make a bit more sense.

From the receiving point of view, NIR has problems too. If photomultipliers were to be used for detection, the photocathode would necessarily have a very low work function and such devices require cooling to have a reasonable dark noise level. NIR photomultipliers generally have low gain and most importantly very low quantum efficiencies; less than 1% compared to 20+% for visible light pmts. None of which are insurmountable obstacles so long as one has a really large receiving telescope.

Alternatively, avalanche photodiodes (APD) have high quantum efficiencies compared to pmts i.e., 50% or more at NIR wavelengths. When operated in the Geiger mode, they can have gains up to 10^8, very fast (picosecond scale) performance and low dark noise when cooled. That sounds perfect, but at present the detection areas are small, the cost is high and there are other problems such as after-pulsing and dead time to be dealt with. However, the state of this art is changing rapidly and a new photometer has been developed by a team headed by S.A. Wright[15] that uses hybrid APD devices. Those devices seem promising for the future of optical SETI at both visible and NIR wavelengths. The factors for transmission and detection of NIR against those for visible wavelengths seem to be balancing out. But NIR has a clear advantage for distances greater than 1000 ly.

Receiving Telescope. Considering the various losses the number of laser photons detected per pulse by a receiving telescope will be

$$N_L = \pi \cdot \eta_o \cdot QE \cdot r_t^2 \cdot \Phi \qquad (6)$$

QE = quantum efficiency of the detector (for pmt ~.20 - .25)
η_o = optical efficiency of the telescope (~0.75)
r_t = telescope aperture radius (m)

Note that for multiple pmts and beam splitters the optical efficiency will be further reduced.

Combining equations (4) and (6)

$$N_L = \pi^2 \cdot \eta_o \cdot QE \cdot r_t^2 \cdot \omega_0^2 \cdot E_0 / z^2 \cdot \lambda \cdot h \cdot c \qquad \text{(photons detected by telescope system)}$$

Stellar Background and the Signal to Backgound Count. To evaluate the free space stellar background it is necessary to determine the flux of photons from the parent star with respect to its visual magnitude. This can be approximated as

$$\Phi_s \approx \alpha \cdot c \cdot 10^{(-0.4*m)}/T \qquad (\text{photons m}^{-2}\,\text{s}^{-1}) \quad \text{(ref. 1)} \qquad (7)$$

α ~ 6.8×10^{13} (from visible light stellar luminance calculations)
c = 0.1 (~fraction of photons emitted by star in 400-625 nm region w/T=5×10^3 K)
m = star visual magnitude
T = star's surface temperature (~5×10^3 K for G, K type stars)

Similar to eq. 6, applying the various detection efficiency factors, the number of stellar photons detected per second by a telescope receiving system is

$$N_s = \pi \cdot \eta_o \cdot qe \cdot r_t^2 \cdot \Phi_s \qquad (\text{photon s}^{-1}) \qquad (8)$$

qe is the average quantum efficiency over the photomultiplier's sensitive range

Remembering that N_L is for the laser pulse period (t_p), e.g., $2.5 \cdot 10^{-8}$ seconds, the signal to background count during the pulse period can be

$$SBC = N_L / N_s \cdot t_p$$

Thus, by restricting the evaluation interval to the period of the laser pulse, a very advantageous signal to background count can be obtained.

Poisson Statistics. We want to be able to detect short duration laser pulses occurring at low repetition rates against a wide range of stellar backgrounds.

The probability of detecting multiple random stellar photons occurring during an interval is given by:

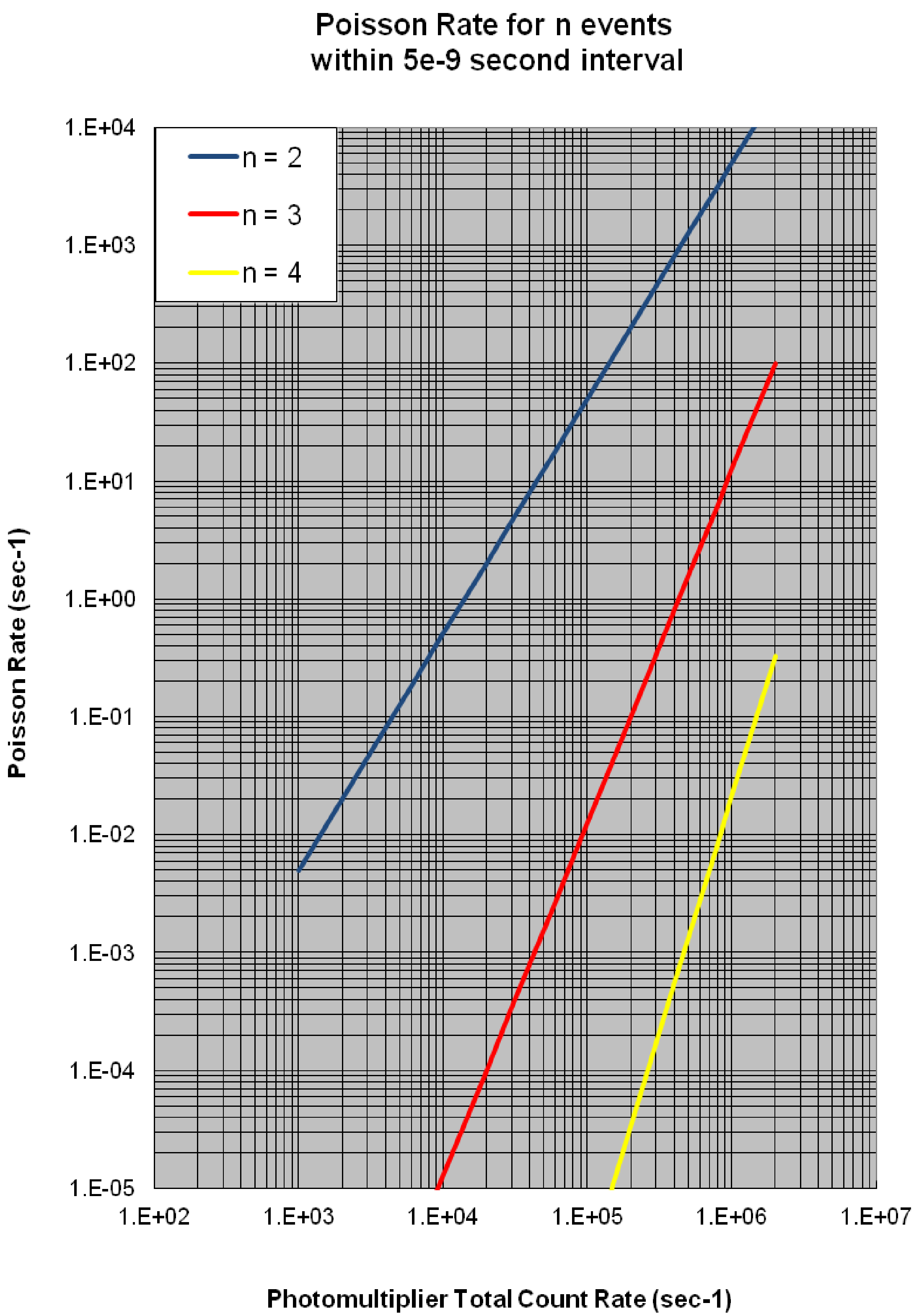
$$P = ((r^{n} \cdot t^{n-1)} \cdot e^{-(r * t)})/(n-1)! \quad (9)$$

r = the rate of random events (counts per second)

t = interval over which measurement is made (s)

n = probable number of events detected in the interval

The graph below describes the number of events, i.e., 2, 3 or 4 that are expected to occur per second during any 5 nanosecond interval for a range of single events (photomultiplier total count rate) from 100 to $2 \cdot 10^{6}$ per second. From this it might be concluded that it is necessary to limit the detection threshold to $n \geq 3$, however, there are other factors yet to be considered. For example, at the Boquete Optical SETI Observatory all detected pulses are processed using a computer-based fast Fourier transform spectrum analyzer to detect periodic pulses. These aspects are discussed in some detail in the *Detectors* and *Signal Processing* sections.


Poisson Rate for n events
within 5e-9 second interval
n = 2
n = 3
n = 4
Poisson Rate (sec-1)
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
Photomultiplier Total Count Rate (sec-1)

Laser Transmission Characteristics. The following chart brackets the presumed useful laser pulse transmission characteristics.

Beam Pulse Lengths	Advantages	Disadvantages
≤ 5 x 10^{-9} seconds Coincidence detection	very low stellar noise	extremely high laser peak power, beam splitter losses. multiple pmt window reflection losses.
< 1 x 10^{-8} seconds Coincidence detection	low stellar noise	very high laser peak power, beam splitter losses, multiple pmt window reflection losses.
1 x 10^{-8} - 5 x 10^{-8} seconds	moderate stellar noise high detection efficiency, coincident and multiple pulse detection possible, less laser peak power required, simpler optics and electronics.	SBC suffers with bright stars especially useful for >8 vis. mag. stars
>1 x 10^{-7} seconds	—	Insufficient SBC

Transmission economics. It has been shown that petawatt laser pulses can outshine even moderately bright stars by orders of magnitude. Reiterating, this means that more photons pass through the receiving area conic section plane per small unit of time than the Poisson statistics for the stellar background predict. But what are the costs?

As a reality check it is useful to make a few assumptions regarding the economics of transmitting signals. The breadths of ideas in this regard represent a range of extremes.

A case has been made by Shostak[9] wherein very low (average) power lasers might be used. In this scheme, it is necessary for the transmitting facility to constrain the beam divergence such that at the receiving end it would be approximately the diameter of the sun. An example laser power of just 8 watts average power was suggested (8 gigawatts peak power w/10^{-9} sec pulse width). The targeting criteria were also addressed such that the number of stars could be limited to the most promising candidates. With our current understanding, the technique would require extreme targeting precision and a very large optical transmission system.

At the other extreme, a 1 megajoule laser illuminating an area having a 5 AU radius at the receiving end presents a photon flux of ~5 photons m^{-2}. Such a signal would be detectable using a 10 meter receiving telescope having 20% detection efficiency. However, it would be hard to argue for the heavy investment in equipment, intelligent and energy resources at the transmitting end with expectations that only a few large telescopes might be capable of detecting the signal.

Reason suggests that a middle ground may be likely. For instance, a laser facility targeting our solar system might restrict the beam to a diameter of 2 AU or less. Having done so, signal detectability is greatly improved even using modest sized receiving telescopes.

We can also make an economic evaluation using our contemporary measures. The energy cost for a single one megajoule laser pulse (having 20% mains efficiency) is about $0.14. A pulse transmitted once per second would require an annual energy budget of approximately $4.4 million. The annual cost of facilities, intelligent resources (manpower in our case) and maintenance would be even more significant. A funding commitment that didn't plan to send signals, more or less continuously, to a large number of stars out to at least 100 light years and to continuously monitor for returning signals would be mostly experimental. Thus, it is probable that laser signal transmissions will be economically constrained. For the purposes of estimating transmission rates, we can look at how a project might be economized.

Assumptions: The observing time of a receiving telescope will average 4 hours/night (very simplistic and parochial, but it’s a starting point). The searching telescopes will only occasionally revisit each star; therefore, detection must be easily achievable and unambiguous.

1. Determine a transmission pulse rate that provides a high likelihood of detection.

    For pulse rates less than 0.01 pps.

    There would be ≤ 144 opportunities for individual pulse detection in four hours and many pulses would need to be detected have contact confirmation.

    Because of facilities limitations and the large number of stars to be observed, broadband search efforts often restrict observations of individual stars to periods significantly less than 4 hours, i.e., a few minutes.

    If spectrum step scanning is employed, low pulse repetition rates would be easily missed.

    Synchronized data collection using 2 or more observatories would greatly improve the chances for detection of low transmission rates.

    At rates from 0.01 to 0.1 pulses per second, signal detection with current means is more probable.

    At rates greater than 1 pulse per second, the energy costs are high and there seems little to be gained in signal detectability.

2. Periodic pauses reduce the probability of detection proportional to the ratio of paused pulses to total pulses in any period. However, at high pulse rates, 0.1 to 1 pps or higher with a pause after each n pulses and for n pulses, for example, reduces energy consumption by 50% and may even help improve signal confirmation.

3. Periodic bursts (pings) of laser pulses at 1 to 100 Hz with quiescent dwell times of, for example, 1000 seconds could be both economic and easily detectable.

3. Advanced civilizations may constrain beam divergence and target the beam to a high degree of precision. They may also have sufficient information about the candidate planets to target them only when they are orbitally well positioned.

For a simple repetitive beacon, we may bracket the most probable transmission pulse rates at between 0.01 and 1 pps and even favor the middle of this range, 0.05 to 0.5 pps, as an appropriate compromise.

Summary. The following boundaries may embody a preferred interstellar laser transmission/signal detection scheme. *These determinations are parochially weighted in favor of the technical limitations we now enjoy*.

pulse length, $<10^{-9}\text{s} < t < 10^{-7}\text{s}$, more preferably $10^{-9}\text{s} < t < 5\cdot10^{-8}\text{s}$
pulse repetition rate, $10^{-3} < r < 10^{2}$ pps, more preferably $0.05 \text{ pps} < r < 0.5$ pps
wavelength, visible light for targets less than 1000 ly distant
photon flux, hopefully sufficient for meter class telescopes to 300 ly or more

The intent of this exercise was to clarify a direction for detector development and perhaps point toward a "sweet spot" for interstellar beacon transmission and detection. It also determined that small observatories do indeed have a reasonable chance of detecting ETI signals.