The Search for Directed Intelligence

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ABSTRACT

We propose a search for sources of directed energy systems such as those now becoming technologically feasible on Earth. Recent advances in our own abilities allow us to foresee our own capability that will radically changes our ability to broadcast our presence. We show that systems of this type have the ability to be detected at vast distances and indeed can be detected across the entire horizon. This profoundly changes the possibilities for searches for extra-terrestrial technology advanced civilizations. We show that even modest searches can be extremely effective at detecting or limiting many civilization classes. We propose a search strategy that will observe more than 10^{12} stellar and planetary systems with possible extensions to more than 10^{20} systems allowing us to test the hypothesis that other similarly or more advanced civilization with this same capability, and are broadcasting, exist.

Keywords: SETI, Search for Extra Terrestrial Intelligence, DE-STAR, Directed Energy, Laser Phased Array

1. INTRODUCTION

One of humanities most profound questions is “are we alone”. This continues to literally obsess much of humanity from the extremely diverse backgrounds and interests from scientific, philosophical and theological. Proof of the existence of other forms of life would greatly influence all of humanity. The great difficulty in finding life is that our physical exploration is woefully inadequate with a fractional search currently of order 10^{-20}. For the foreseeable future we lack the ability to physically search much beyond this. With remote sensing, as has been the domain of traditional SETI programs, we can greatly expand this search fraction assuming that there are other civilizations with comparable or greater technological evolution to our own AND that such civilizations are actively seeking detection in parts of the electromagnetic spectrum we can search in. All such remote sensing searches require us to make assumptions that may have no basis in reality. Hence the great difficulty in converting searches to statements on the existence of life beyond our own. But it is all we have to go on and hence it should be pursued consistent with reasonable levels of effort. A detection would forever change humanity while an upper limit based on our assumptions has only a modest effect. This is truly a “high risk, high payoff” area of inquiry and always has been. As always we are “now” centric and “anthropomorphic” centric in that we expect all other advanced civilizations to be like minded in their desire to answer the same profound question AND to go about searching in a similar manner. However, if all civilizations “listened” but did not “speak” there would be a profound universal silence. Hopefully, other advanced civilizations do not share our relative silence. A serious and important question is to envision our time evolution of detection by other civilizations. Our ability to seriously ponder the issue of remote sensing of life has only become possible in the last 100 years. This represents about 1% of civilized human existence , less than 0.1% of total human existence, less than 10^{-7} of life on Earth and less than 10^{-8} since the first stars and galaxies formed. While predictions are fraught with uncertainty, especially those concerning the future, it is somewhat easier to look into the recent past at our technological progress in relevant areas.

2. TECHNOLOGICAL DEVELOPMENT

One of the enabling technologies that is relevant is the extremely dramatic progress in solid state lasers and in particular to laser amplifiers that can be arrayed into larger elements. The latter point is the analog of phased array radar that is becoming more common. An analogous revolution is taking place in visible and near IR coherent systems allowing for free space beam combining with no upper limit to power. This is very much analogous to the revolution in computing that has been brought about by parallel processing where large arrays of modest processors are now ubiquitous for super computing with no upper limit to computation. There is a very close analogy both technologically and in system design to the use of large arrays of modest phased arrays (parallel processing) lasers to form an extremely large directed energy system. Indeed the typical doubling time for performance in the semiconductor computational domain per computational element (CPU) is approximately 1.5-2 years over nearly 5 decades of time. We plot the power from CW fiber lasers as an analog to the CPU, and see the doubling time over the last 25 years has been approximately 1.7 years or 20 months. This is remarkably similar to "Moore's Law" and has not hit a plateau yet. CPU speed hit a plateau for Si devices nearly a decade ago and the path forward has been to increase the number of processors – ie to go toward parallel computer. You are likely reading this on such a CPU. Our current technology (early 2015) is above 1 Kw in a single mode fiber per amplifier with the analog of multi core CPU's being multi spectral injection with many fiber amplifiers per single mode fiber which now exceeds 30 Kw per fiber. It is estimated that this can be pushed to beyond 100 Kw per single mode fiber in the near future. We assume that other civilization possess the basic technology of arrayed (parallel) directed energy systems below but we only assume 1 Kw per fiber that we have already achieved. The efficiency of laser amplifiers is nearly 50% and thus only modest efficiency improvement is possible since we are already within a factor of two of unity. The power density is currently at about 5kg/kw and will drop to about 1 kg/kw in the next few years. All of this is a remarkable statement about our current technological capability in directed energy systems. As we will see we now possess the capability to deploy this technology in a way that enables us to direct energy for revolutionary purposes one of which is to be "seen" across the entire universe. This is truly a remarkable statement. The question that is relevant here is "if there are other advanced civilization do they have similar capabilities" and if so are they directing it to us? We have never been in a technological state where we could make such a statement and hence it is logical to explore its ramifications in many areas, SETI being one of them.

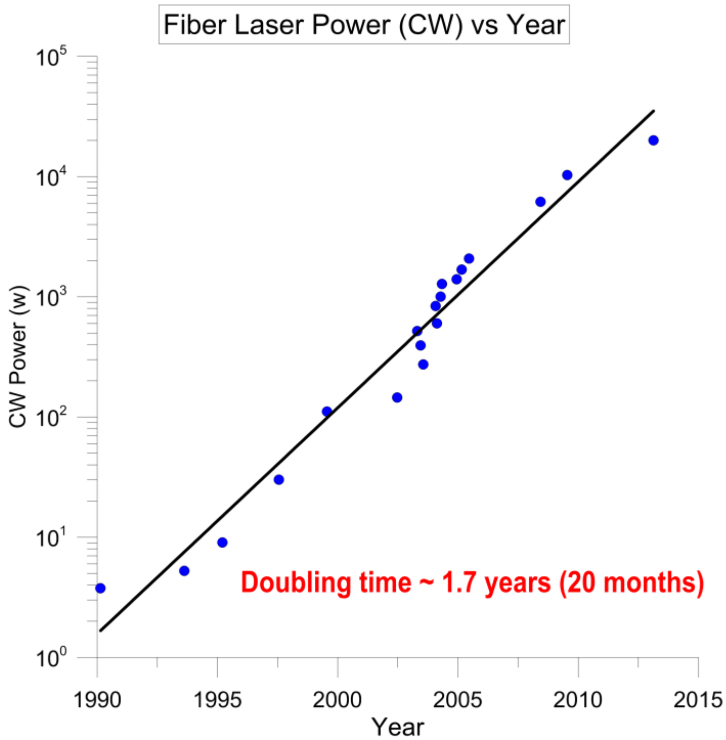

Figure 1 – Fiber laser CW output power vs year over the past 25 years.

3. CIVILIZATION CLASSES AND SIGNAL LEVEL

All SETI programs require assumptions about the technological expertise of the civilizations being sought out. We will assume that the civilizations we are seeking have directed energy capability to equals or exceed our currently and reasonably projected capability in the near future. This is a modest assumption given the rapid advances in this area and we will see that we already possess the basic technology to see and be seen across the entire horizon. In particular we will assume that the civilizations possess the ability to build the equivalent of our DE-STAR program, namely phased arrays of lasers. This allows for a significant advances beyond what has previously been done and has the long term capability allowing extremely large systems. It is this latter than dramatically changes the SETI analysis. We assign the same civilization classifications (denoted as S) scheme as we use for the DE-STAR array classification where the civilization class indicates both the power level and beam size of the emitted laser. We assume a standard DE-STAR (S) with nominal Earth like solar illumination (1400 w/m^2) and a square laser array size (d) where d(m)=10^S and beam divergence full angle $\theta = 2\,\lambda(m)/d(m) = 2\,\lambda 10^{-S}$ and solid angle $\Omega(st) = \theta^2 = 4\,\lambda^2\,10^{-2S}$ for small angles . The power is assumed to be CW rather than pulsed with a value of approximate P(kw) =1.4 $\varepsilon_c\,10^{2S}$ where ε_c is the conversion efficiency of solar to laser power.

The critical observable is the flux (w/m^2) at the (Earth) telescope and this is the transmit power P (w)/$L^2\,\Omega$ where L(m) is the (luminosity) distance. Thus the critical ratio at given distance is P(w)/ Ω(st). For a DE-STAR system of class S we have

$$P(w)/\ \Omega(st) = 1400\ \varepsilon_c\ 10^{2S}/4\ \lambda^2\ 10^{-2S} = 350\ \varepsilon_c\ \lambda^{-2}\ 10^{4S}.$$

We can thus calculate the civilization class S from any system with a given power and solid angle, even if not a DE-STAR class system, as:

$$S = \frac{1}{4} \mathrm{Log}_{10} ([P(w)/ \Omega(st)]/(350\ \varepsilon_c\ \lambda^{-2})) = \frac{1}{4} \mathrm{Log}_{10} ([P(w)/ \Omega(st)]/(175\ \lambda^{-2})).$$

We assume $\varepsilon_c = 0.5$ total conversion efficiency of solar (stellar) illumination to laser output. This is about a factor of two higher than our current state of the art for CW systems (present efficiency of concentrated space solar is 50% and laser efficiency is above 50% for the most efficient systems).

For reference a class 0 civilization would possess the equivalent of a 1 meter diameter optical system transmitting approximately 1 kw while a class 4 civilization would be able to build a 10 km array with transmitting approximately 100 Gw and a class 11 civilization would be able to harness the power of a star like our Sun and convert it into directed energy. A class 5 civilization would be similar in this sense to a Kardashev Type I while a class 11 civilization would be similar in this sense to a Kardashev Type II or similar to civilization that can harness a typical star. We are currently about a class 1.5 civilization and rising rapidly. We already have the technological capability to rise to a class 4 civilization in this century should we choose to do so. As one example, two class 3 and above civilizations can "see" each other across the entire horizon modulo the time of flight. Here we use the term (entire horizon) to refer to high redshift galaxies we feel have had sufficient time to develop life. This is discussed further below.

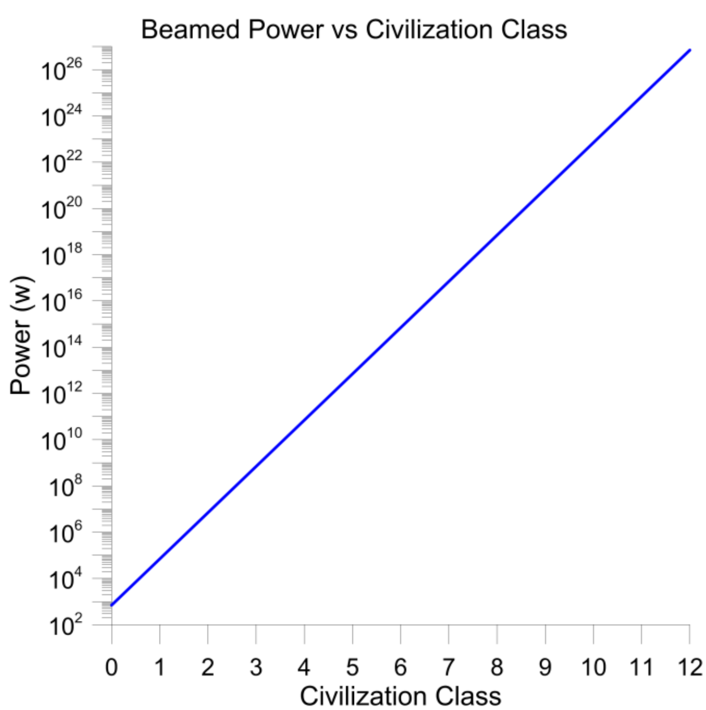

Figure 2 – Civilization class and laser emitted power level (CW).

Flux and Magnitude Equivalents vs Civilization Class and Distance - We can now compute the flux at the Earth from a distant civilization which we show in Figure 3. The distances are the effective "luminosity distance" which at non cosmological distances is simply the normal Euclidean distance we are used to measuring. At cosmologically significant distances we need to use the cosmological correction reflecting the geometry of our universe. This is discussed and computed below. It is helpful to also think of the received flux in terms of the equivalent photometric magnitude that is commonly used in astronomy. We show this in Figure 4 as a rough indication of how "bright" the signal is. The equivalent magnitude is computed as if the signal were uniformly distributed over the typical photometric bandwidth of R~ 4. Of course the laser lines we look for are much narrower so we have vastly less background that in a photometric band. Nonetheless this is instructive when comparing to the common language of magnitudes in astronomy. As can be seen at the distance of the typical Kepler planets (~ 1 kly distant) a class 4 civilization appears as the equivalent of a mag~0 star (ie the brightest star in the Earth's nighttime sky) while the same civilization at the distance of the nearest large galaxy (Andromeda) would appear as the equivalent of a m~17 star. The former is easily seen with the naked eye (assuming the wavelength is in our detection band) while the latter is easily seen in a modest consumer level telescope.

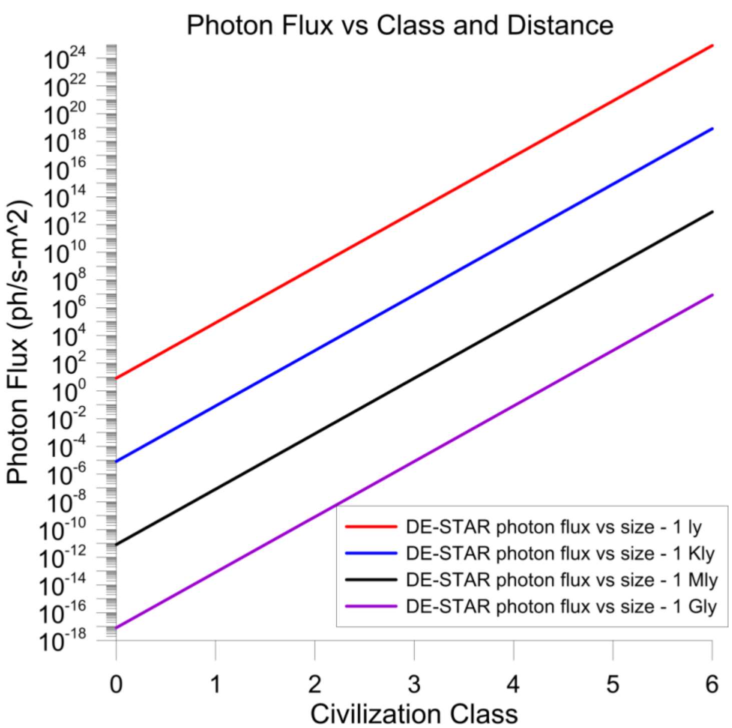

Figure 3 – Photon flux at Earth vs civilization class and distance. Distances are luminosity distance. See below for cosmological effects at higher redshift.

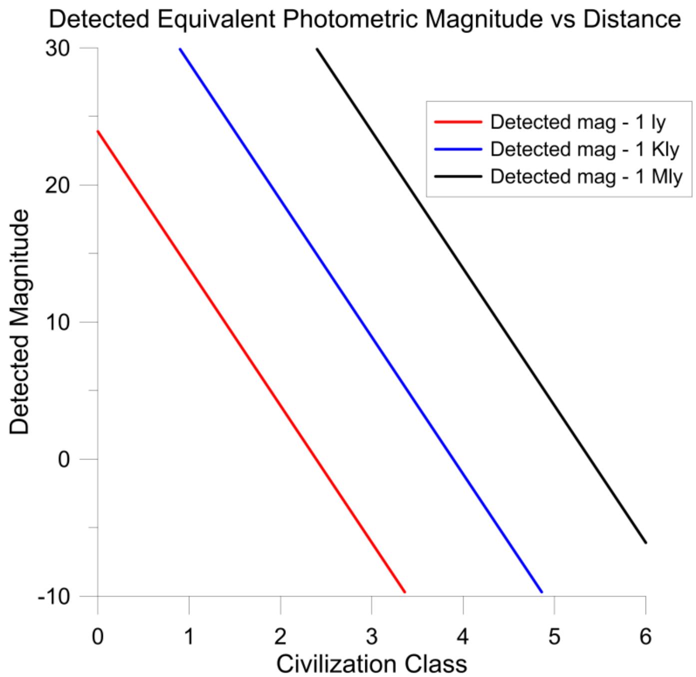

Figure 4 – Equivalent photometric magnitude vs civilization class and luminosity distance. At distances small compared to cosmological scales the Euclidean distance and luminosity distance are equivalent. The equivalent photometric magnitude is based on an equivalent R~ 4 photometric filter band.

4. ATTENUATION AND GRAVITATIONAL LENSING

4.1 K Corrections due to dust and gas

Gas and dust in interstellar and intergalactic space absorb and scatter radiation. This is sometimes known as “reddening” since the SED from distant stars and galaxies is shifted towards the red portion of the spectrum as the dust preferentially absorbs and scatters the shorter wavelength light (the “bluer part”) and allows more of the longer wavelength portion (the “redder portion” to pass through. This is analogous to the reddening of the sun at sunset. The details of this process depend on the form and distribution function of the dust grains. Normally objects are studied whose host spectrum is assumed to be known and the observed spectrum is a measure of the dust. The difference between the as observed and as emitted vs wavelength is known as the “K correction”. K is conventionally given in magnitudes and depends on wavelength, direction of the target and distance to the target. It is also conventional to use a K correction to take account of the atmospheric transmission discussed below. In general the shorter wavelengths are absorbed more by dust and gas while the longer IR wavelengths are much less affected.

$F_0(\lambda) =$ flux without dust and gas

$F(\lambda) =$ flux with intervening dust and gas

$m_0(\lambda) =$ magnitude without dust and gas

$m(\lambda) =$ magnitude with intervening dust and gas

$\alpha(\lambda) =$ attenuation coefficient from dust and gas

$K(\lambda) = K$ correction magnitude due to intervening dust and gas

Note that $\alpha(\lambda)$ depends on the target direction and distance

$F(\lambda)/F_0(\lambda) = e^{-\alpha(\lambda)} \equiv$ transmission

Since magnitude differences are defined as the log of flux ratios we have:

$$K(\lambda) \equiv m(\lambda) - m_0(\lambda) \equiv -2.5\log[F(\lambda)/F_0(\lambda)] = 2.5\log[e^{-\alpha(\lambda)}] = 2.5\alpha(\lambda)\log(e) \sim 1.086\alpha(\lambda)$$

$m(\lambda) = m_0(\lambda) + K(\lambda)$ {hence the term K correction}

The transmission thru the dust and gas is given by:

$$F(\lambda)/F_0(\lambda) = e^{-\alpha(\lambda)} = e^{-K(\lambda)/2.5\log(e)} \sim e^{-0.921K(\lambda)}$$

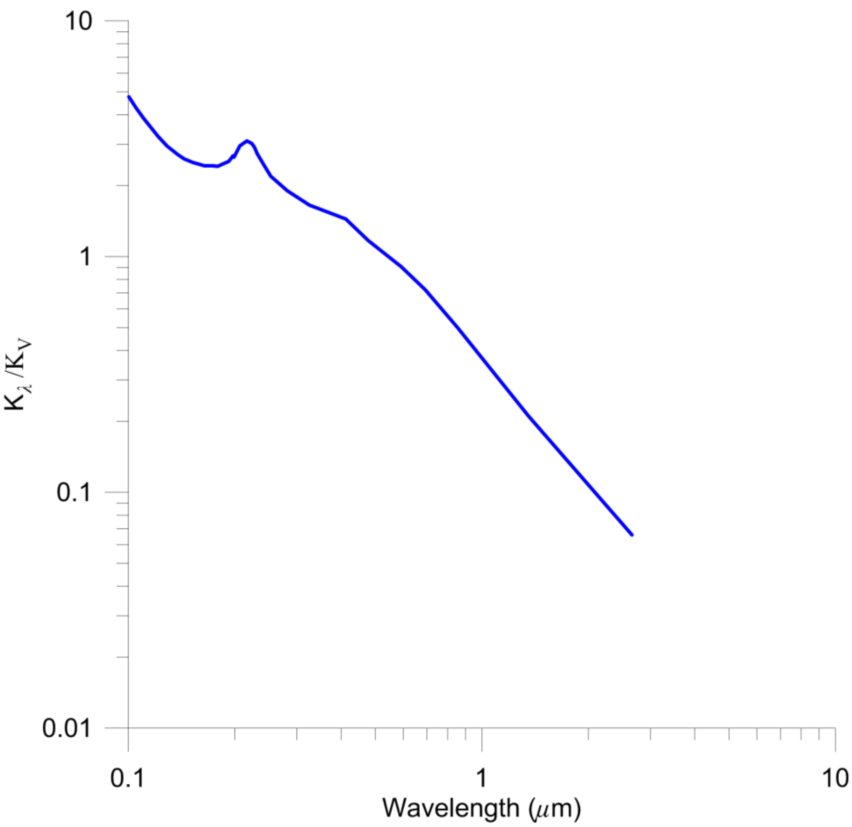

Figure 5 - Ratio of extinction coefficient at a given wavelength to the same but in V band (~ 0.5 microns) in our galaxy. Note this is an approximation as the extinction coefficients are anisotropic. As is typical the extinction coefficient decreases with increasing wavelength.

4.2 Gravitational Lensing

Gravitational lensing occurs due to the gravitational interaction of photons with the gravitation field due to matter (both Baryonic and Dark). Gravitational lensing is well known but not on the small angular scales that may be relevant here. In addition there is a time varying component due to the motions of matter along the null geodesic. There are numerous studies of gravitational lensing in the visible as well as the large scale power spectrum studied by the Planck mission. The primary issue here is less the overall deflection of the beam but rather the gravitational focusing and defocusing that may occur. This requires a more sophisticated simulation for various realizations and will not be covered in this paper.

5. FUNDAMENTAL BACKGROUNDS

5.1 Backgrounds relevant for detection

In order to determine the signal to noise of the return signature it is necessary to understand the non-signal related sources of photons. This is generically referred to as the background. There are a number of such backgrounds that are important. Going outward from the detector to the target and beyond, there is:

- Dark current and “readout noise” associated with the detector
- Thermally generated photons in the optical system, under the assumption that the optical system is mostly running near 300 K.
- Photon statistics of the received signal.
- Atmospheric emission – sky glow if the observations are inside the Earths atmosphere.
- Solar system dust that both scatters sunlight and emits from its thermal signature. Dust in the solar system is typically at a temperature of about 200 K. This is generically called Zodiacal scattering and emission, respectively, or simply Zodiacal light. This assumes a mission inside the solar system. We assume that there is a similar level of equivalent dust in the host civilization “solar system”
- Distant background stars that are in the field of view
- Sunlight scattered into the field of view for targets that are near to the sun in the field of view. This is generally only important for targets that are very close to the sun along the line of sight, though off axis response of the optical system can be an issue as well.
- Scattered galactic light from dust and gas in our galaxy.
- The far IR background of the universe, known as the Cosmic Infrared Background or CIB. This is the total sum of all galaxies (both seen and unseen) in the field of view in the laser band.
- The Cosmic Background Radiation or remnant radiation from the early universe. This is negligible for short wavelengths.

In all of these cases the fact that the laser linewidth (bandwidth) is extremely narrow (from kHz to GHz depending on the laser design) and the field of view is extremely narrow, mitigates these effects which would otherwise be overwhelming for a broadband photometric band survey. Heterodyning is also possible could be used in the future but is not assumed as we do not posses large focal plane arrays of such detectors.

5.2 Cosmic IR Background - CIB

The CIB was first detected by the Diffuse IR Background Explorer (DIRBE) instrument on the Cosmic Background Explorer (COBE) satellite launched in 1989 and studied by numerous other experiments including the recent Planck mission.[27,28,29,30] It is an extremely faint background now thought to be due to the sum of all galaxies in the universe from both the stellar (fusion) component at short wavelengths near 1 μm and from the re-radiated dust component near 100 μm. On large angular scales (degrees) it is largely isotropic though at very small angular scales (arc sec) individual sources can be detected. The diffuse CIB component, using data collected by DIRBE, is shown in the attached Fig. xx.

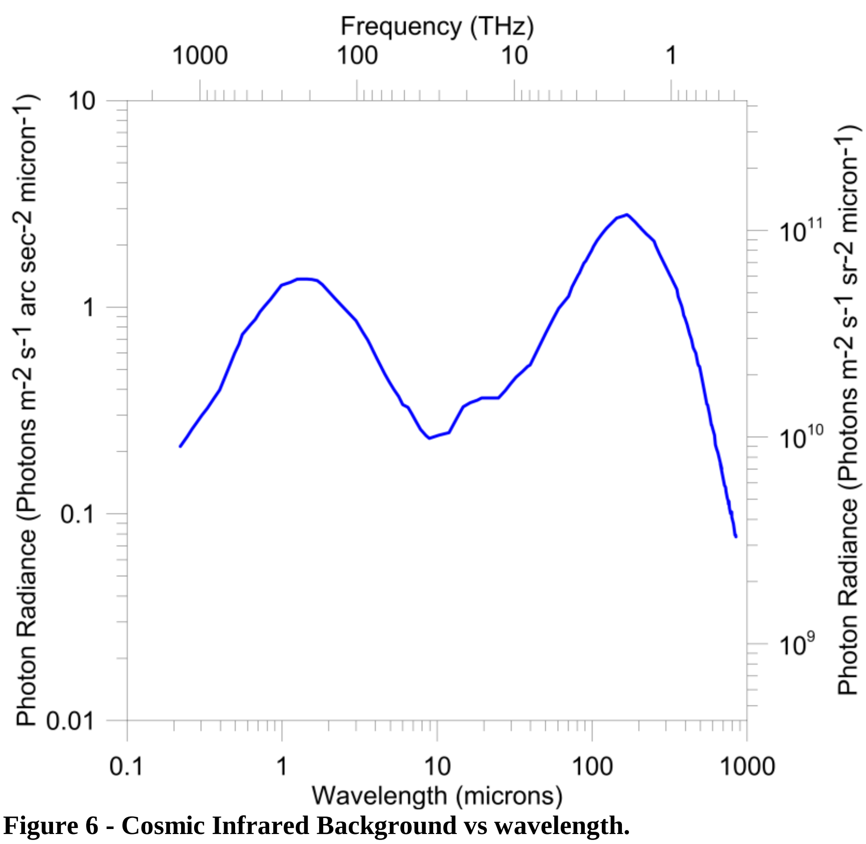

Figure 6 - Cosmic Infrared Background vs wavelength.

5.3 Zodiacal Light

Like the CIB the zodiacal light has two components and both involve dust in the solar system and the Sun. The sunlight both scatters off the interplanetary dust grains giving a “streetlight in fog” effect as well as heating the dust grains which then reradiate in the mid to far IR. The scattered component can be seen with the unaided eye in dark extreme latitudes and is sometimes known as the “Gegenschein” and traces the ecliptic plane. The dust grains are in rough equilibrium through being heated by the Sun and cooling through their own radiation. This background is not isotropic but is highly anisotropic depending on the position and orientation of the observer in the ecliptic plane. This was studied in detail by the DIRBE instrument on COBE.[27,28,29] As seen in Fig. xx, based on some of the DIRBE measurements, the brightness of both the scattered and emitted components vary dramatically with the observed line of sight relative to the ecliptic plane. In the plot the angle relative to the ecliptic plane is given by the ecliptic latitude (Elat) where Elat = 0 is looking in the plane and Elat = 90 is looking perpendicular. The situation is even more complex as the scattered and emitted components vary with the Earth’s position in its orbit around the Sun. By comparing the CIB and the Zodiacal light, it is clear that even in the best lines of sight (perpendicular to the ecliptic plane) the Zodiacal light completely dominates over the CIB. For the JWST mission the Zodiacal light is typically the limiting factor for IR observations, for example. However, since illumination will occur in a system with an extremely narrow laser bandwidth, and detection occurs with a matched narrow bandwidth (allowing for Doppler shifting) , it is possible to largely reduce the Zodiacal light and the CIB to negligible levels. This is not generally true for broadband photometric (typically 30% bandwidth) surveys.

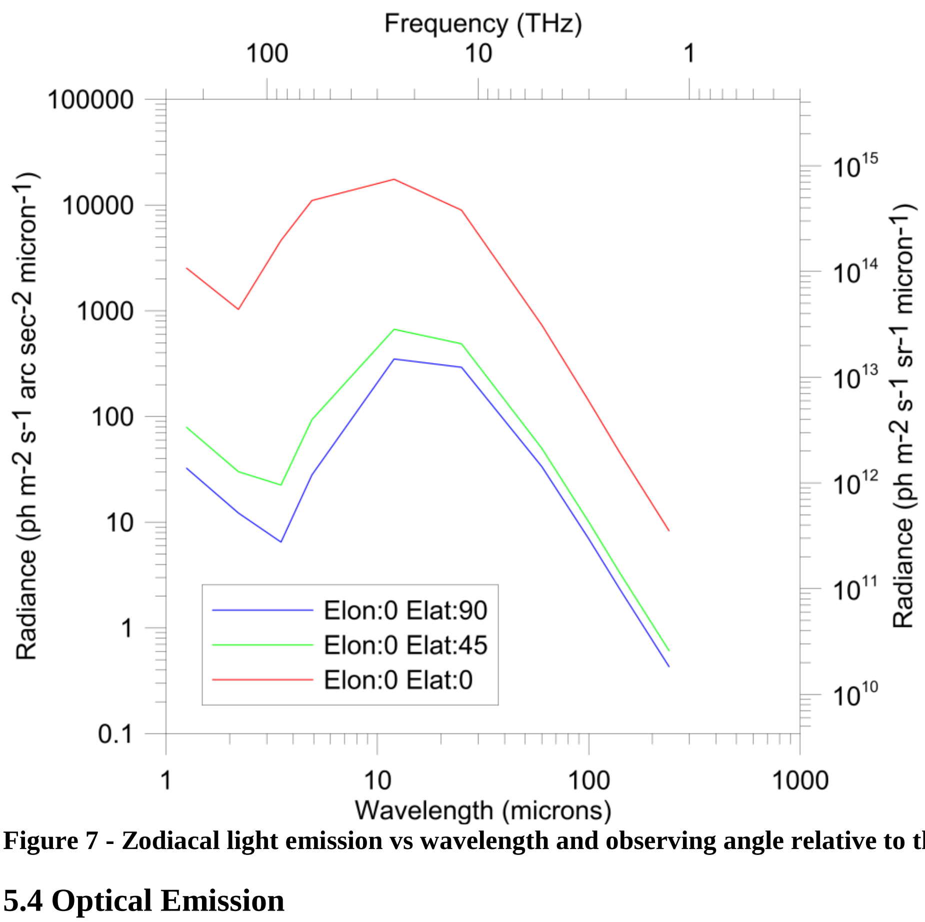

Figure 7 - Zodiacal light emission vs wavelength and observing angle relative to the ecliptic plane.

5.4 Optical Emission

The optical emission from the telescope also needs to be considered. The optics are assumed to be at roughly 300 K for simplicity (this could be changed in some scenarios), giving a brightness of about 1×10^7 ph/s-m^2-sr-µm for unity emissivity (or for a blackbody emitter) at the baseline wavelength of 1.06 μm. Unity emissivity is clearly an over estimate but represents a worst case. Under the assumption of a diffraction limited system, the entendue of the optics is such that A Ω = $\lambda^2 \sim 10^{-12}$ $m^2 \cdot sr$ where A is the effective receiving area and Ω is the received solid angle. The bandwidth of reception must also be included. Here a matched filter spectrometer or heterodyning is assumed (to get Doppler) with a bandwidth equal to the laser linewidth. As mentioned above, this is typically10^4 - 10^{10} Hz or approximately 4×10^{-11} to 4×10^{-5} μm. The total per sub element is thus an emission of about 4×10^{-16} to 4×10^{-10} ph/s again for an emissivity of 1. This is an extremely small rate compared to the other backgrounds (air glow, Zodi, CIB) as well as the signal itself. Comparing the optics emission of 1×10^7 ph/s-m^2-sr-μm for unity emissivity to the CIB and Zodiacal light shows the CIB and Zodiacal light are both much larger than the optics emission.

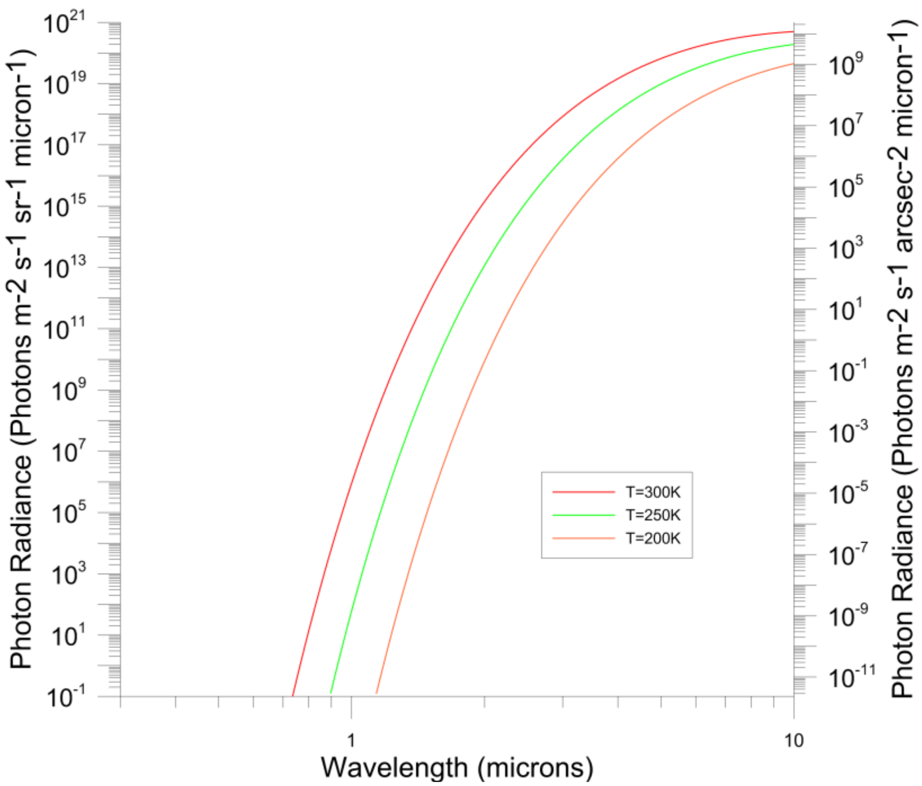

Figure 8 - Optical emission assuming unity emissivity

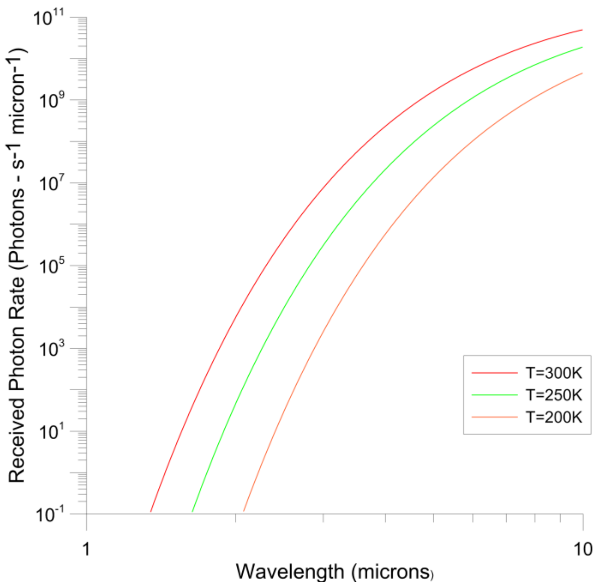

Figure 9 - Optical emission assuming a diffraction limited optical system

5.5 Atmospheric Transmission and Radiance

For studies inside the Earth's atmosphere we need to consider the transmission and emission of the atmosphere. We consider the transmission and thermal radiance of the Earth's atmosphere for different observation scenarios from sea level, to high mountain observatories to aircraft and finally stratospheric balloons. There are a number of observational windows that allow us to observe in the visible and IR that must be taken into account to optimize a search strategy especially one at high redshift. We will see that observations at high redshift become feasible for some scenarios. In addition to atmospheric thermal radiance we consider non thermal processes below as well as anthropomorphic produced lines.

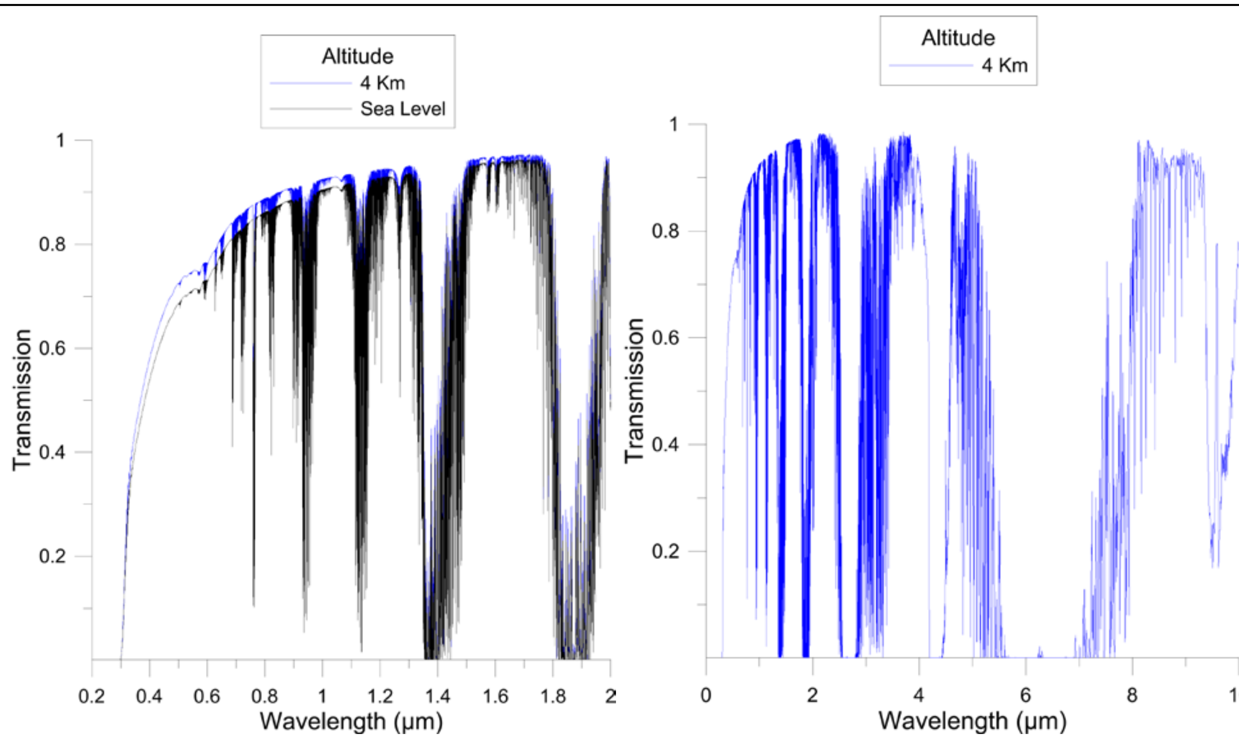

Figure 10 – Left: Atmospheric transmission from 0.25 to 2 microns. Right: Transmission from 0.25 to 10 microns

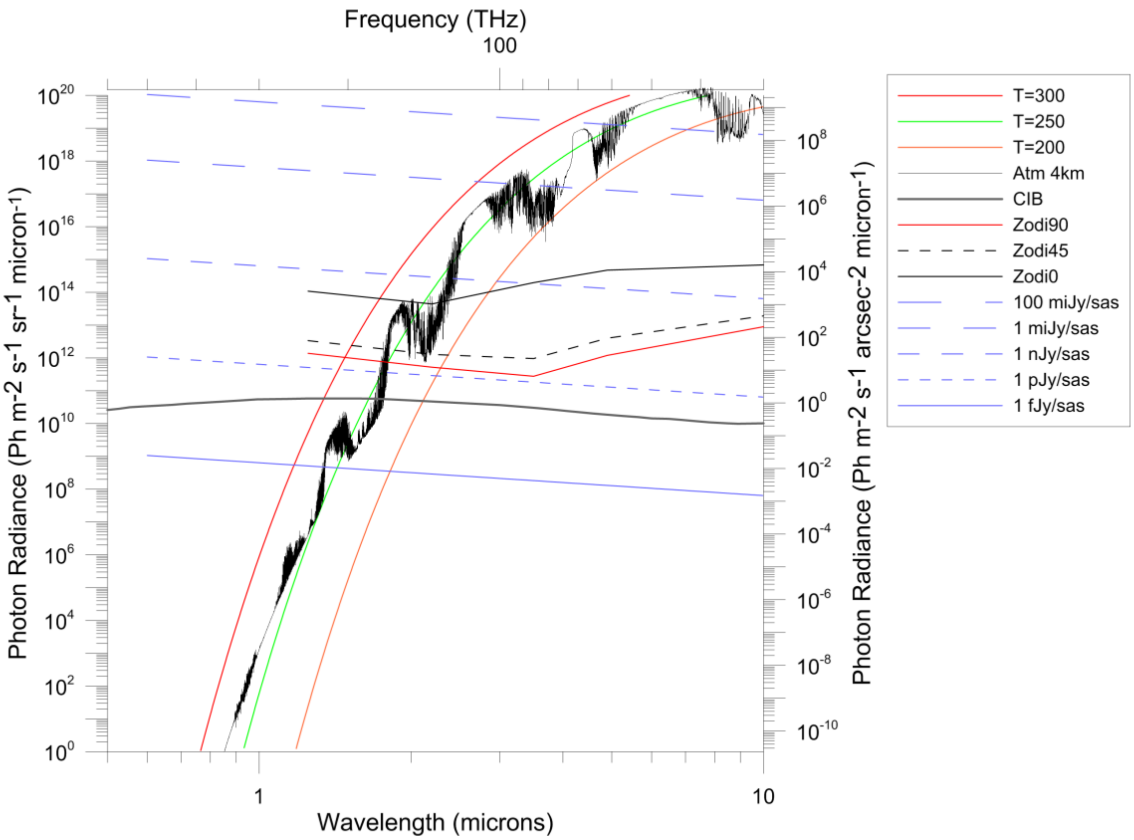

Figure 11 - Thermal emission from optics, atmospheric thermal radiance, CIB and Zodiacal light in the ecliptic plane (0) at 45 degrees relative to the plane (45) and perpendicular to the plane (90). Zodi is for COBE DIRBE day 100.

5.6 Non LTE Atmospheric Emission

There are additional processes in the Earth's atmosphere that are not in local thermodynamic equilibrium with the atmosphere. In particular various atomic and molecular transitions are excited by the solar wind and other energetic phenomenon. In the visible and IR there are a variety of non LTE lines that are highly time variable include Oxygen and OH emission. In general these have modest low spatial frequency variations but the variable background rates will be an issue at extremely low intensities. OH emission originates at altitudes above 80km typically and is most problematic in J (1.1-1.3 microns) and H (1.5-1.8 microns) bands with some in K (2-2-4 microns) band. Rousellot et al (2000) have computed the theoretical OH spectra of 4732 lines from 0.6 to 2.6 microns and spectrometers at major telescope measure the brighter OH lines. As mentioned the OH line emission is highly variably both temporally and spatially. OH lines are extremely narrow (unresolved at R=10,000) and while there are many lines they occupy a very small fraction of the spectrum due to their narrow linewidth. There is also a very large dynamic range in predicted OH line emission (over 14 orders of magnitude). Only the brighter lines are typically visible and longward of 2.6 and shortward of 0.6 there is very little OH emission. We also show a zoom in near the 1.064 micron Yb transition that is the baseline for our larger DE-STAR system as an example of the narrow nature of the lines and their spacing near the Yb line. This is one example. Fortunately we can achieve some additional rejection of OH due to the assumed point like structure of the source we are looking for while OH is spatially broad so some spatial filtering will be useful. This is analogous to photometry determination of the local sky background in aperture photometry.

Comparing OH emission in J and H bands it is clear that the OH lines dominate when using broad band filters while in the visible bands and beyond K band OH lines become sub dominant. This applies to ground based measurements while for space based measurements OH lines are not relevant. Since the OH lines are very narrow reducing the filter bandwidth does not allow us to completely mitigate them until we get to extremely narrow band filters or use an IFU both of which are problematic. Note that in a filter bandwidth the total OH emission is the sum of all the OH lines within the band. The use of aperture photometry and synthetic sky techniques will help us model and reduce the effects of OH line emission (as with all large angular scale emission) but we are still left with the nose from both photon statistics and systematic errors that will need to be taken into account. In this sense the problem is similar to classical LTE emission from optics and the atmosphere as well as from the detector but with the added complexity of more challenging temporal and spatial variations in the OH emission. In the visible bands and beyond 2.4 microns the OH emission is relatively small. The primary problem occurs between 1 and 2.4 microns. For broad band photometric systems non thermal emission dominate out to about 2 microns. For narrow bandwidth or spectroscopic systems zodiacal emission and scattering dominates out to about 1.5 microns. In the long run space based searches are preferred.

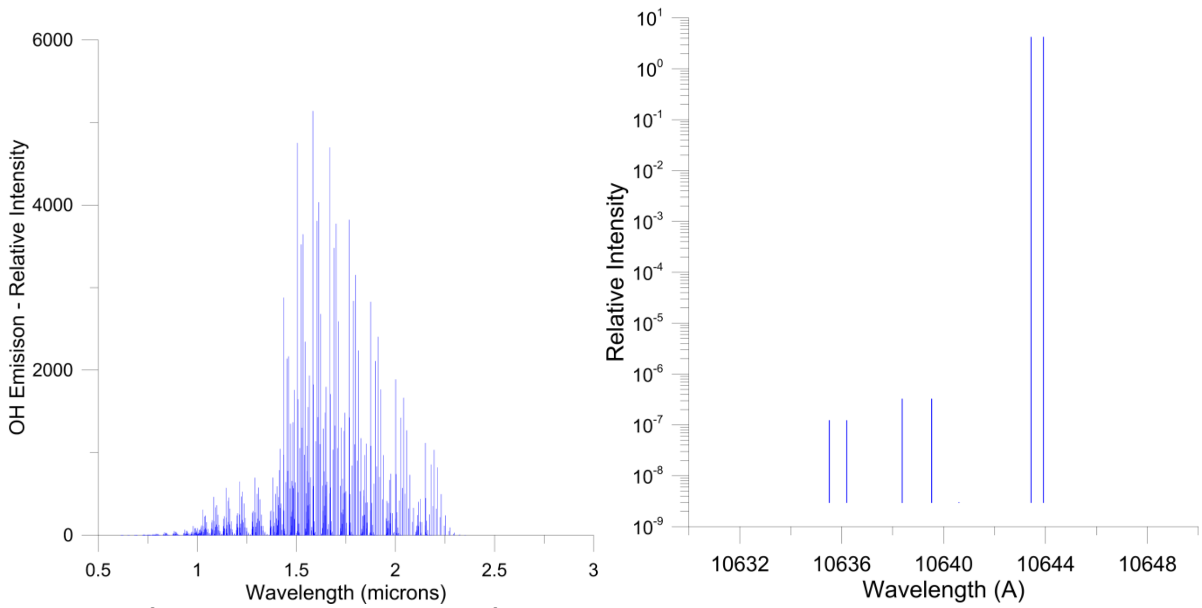

Figure 12 - Left: Theoretical OH emission lines from 0.6 to 2.6 microns - Right: Expanded region close to 1.064 micron Yb laser line. From Rousellot et al (2000) Note that the theoretical excitations leading to emission does not necessarily match the measured atmospheric OH lines due to excitation mechanisms in the atmosphere.

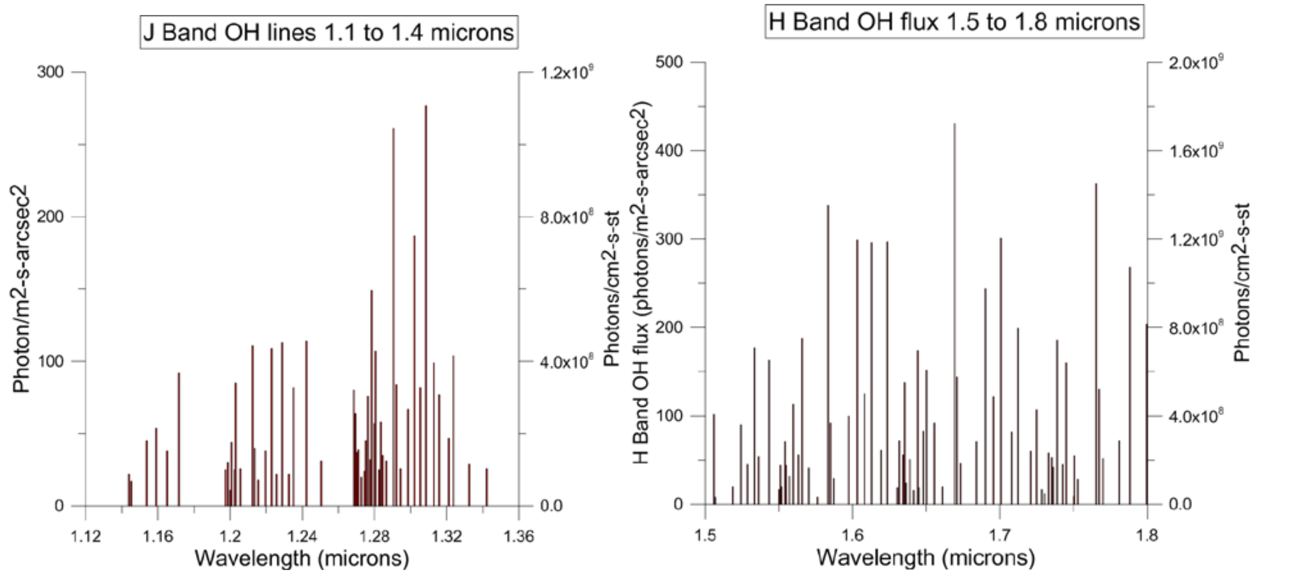

Figure 13 - Left: Measured J band OH emission at Subaru telescope - Right: Measured H band OH emission at Subaru telescope.

5.7 Measured Total Sky Background

For the best observatory sites the sky background minimum is about 22 mag/sq arc sec in V band (centered at λ ~0.55μm with bandwidth Δλ ~ 0.1μm). This corresponds to a flux of approximately 10 photons/s-m^2 -sq arc sec. This includes thermal as well as non thermal processes (air glow) , zodi etc. Comparing to the figures above we see this is in reasonable agreement. In the V band the dominant emission is from Zodi scattering of sunlight as well as non thermal atmospheric (air glow) processes. As we move towards into IR the thermal emission of the atmosphere and optics as well as OH lines begin to dominate with OH diminishing beyond K band (2.4 μm) .

5.8 Terrestrial illumination

Human lighting is an issue but in general is not as severe for our search as it tends to be a relatively slow temporal and spatial function. Some Hg and Na lines from HID lights are notable and increasingly LED lighting though the latter is generally broadband due to phosphor coatings. All of these are site dependent and can be mitigated by observing targets at multiple locations and over multiple time scales.

5.9 Stellar and Interstellar line emission

Host and intervening stellar atmospheres will provide some confusion due to the emission lines and to a lesser extend from absorption lines. In addition to common know lines we can also check their temporal distribution to see if they are natural or not. Using temporal photon statistics allows us an additional cross check as well as more conventional tests for unnatural time modulation of possible positive targets.

5.10 Unresolved stellar background

In many surveys we will not resolve individual stars and thus will have many stars per pixel. These unresolved stars will form a background, much like the CIB. Since the stellar distribution in galaxies is a strong function of position in the galaxy it is unlike the CIB in this sense and is highly spatially variable. This has implications for the coupling of pointing jitter and seeing variations into our data. In particular the unresolved stars have emission lines that will form a line background in addition to the continuum background.

5.11 Unresolved galactic signatures

Along any given direction we will have a number of distant galaxies in a pixel for ground based surveys as well as small aperture space based surveys. This is basically the CIB but in this instance there is an additional component to the usual CIB in that each galaxy has some billion to trillion possible civilizations. On average in a square arc second, typical of ground based seeing without adaptive optics, we will have an unresolved and undetected distant galaxy at an unknown redshift.

5.12 High Redshift surveys

We can detect civilizations at a variety of redshifts and this poses unique opportunities and challenges. For higher civilization classes we can detect them at any redshift which is both good and problematic for our detection algorithm.

We show the relationship between distance and redshift in the attached plot for several cosmological models. There is relatively little difference in the models for luminosity distance even ignoring dark energy at low redshift. The distances we normally quote are luminosity distances even if just labeled distance. We also show cosmological age vs redshift and cosmological age vs luminosity distance. By redshift z=5 the age of the universe is only about 1.2 Gyr. If life does not evolve rapidly after star formation then there would not be sufficient time to evolve technologically advanced civilizations capable of emitting detectable directed energy signatures. The luminosity distance at z=5 is about 47 Gpc corresponding to a Euclidean distance of about 150 Gly. While still detectable for some higher civilization classes the time for advanced technological evolution is short. Correspondingly at z=1 the cosmological age is about 5.8 Gyr corresponding to a luminosity distance of about 6.7 Gpc allowing much more time for life to evolve. For reference our evolution on Earth is about 3-4 Gyr. We also show the commoving volume of the universe vs the redshift we observe to as well as the normalized commoving volume explored to a given z relation to z=20 where we chose z=20 to be a reasonable approximation for the first stars and planets. Note that z=20 contains the vast majority of the volume of our horizon but that z=20 is only about 150 Myr after the beginning and this is likely not sufficient time for intelligent life to form. If we assume intelligent life needs 4.5 Gyr to form (approximately our evolution time after the formation of the solar system) this would correspond to about z~1.5. We also show the normalized comoving volume normalized to z=1.5. The normalized comoving volume is essentially the fraction of the accessible universe where we might expect to find technologically advanced life based on our own evolution. These are obviously large assumptions on our part. We use a concordance model (2015 Planck) which yields a current age of around 13.8 Gyr.

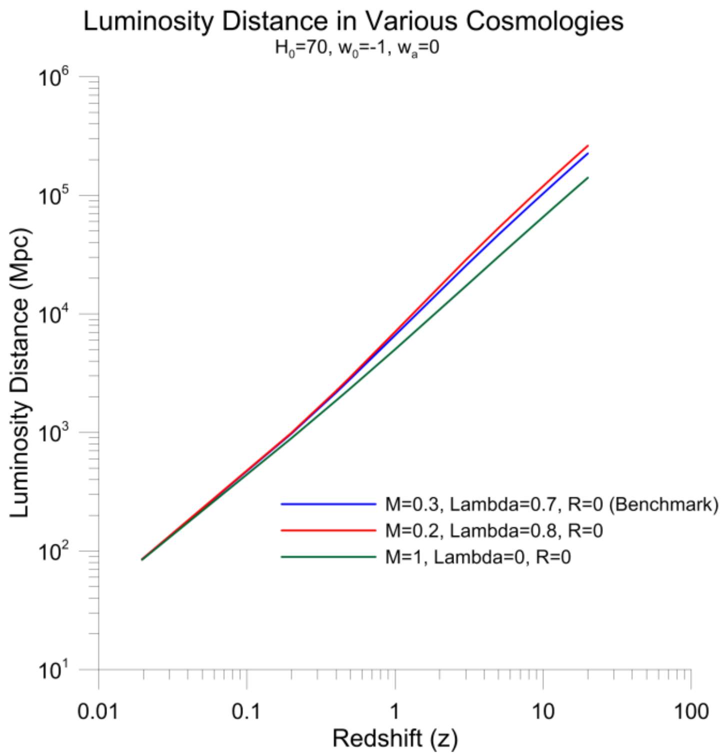

Figure 14 - Luminosity vs Redshift for several cosmological models. The "benchmark" model is closest to the current concordance models.

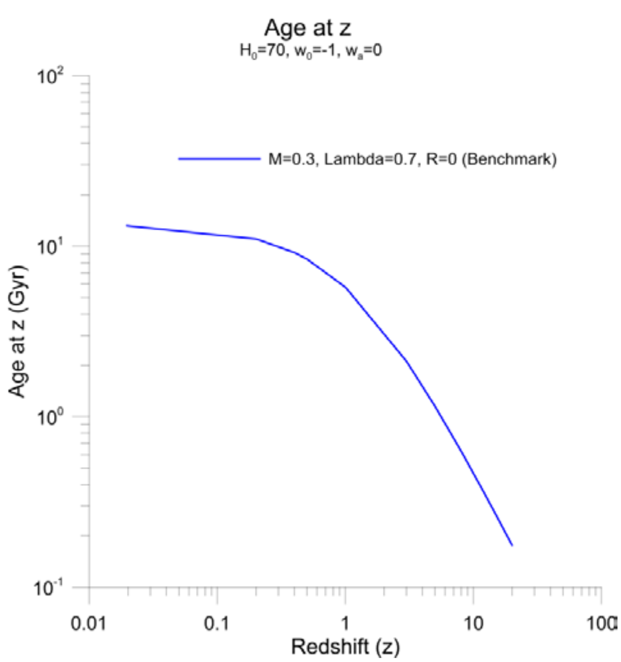

Figure 15 - Age of the universe vs redshift for the current concordance model. This is critical for understanding the possibilities of life forming in enough time at high redshift. Concordance universe assumed.

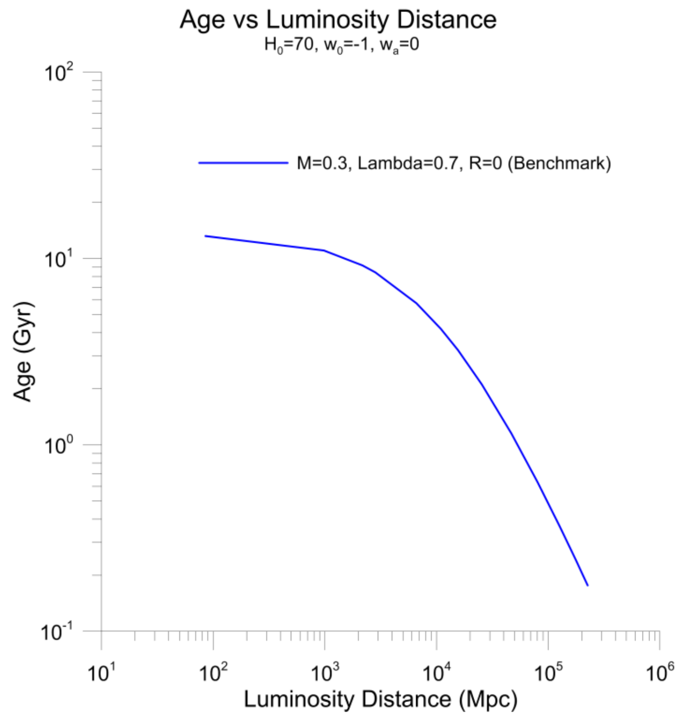

Figure 16 - Age of the universe vs luminosity distance. This is critical for understanding the time scale for the evolution of life and the effective luminosity distance it corresponds to. Concordance universe assumed.

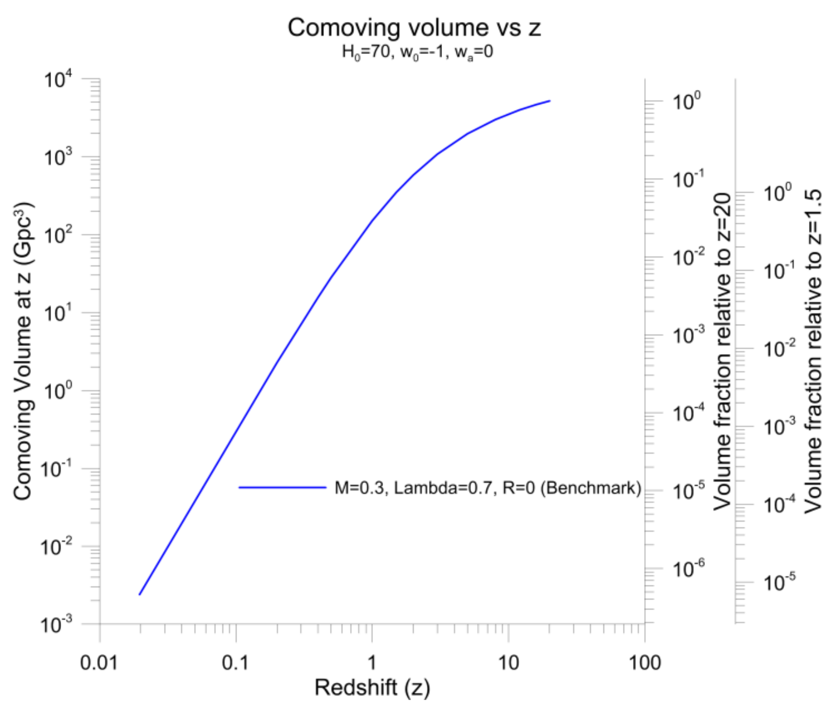

Figure 17 - Comoving volume vs redhsift. Also shown is the normalized fraction of the volume at z=1.5 and 20. By z=20 virtually all the comoving volume is explored while at z=1.5 a bit less than 10% of the volume is.

5.13 Detection bandwidth

The intrinsic bandwidth of lasers is extremely narrow by most astronomical standards. Laser lines as narrow as 1 Hz or even less have been demonstrated. For current high power laser amplifiers the bandwidth is typically at the 0.1-1 KHz level but to achieve the highest power levels this is artificially broadened to about 10 GHz/Kw , at a wavelength near 1 micron, to overcome the Stimulated Brillion Scattering (SBS) limits in the fibers. There is no intrinsic reason this broadening needs to be implemented if lower power per fiber amplifiers are used and indeed at the 10-100 watt amplifier level bandwidths below 1 KHz are already achievable. The bandwidth language of lasers is usually given in Hz while the astronomical language of bandwidth is usually discussed in microns or nanometer. The relationship between the two is simply $\Delta\lambda = c\nu^{-2}\ \Delta\nu$. The effective spectroscopic resolution is defined as $R=\lambda/\ \Delta\lambda = \nu/\ \Delta\nu$. To put this in perspective a laser line at 1 micron ($\nu \sim 300$ THz) with a 1 Hz bandwidth (mixing units is typical in this field unfortunately) has an $R \sim 3\text{x}10^{14}$. By astronomical standards of spectrometers this is a phenomenally large R. Even with the current broadened SBS limit mitigation techniques of 10 GHz/Kw the effective R ~ 30,000 for a 1 Kw fiber amplifier at 1 micron. The current state of the art for astronomical spectrometers whether fiber fed or free space is about 10^4 -10^5. Heterodyne spectroscopy is now becoming possible at optical and IR wavelengths and offers much higher R for the future if needed.

In the accompanying plot we show the laser linewidth (usually quoted in Hz) to the equivalent width in microns. We have chosen a wavelength of 1.06 microns for convenience. It corresponds to a particularly efficient Yb transition we are using as the baseline for the DE-STAR program but it is representative of any system. In this case the bandwidth in microns also corresponds to the equivalent $\beta = v/c$. While sources and receivers are in relative motion the effect is to shift the central line not to broaden it since the systems we envision are localized. The bandwidth is also approximately1/R where R is the spectral resolving power for a 1 μm signal.

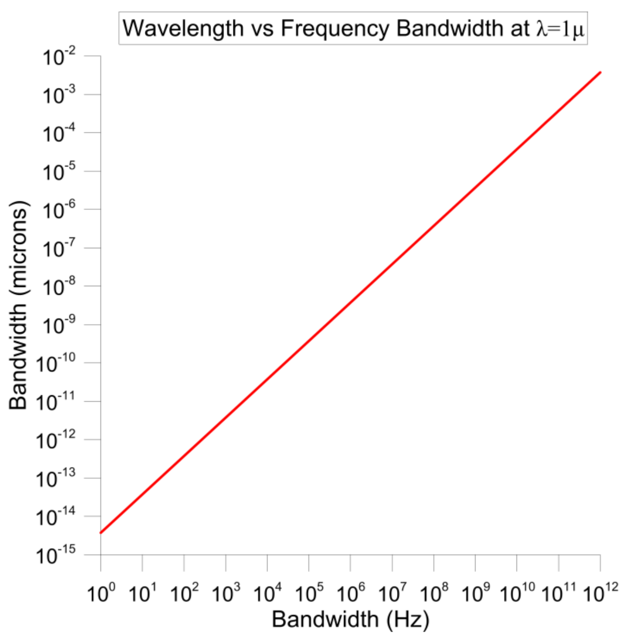

Figure 18 - Bandwidth of laser line in microns vs Hz. Typically laser linewidths are specified in Hz while the more relevant parameter for astronomical discussion is in microns.

5.14 Comparison to in-band emission from natural sources

Since the laser line is very narrow it is important to understand how the “in-band” received flux integrated over the bandwidth of the line from the laser compares to natural sources of radiation. It is useful to compare the radiance (w/m^2-st) for a laser and for a star when both are integrated over their respective areas and over the linewidth or filter bandwidth. In this way we compare to emitters at their source assuming the laser is associated with a planet near a star.

For simplicity we model the star as a thermal source.

The brightness is then $B_\lambda = \frac{2hc^2}{\lambda^5\left(e^{hc/\lambda kT}-1\right)}$ (W/(m^2-sr-m)). We then integrate this over the forward facing hemisphere of the star and over the linewidth and compare to the laser for a given civilization class. As an example we compare the brightness of our Sun, modeled as a 5700 K blackbody, at a wavelength of 1.06 microns and get 9 MW/m^2/sr-µm. With a diameter of 1.4x10^9 m this gives 1.4x10^{25} w/sr- µm. The relationship between wavelength and frequency bandwidth $\Delta\lambda = c\nu^{-2}\,\Delta\nu$ at 1.06 microns is $\Delta\lambda(\mu m) = 4\times10^{-15}\,\Delta\nu$ (Hz). Assuming a laser linewidth of 1 kHz (typical for current state of the art modest power (~ 0.1 KW) amplifiers) this would yield $\Delta\lambda(\mu m) = 4\times10^{-12}$. For current high power amplifiers (KW class) that are SBS limit artificially broadened with a linewidth of 10^{10} Hz this yields $\Delta\lambda(\mu m) = 4\times10^{-5}$. Both of these are small linewidths by astronomical standards but not by laser standards. Both linewidths currently exist in the relevant technology. However the primary effect of directed energy is in fact that it is directed. For example a class S civilization has a laser array size (d) where d(m)=10^S and beam divergence full angle $\theta = 2\,\lambda/d$ with a projected solid angle of approximately $\Omega = (2\,\lambda/d)^2 = 4\,\lambda^2 10^{-2S}$. As an example a class 4 civilization has projects a beam with a solid angle of approximate 4x10^{-20} sr.

Comparing the Sun to a class 4 civilization gives the following into the same solid angle:

Linewidth (1 KHz ~ $\Delta\lambda(\mu m) = 4\times10^{-12}$)	Sun: 2x10^{-6} W	Laser: 7x10^{10} W
Linewidth (10 GHz ~ $\Delta\lambda(\mu m) = 4\times10^{-5}$)	Sun: 20 W	Laser: 7x10^{10} W

Here we treat the Sun as a prototype for a distant star, one that is unresolved in our telescope (due to seeing or diffraction limits). Clearly the laser is vastly brighter in this sense. Indeed for the narrower linewidth the laser is much brighter than an entire galaxy in this sense**.** ***For very narrow linewidth lasers (~ 1 Hz) the laser can be nearly as bright as the sum of all stars in the universe within the linewidth.*** **Thus even modest directed energy systems can stand out as the brightest objects in the universe within the laser linewidth.**

5.15 Orbital considerations and optimal detection bandwidth

As we do not apriori know the orbital speeds of the targets we are searching for we need to consider the optimum search strategy. There is also the issue of the bulk speed of the galaxy the target is embedded in. The shorter term, but predictable, orbital velocity variations due to the rotations of the Earth, orbit of the Earth around the Sun etc and the similar but unknown orbital environment of the target leads to a complex search optimization. Ideally broadband FFT like heterodyne searches will be possible in the future but we will concentrate on more (currently) practical methods such as using narrow band filters and IFU’s. For example if we adopt a series of narrow band filters as one approach to detection then one of the fundamental issues is to temporally “chop” the spectral bands so that the Doppler shift due to orbital shifts during the period of observing for that the shift over this period is small compared to the filter bandwidth. For example the earth’s rotation speed (~ 1 km/s) yields a Doppler shift of roughly $3x10^{-6}$ while the Earth’s rotation around the Sun (~ 30 km/s) gives a Doppler shift of about 10^{-4}. The time scales of these is very different being 1 day and 1 year respectively. Our typically observing times for a complete series of filters will be typically measured in hours so spectral chop period is even less than one rotation of the Earth. The equivalent for the target is completely unknown but we assume a comparable situation both for simplicity and based on the issue of habitability and known detected exo-planets.

5.16 Detection Bandwidth and Background Noise levels

To achieve the maximum signal to noise ratio we need to understand the level of the background noise vs the signal. The optimal filter bandwidth would be large enough to encompass the emitted laser line and any broadening mechanisms but not so wide as to significantly increase the background noise. On the other hand the filter bandwidth affects the search strategy if individual filters are used. There is a tradeoff. Ideally a large portion of the both spectral and spatial space would be simultaneous sampled to give a fast mapping speed. Currently there are no simple technical solutions consistent with both of these needs. Spectrometers exists with high R but they are limited to a very modest number of pixels. Our initial search strategy will focus of trading large simultaneous spatial coverage for large simultaneous spectral coverage. Ideally in the future this will change. Given all the sources of noise there is a point where having a filter that is too narrow becomes counter productive. This is the optimization that is required. For example if the filter bandwidth reduces the background levels to be much less than readout noise in the detector than no additional gain is added by reducing the filter bandwidth. There is a large parameter space to tradeoff here and with the target unknown it is simply a subjective trade. Adding in practical considerations such as telescope time and systems costs pushes the trade to larger filter bandwidths currently. Multichroic beam splitters is another option to increase thruput that we are exploring in addition to other techniques.

5.17 Search Strategies

To decide on a search strategy we first need ot decide what it is we are looking for. At first this seems obvious (find “unnatural” sources, but the optimum search given limited time and resources is more subtle.

Modulation detection - One method is to look for sources of temporal or spatial modulation that is unnatural. If we focus on temporal modulation we think of laser communication modulation. For use this is typically in the Gbps or nanosecond modulation range. But this is another “anthropomorphic now” mindset. If we are observing at a wavelength around 1 micron the available bandwidth far exceeds 300 Tbps with proper encoding. We do not currently possess this technology nor is it obvious that given the time of flight for distances that are astronomically relevant that directed energy based data communication (streaming of “intelligent” information) would be logical. As always “we do what we can do”. Hence searches for high frequency modulation at the reasonable limits of our current technology does make sense. There is of course no particular reason why civilization far more advanced that us would be transmitting data in the realm we can detect unless they are specifically trying to beacon other civilizations. This rapidly degenerates into a nearly useless philosophy of the unknown.

Ignoring modulation and searching for narrow but unnatural lines – Massively parallel search strategies - Another search option and the baseline we adopt is to search for narrow line emission that are unnatural and then follow up to determine if these lines contain intelligent information. The advantage here is we do not depend solely on temporal modulation to search but can observe extremely large number of possible targets simultaneously without knowledge of their modulation. In the past several group have looked for short pulses as an indicator of unnatural sources. The advantage in this strategy is that high peak power can be produced much more easily in short pulses but the disadvantage is the average power of terrestrial pulsed lasers is generally significantly lower than CW systems and from a search strategy we have no apriori knowledge that extra-terrestrial civilization would use pulsed systems. Indeed on Earth we do not generally use pulsed systems for communications, though this should not be a guide. For a given amount of average power the SNR is not necessarily higher for a pulsed system. Another and much greater disadvantage to searching for pulsed signals is that they are usually done with a single pixel on the sky while in the CW search one can use a large format array detector with multiple megapixels (Gigapixels are possible now) and thus there is a tremendous parallel advantage to a CW imaging search. Both approaches should be used.

For example in any square arc second of the sky there is approximately one galaxy even if not currently known and in this galaxy there are approximately 100 billion solar systems IF the galaxy is similar in star and planet formation to our own. In a single square degree that are thus about 10^7 galaxies and some 10^{18} possible stellar systems. This allows a massively parallel search strategy with no apriori pointing knowledge though we can directly image nearby galaxies. The fundamental issue here is to understand the SED (both line and continuum) well enough to model and subtract it. This then gets to the optimization of the filters. As we will see below, even with modest Earth based telescope, we can detect some advanced civilization across the entire horizon with current telescopes.

Sources not directly beamed towards us – A possibility is that we will "ease drop" on a laser communications system that is not intentionally beamed for other civilization detection. One option here is accidental line up (glint) that we just happen to intercept. The other option is to detect the side lobes or possible scattering of the main beam. The basic problem with these latter two is that the signal we would intercept would be drastically reduced as the typical side lobes and interstellar scattering is generally extremely small with far off axis side lobes of 40-100 db down from the main lobe not being unusual. Scattering of the target of the "laser communications" system is another possibility but this also drastically reduces the observed flux.

5.18 Life at High Redshift

Life on Earth is thought to have evolved between 3 and 4 billion years ago with what we now call intelligent life being relatively recent. This puts the beginnings of life at about 1 billion years after the formation of the Earth. We have little idea of the "why" of the evolutionary path that life took and much was externally influenced by bombardments for example. The first stars in the universe are thought to have formed within a few hundred million years after the beginning of the universe.

Planet formation presumably was on a similar time scale though the processes needed for life may have taken significantly longer. The times scales are sufficiently uncertain that we cannot rule out life at high redshift and this would allow many billions of years more for life to evolve than on Earth. Our own technological capabilities are an extremely non linear function of time with virtually no technology being achieved until the 1 part per million. This places us on an extremely nascent portion of the curve of intelligence and technology. If we imagine not a few thousand years of technological evolution but a few billion years of this it becomes sobering to contemplate intelligent life evolving at high redshifts and having billions of years (or a million time more than our technological time scale) to grow technologically. As we look at any patch of sky, with a typical square degree field of view, we will be observing some 10 million galaxies or some $10^{17} - 10^{18}$ possible planets if high redshift planet fractions are similar to today. As shown below we can detect class 4 and above civilizations at high redshift even with modest ground based (meter class) telescopes if they transmit in our direction when we are observing.

6. DETECTION AND SIGNAL TO NOISE CALCULATIONS

We model the detection system in a standard way assuming a model for quantum efficiency, dark current, read noise, combined "sky background" etc.

F= flux from target (γ/s-m^2)
F_B = flux per solid angle from all background sources integrated over bandwidth (γ/s-m^2 -st)
A = telescope area
A_ε= effective telescope area including transfer efficiency and quantum efficiency
ε = telescope transfer efficiency
i_{DC} = detector dark current (e^-/s)
Q_e = quantum efficiency of detector (e^-/γ)
Ω = solid angle of pixel
τ = integration time (s)
S=signal due to target at detector over integration time (e^-)
S_{DC} = signal due to dark current over integration time (e^-)
S_B = signal due to background over integration time (e^-)
S_{time} = total signal over integration time (e^-)
N_R = readout noise (e^-)
N_S = noise due to signal (shot noise) (e^-)
N_{DC} = noise due to dark current (e^-)
N_B = noise due to background sources (e^-)
N_{time} = time dependent part of noise (not including readout noise) (e^-)
n_t = signal, dark current and background noise (e/Hz$^{1/2}$)
N_T= total noise including read noise (e^-)
S_N = signal to noise ratio = SNR = S/ N_T

$$S = F\tau A\epsilon Q_e$$

(we assume we have dark field and bias subtracted the image)

$$S_{\text{time}} = S + S_{DC} + S_\beta$$

$$N_S = \sqrt{S} \qquad N_{DC} = \sqrt{S_{DC}} \qquad N_\beta = \sqrt{S_\beta}$$

$$N_{\text{time}} = \sqrt{N_S^2 + N_{DC}^2 + N_\beta^2} = \sqrt{S + S_{DC} + S_\beta} = \left(\tau(FA\epsilon Q_e + i_{DC} + F_\beta A\epsilon Q_e\Omega)\right)^{1/2} = \left(\tau n_t^2\right)^{1/2} = \tau^{1/2} n_t$$

$$n_t = \left(FA\epsilon Q_e + i_{DC} + F_\beta A\epsilon Q_e\Omega\right)^{1/2}$$

$$N_T = \sqrt{N_R^2 + N_{\text{time}}^2} = \left(N_R^2 + \tau(FA\epsilon Q_e + i_{DC} + F_\beta A\epsilon Q_e\Omega)\right)^{1/2} = \left(N_R^2 + \tau n_t^2\right)^{1/2}$$

We define the effective area A_ϵ

$$A_\epsilon = A\epsilon Q_e$$

$$\frac{S}{N} = \frac{S}{N_T} = \frac{FA_\epsilon \tau}{\left[N_R^2 + \tau(FA_\epsilon + i_{DC} + F_\beta A_\epsilon \Omega)\right]^{1/2}} = \frac{FA_\epsilon \sqrt{\tau}}{\left[\frac{N_R^2}{\tau} + n_t^2\right]^{1/2}} = \frac{FA_\epsilon \tau}{\left[N_R^2 + \tau n_t^2\right]^{1/2}}.$$

At short time scales the S/N increases linearly with integration time τ since the read noise dominates the noise and then transitions to increasing as $\tau^{1/2}$ at increasing times as the shot noise from the source backgrounds and dark current begin to dominate. We define the transition time between these two domains as τ_c.

$$\tau_c = \frac{N_R^2}{FA_\epsilon + i_{DC} + F_\beta A_\epsilon \Omega} = \frac{N_R^2}{n_t^2}$$

$$S/N(\tau = \tau_c) = \frac{FA_\epsilon N_R}{\sqrt{2}(FA_\epsilon + i_{DC} + F_\beta A_\epsilon \Omega)} = \frac{FA_\epsilon N_R}{\sqrt{2} n_t^2}$$

We solve for the time to achieve a given S/N as follows:

$$S_N \equiv S/N = FA_\epsilon \tau / \left[N_R^2 + \tau n_t^2\right]^{1/2}$$

$$S_N^2 (N_R^2 + \tau n_t^2) = F^2 A_\epsilon^2 \tau^2$$

$$F^2 A_\epsilon^2 \tau^2 - S_N^2 n_t^2 \tau - S_N^2 N_R^2 = 0$$

$$\tau = \frac{S_N^2 n_t^2 \pm \sqrt{S_N^4 n_t^4 + 4F^2 A_\epsilon^2 S_N^2 N_R^2}}{2F^2 A_\epsilon^2} = \frac{S_N^2 n_t^2}{2F^2 A_\epsilon^2}\left[1 + \sqrt{1 + \frac{4F^2 A_\epsilon^2 N_R^2}{S_N^2 n_t^4}}\right]$$

We note that the computation of the SNR above assumes the shot noise from the source also contributes to the noise term. This is reasonable IF the SNR is computed relative to the pixel the source is detected in but in most search strategies we will be doing spatial filtering and the SNR should be computed relative to the nearby pixels that do not have the source term in them.

Thus in the above we set $n_t = \left(i_{DC} + F_\beta A \epsilon Q_e \Omega\right)^{1/2}$ (noise in pixels outside source) in computing the SNR, τ and τ_c for comparing SNR of a possible source to its nearby pixels without the source. This increases the effective SNR.

7. SIMULATIONS

We compute some examples of the SNR for differing civilization classes, distances and hence redshifts for existing or soon to exist telescopes below. He we include all backgrounds and modest seeing and detectors but assume we have narrow enough filters to exclude airglow and OH lines or that we are in regions where these are minimal.

A more aggressive approach is to assume we use the same technology to receive as is used to transmit by the civilization target. In the latter case the SNR becomes extremely large across the entire horizon for space based surveys using this approach with civilizations of class 3 and above assuming we also become a class 3 civilization.

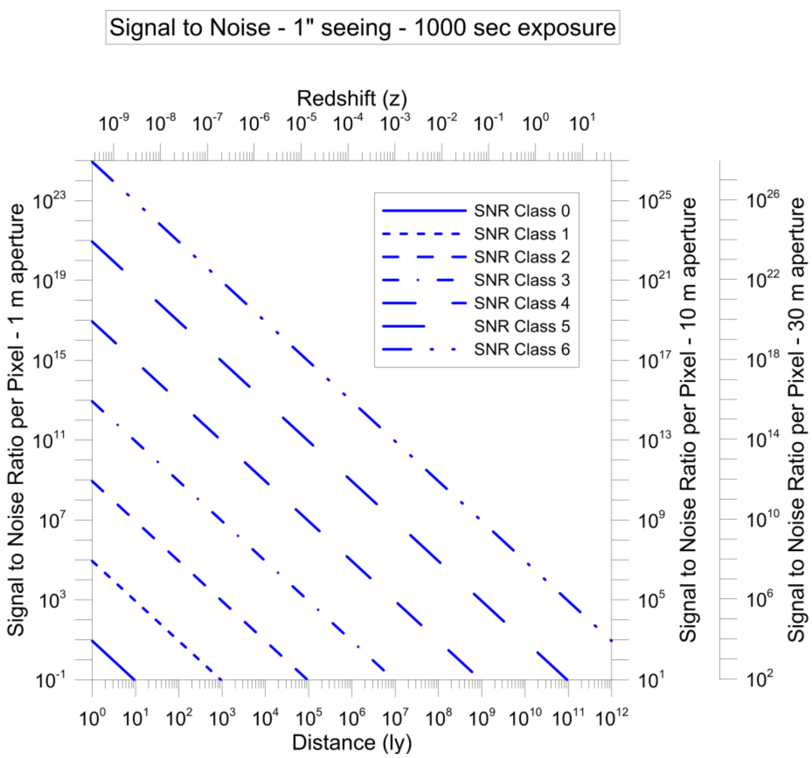

Figure 19 - SNR vs distance and civilization class for a 1, 10, 30 meter ground based telescope with a 1000 sec integration and very modest system assumptions with seeing of 0.5" RMS without adaptive optics, pixel size of 0.5", readout noise of 10e, dark current of 1e/s, QE =0.5 and atmospheric transmission of 0.5. The total noise is dominated by the readout noise and dark current and relatively insensitive to bandwidth. This represents our current (or soon to exist) capability for modestly wide field imaging. Our current technology for adaptive optics would be useful for narrow spatial surveys or follow up but is not currently feasible for wide field (degree class) surveys. The bottom line for even 1 m class telescopes is that class 3 civilization are detectable across our galaxy, class 4 civilizations are detectable in nearby galaxies and class 5 civilization are detectable out to modest redshifts. With 10 and 30 m class telescopes the situation is even more optimistic. A wide field LSST like telescope (8m class) could detect class 4 civilizations out to high redshift. We can reduce the readout noise to 1e and the dark current to negligible levels if needed and can enter a photon counting regime for narrow bandwidth cases.

7.1 – Space based options

While ground based options are the least costly to implement, space based approaches offer a number of advantages. There is no atmospheric windows to deal with and the backgrounds drop to the zodiacal light limit (assuming missions within the solar system). This can dramatically open up the wavelength search space and offer much greater sensitivity for a given aperture. The main issue is cost, complexity and aperture limit. The same system we propose for the phased array transmission in DE-STAR can be used in a bidirectional mode as a receiver as well. If we imagine we expand our space based capability so that we become a class 2,3 or 4 civilization the ability to detect other distant civilization becomes much greater. One disadvantage in the phased array receive mode is that the simplest designs are single pixel and thus we lose the advantage of spatial multiplexing. There are future approaches to the spatial multiplexing problem but they are not yet practical. Ground based variants of this approach also offer the possibility of extremely large aperture though with limited number of spatial pixels.

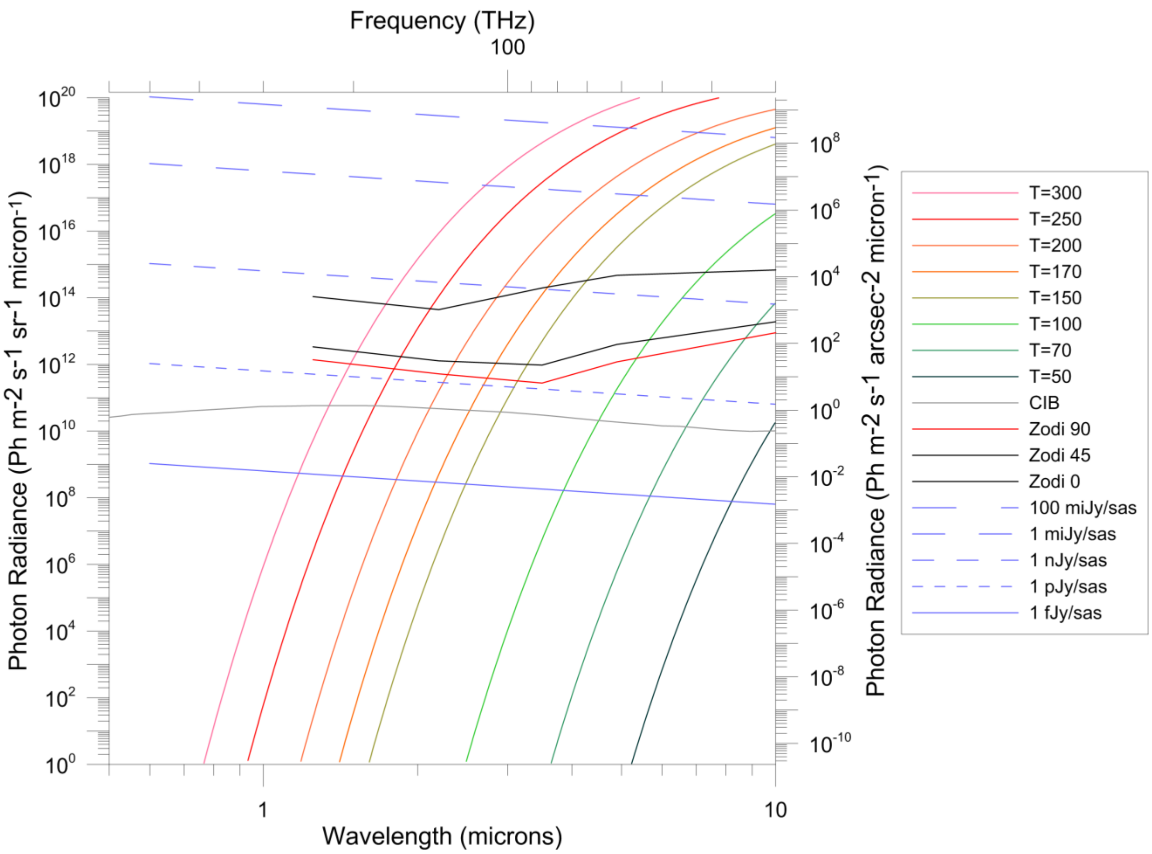

Figure 20 - **Space based mission thermal emission from optics, CIB and Zodiacal light in the ecliptic plane (0) at 45 degrees relative to the plane (45) and perpendicular to the plane (90). Zodi is for COBE DIRBE day 100.**

7.2 – Effects of filter bandwidth on SNR – filter optimization

The filter bandwidth affects the SNR since the wider the filter the greater the background light accepted. The wider the filter the less bands are needs to cover a broad range of possible laser lines but the less wavelength specificity and the poorer the SED modeling possible. If we focus on the SNR while parameterizing the various backgrounds and detector noise terms we can compute the effect of varying the filter bandwidth.
We write the noise contribution as above:

$$N_T = \sqrt{N_R^2 + N_{\text{time}}^2} = \left(N_R^2 + \tau(FA\epsilon Q_e + i_{DC} + F_\beta A\epsilon Q_e\Omega)\right)^{1/2}$$

$$\rightarrow \left(N_R^2 + \tau(i_{DC} + F_\beta A\epsilon Q_e\Omega)\right)^{1/2}$$

where we have removed the photon statistics of the source itself since we are comparing to nearby pixels without the source noise.

$$\frac{S}{N} = \frac{FA_\epsilon\tau}{\left[N_R^2 + \tau(i_{DC} + F_\beta A_\epsilon\Omega)\right]^{1/2}}$$

For narrow bandwidths Δλ, we can write the photon flux terms F (γ/s-m^2)and F_B (γ/s-m^2 -st) as:
F = <u>B</u>Δλ and F_B = <u>B_B</u> Δλ where <u>B</u>(γ/s-m^2 -μ) and <u>B_B</u> (γ/s-m^2 –st-μ) are per unit bandwidth.
This gives a total noise term (in pixels away from signal) of $N_T = \left(N_R^2 + \tau(i_{DC} + B_\beta\Delta\lambda A\epsilon Q_e\Omega)\right)^{1/2}$
In this case the S/N between the signal pixels and the non signal pixels is:

$$\frac{S}{N} = \frac{FA_\epsilon\tau}{N_T} = \frac{FA_\epsilon\tau}{\left[N_R^2 + \tau(i_{DC} + B_\beta\Delta\lambda A\epsilon Q_e\Omega)\right]^{1/2}}$$

From this we see that for very small filter bandwidths the background contribution to the noise term $\tau B_\beta\Delta\lambda A\epsilon Q_e\Omega$ is negligible and it is only at long integration times with small dark currents and large backgrounds B_β that this bandwidth dependent term becomes important. Note that B_β includes all sources of background except the detector. These include the telescope emission, atmosphere including air glow and OH lines, Zodiacal light, unresolved stars and the CIB. The background can become large due to OH emission as well as optical and atmospheric thermal emission in the IR, especially beyond 2.4 microns. This is where very narrow bandwidth filter will be very helpful even though OH lines will remain until the filter bandwidth becomes extremely narrow (essentially an IFU) where we can then observe between the OH lines. Beyond 2.5 microns there is little OH emission as discussed previously. See the discussion and plots above.
When we reach the level of a total noise, in our integration time, of roughly 1 electron there is little reason to go lower. Since we rapidly become signal photon starved, for modest civilization classes at large distances, there is a premium on low readout noise devices to achieve one electron of (including detector) noise. With modern detector arrays and narrow band filters it is feasible to approach this level of noise. When observing nearby bright galaxies in the core regions with the most stars the effective background due to the unresolved (but bright) star light can be a significant background term and here reducing the filter bandwidth is important. It is the relative relationship between the read noise , the dark current and the background term that is critical to understand to

optimize the filter. If telescope time is not an issue and if filter costs are not important then a very narrow bandwidth filter is preferable.

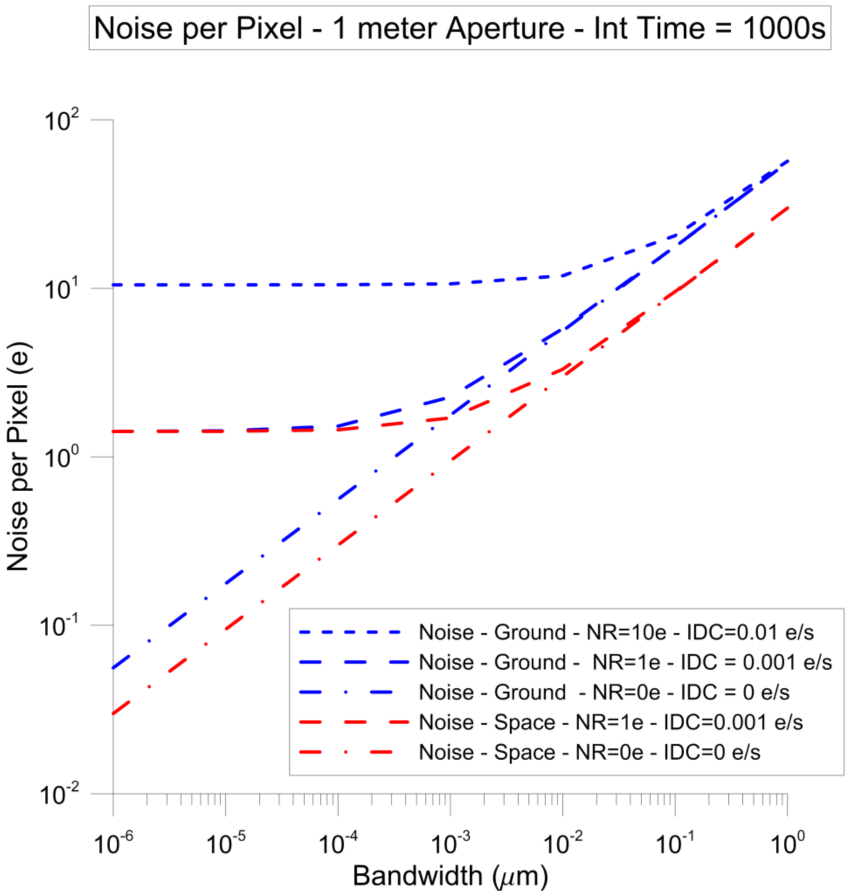

Figure 21 – Noise per pixel vs filter bandwidth for several hypothetical wide field cases. Includes detector noise is given as well as background noise. For small filter bandwidths the noise is detector noise limited while for large bandwidth the noise is background limited. At very large bandwidth the noise converges and is proportional to $\beta^{1/2}$ where β is the filter bandwidth. For a space mission the measurements are limited by zodiacal light and detector noise, assuming the optics are cooled sufficiently (for the IR cases) as to not dominate. In general a space mission will used diffraction limited optics and there will be no atmospheric "seeing issues". For the ground based cases we assume a wide field system and we assume adaptive optics cannot be used over the wide FOV. We also show a noiseless detector case for reference which could be realized for photons counting systems such as superconducting MKIDs or possible advanced cooled APD arrays. Neither is currently available in the large formats ideally needed. For the ground case we assume the atmospheric transmission is 0.5, the pixel size is 0.5", the seeing is 1", the total telescope optical efficiency is 0.5, the detector QE = 0.5 and the atmospheric and extraterrestrial background is 100 γ/s-m^2-µm-sq-arcsec. Note that depending on the wavelength and the sky conditions the background could be significantly larger especially in the presence of OH lines in systems with low resolving power (wider filter bandwidth). For the space based case we assume the system is diffraction limited, the total telescope optical efficiency is 0.7, the detector QE = 0.8 and the extraterrestrial background is 10 γ/s-m^2-µm-sq-arcsec and that the optics are sufficiently cooled. The primary advantage of space is the lack of atmospheric emission, particularly of OH lines in J and H bands as well as the ability to cool the optics for K band and beyond.

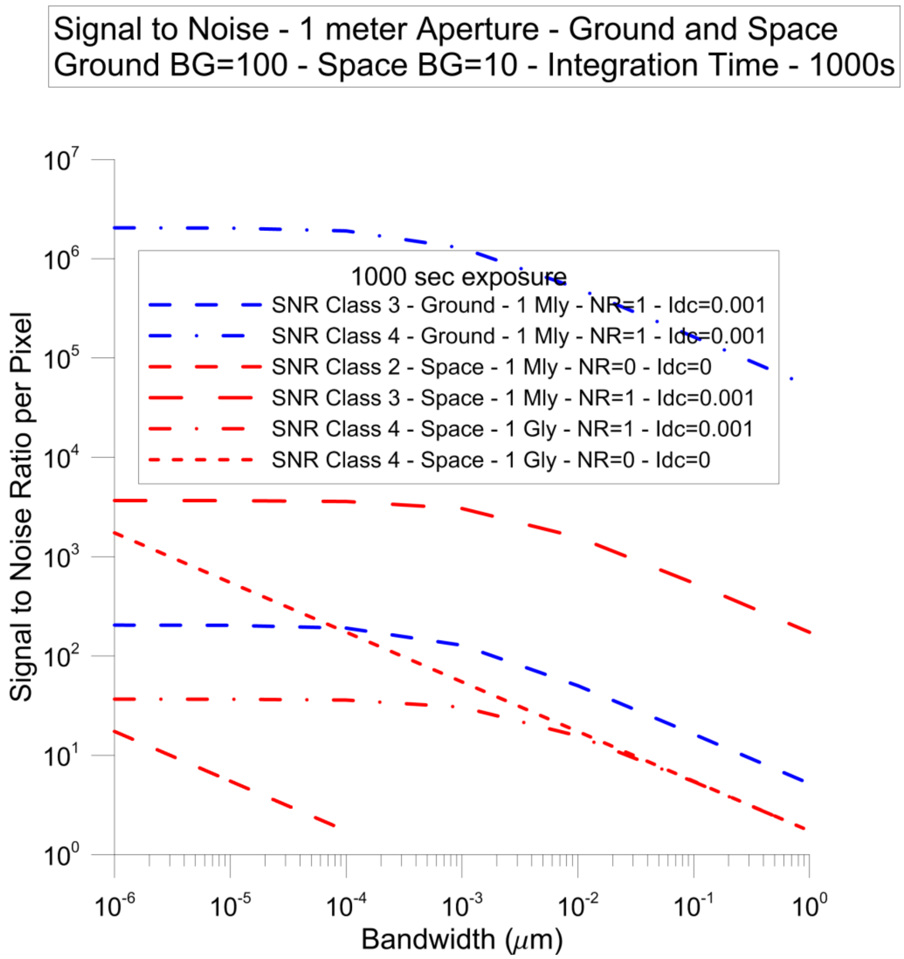

Figure 22 – Signal to noise ratio for several ground and space based scenarios with a 1 meter aperture at the Earth. NR is the detector readout noise in e and Idc is the detector dark current in e/s. For the ground case we assume the atmospheric transmission is 0.5, the pixel size is 0.5", the seeing is 1", the total telescope optical efficiency is 0.5, the detector QE = 0.5 and the atmospheric and extraterrestrial background is 100 γ/s-m^2-µm-sq-arcsec. Note that depending on the wavelength and the sky conditions the background could be significantly larger especially in the presence of OH lines in systems with low resolving power (wider filter bandwidth). For the space based case we assume the system is diffraction limited, the total telescope optical efficiency is 0.7, the detector QE = 0.8 and the extraterrestrial background is 10 γ/s-m^2-µm-sq-arcsec and that the optics are sufficiently cooled.

7.3 – Effects of Pixel size on SNR

In analogy with the discussion above of the effects of the filter bandwidth on the noise and SNR we now apply the same formalism to the effects of the pixel size. The pixel size affects the noise and SNR since the wider the pixel size the greater the background light accepted. The pixel size (θ) is the full angle of a pixel and the solid angle of the pixel is related simply as (for small angles) $\Omega = \theta^2$ We write the noise contribution and SNR as above:

$$N_T = \sqrt{N_R^2 + N_{\text{time}}^2} = \left(N_R^2 + \tau(FA\epsilon Q_e + i_{DC} + F_\beta A\epsilon Q_e\Omega)\right)^{1/2}$$

$$\rightarrow \left(N_R^2 + \tau(i_{DC} + F_\beta A\epsilon Q_e\Omega)\right)^{1/2}$$

where we have removed the photon statistics of the source itself since we are comparing to nearby pixels without the source noise.

$$\frac{S}{N} = \frac{FA_\epsilon\tau}{\left[N_R^2 + \tau(i_{DC} + F_\beta A_\epsilon\Omega)\right]^{1/2}}$$

We use the same notation where we write the photon flux terms F (γ/s-m^2)and F_B (γ/s-m^2 -st) as:
F = $\underline{B}$Δλ and F_B = $\underline{B_B}$ Δλ where $\underline{B}$(γ/s-m^2 -μ) and $\underline{B_B}$ (γ/s-m^2 –st-μ) are per unit bandwidth.
This gives a total noise term (in pixels away from signal) of $N_T = \left(N_R^2 + \tau(i_{DC} + B_\beta\Delta\lambda A\epsilon Q_e\Omega)\right)^{1/2}$
In this case the S/N between the signal pixels and the non signal pixels is:

$$\frac{S}{N} = \frac{FA_\epsilon\tau}{N_T} = \frac{FA_\epsilon\tau}{\left[N_R^2 + \tau(i_{DC} + B_\beta\Delta\lambda A\epsilon Q_e\Omega)\right]^{1/2}}$$

In analogy with spectral bandwidth we see that for very small pixel sizes the background contribution to the noise term $\tau B_\beta\Delta\lambda A\epsilon Q_e\Omega$ is usually negligible and it is only for very large pixels at long integration times with small dark currents and large backgrounds B_β that this solid angle dependent term becomes important. As before B_β includes all sources of background except the detector. These include the telescope emission, atmosphere thermal and lines (air glow) and OH lines (if inside the atmosphere based), Zodiacal light, unresolved stars and the CIB. In the near IR the background can become large due to OH emission as well as optical and atmospheric thermal emission in the IR, especially beyond 2.4 microns. Beyond 2.5 microns there is little OH emission as discussed previously.
The obvious question is why would we want large pixels? The answer is the following. In some search scenarios we are looking for any source of anomalous spectral emission and IF we use a high resolving power spectrometer with a wide "pixel" we might be able to leverage the spectral resolution to get to lower backgrounds by observing between the "lines" and cover a larger field of view (large pixel) and hence multiplex the observation by looking at a larger number of sources. This trades off spatial resolution for spectral resolution but with the ability to use a spectrometer. This would be an unusual spectrometer which present challenges in construction but may allow a higher thruput in some circumstances. Functionally this could be a larger fiber spectrometer.
Note that the background contribution to the noise term $\tau B_\beta\Delta\lambda A\epsilon Q_e\Omega$ is proportional to the product of spectral bandwidth, aperture area and pixel solid angle $\Delta\lambda\Omega = \Delta\lambda\theta^2$ and hence we have the same scaling of noise and SNR with bandwidth and with solid angle.

In the case of a diffraction limited telescope we note the background contribution to the noise term $\tau B_\beta\Delta\lambda A\epsilon Q_e\Omega$ is proportional to $\Delta\lambda A\Omega$. For a diffraction limited telescope the diffraction limited pixel size (not over sampled) is such that $A\Omega = \lambda^2$ and hence the background noise contribution term is $\tau B_\beta\Delta\lambda A\epsilon Q_e\Omega$ = $\tau B_\beta\Delta\lambda\epsilon Q_e\lambda^2$.

OH lines are unresolved at R=10,000 so there will be a practical tradeoff between observing between OH and air glow lines and fractional "clean" spectral coverage. R=1000 to 10,000 is generally a practical range. Spectral cross talk with larger pixels will likely be an issue to be explored. Ideally both a spectrometer and an spatial search using narrow band filters would be employed. This is allow both rapid and deep searches as well as integral follow up and filtering of atmospheric lines (for ground based systems).

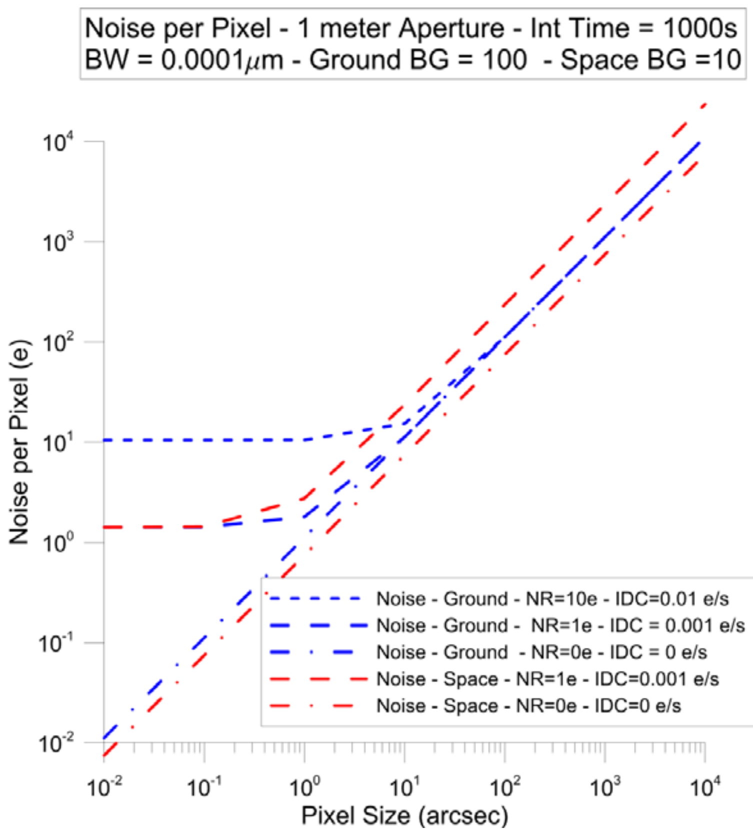

Figure 23 - Noise per spectrometer pixel vs pixel size for several hypothetical cases where a high resolution spectrometer is used (1 Angstrom – R=10,000 at 1 micron). We assume observations are made near 1 micron (visible to near IR). Includes detector noise is given as well as background noise. For a small spectrometer "pixel" the noise is detector noise limited while for large "pixel" input the noise is background limited. At very pixel size the noise converges and is proportional to the pixel size. For a space mission the measurements are limited by zodiacal light and detector noise, assuming the optics are cooled sufficiently (for the IR cases) as to not dominate. In general a space mission will used diffraction limited optics and there will be no atmospheric "seeing issues". For the ground based cases we assume a seeing of 1 arc sec. The small pixel values for the ground case (smaller than seeing) are not relevant. We also show a noiseless detector case for reference which could be realized for photons counting systems such as superconducting MKIDs or possible advanced cooled APD arrays. Neither is currently available in the large formats ideally needed. For the ground case we assume the atmospheric transmission is 0.5, the total telescope optical efficiency is 0.5, the detector QE = 0.5 and the atmospheric and extraterrestrial background is 100 γ/s-m^2-μm-sq-arcsec. Using a high resolving power spectrometer allows us to observe with low background between the atmospheric telluric lines. Note that depending on the wavelength and the sky conditions the background could be significantly larger especially in the presence of OH lines.. For the space based case we assume the system is diffraction limited, the total telescope optical efficiency is 0.7, the detector QE = 0.8 and the extraterrestrial background is 10 γ/s-m^2-μm-sq-arcsec and that the optics are sufficiently cooled.

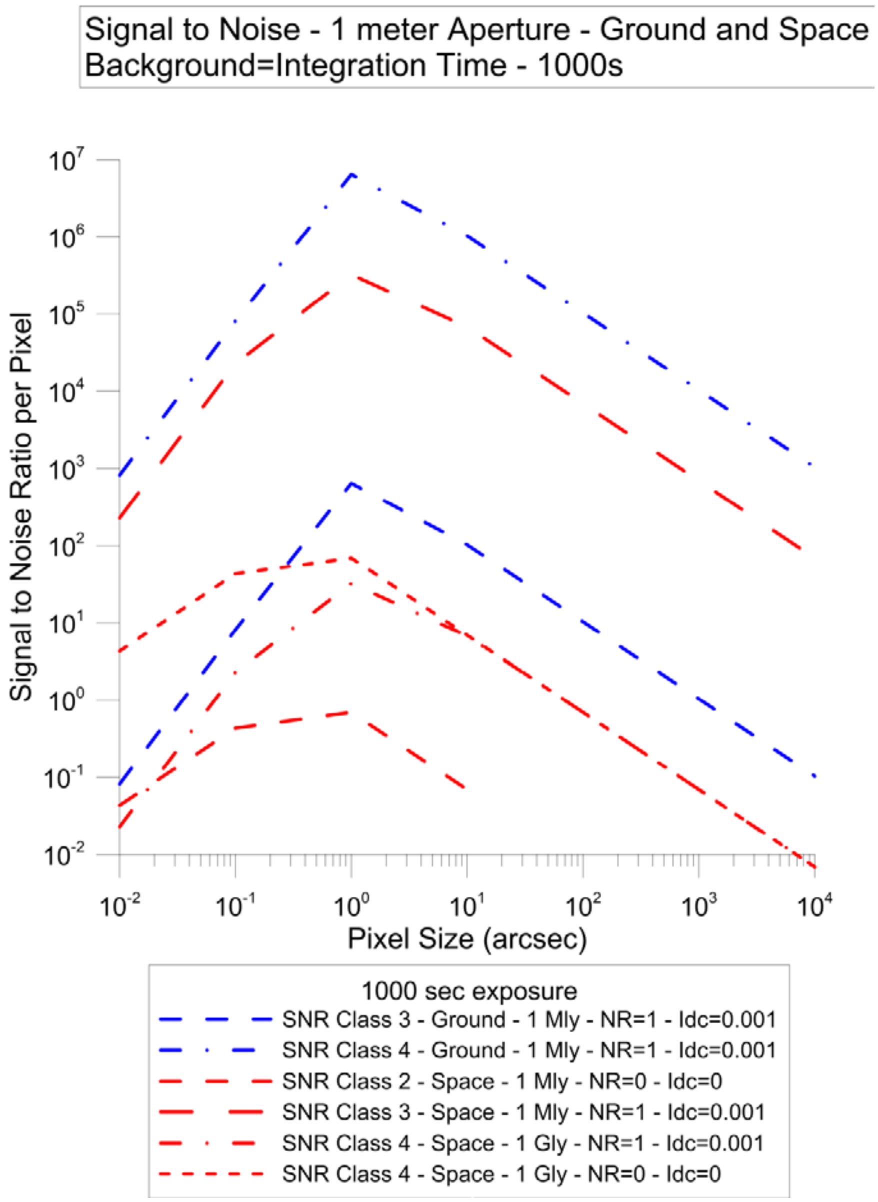

Figure 24 - Figure 25 – Signal to noise ratio vs pixel size for a high resolution spectrometer (0.1nm - R=10,000 at 1 micron) for several ground and space based scenarios with a 1 meter aperture. Larger pixels are background limited and smaller ones are detector limited. NR is the detector readout noise in e and Idc is the detector dark current in e/s. For the ground case we assume the atmospheric transmission is 0.5, the pixel size is 0.5", the seeing is 1", the total telescope optical efficiency is 0.5, the detector QE = 0.5 and the atmospheric and extraterrestrial background is 100 γ/s-m^2-μm-sq-arcsec. Note that depending on the wavelength and the sky conditions the background could be significantly larger especially in the presence of OH lines in systems with low resolving power (wider filter bandwidth). For the space based case we assume the system is diffraction limited, the total telescope optical efficiency is 0.7, the detector QE = 0.8 and the extraterrestrial background is 10 γ/s-m^2-μm-sq-arcsec and that the optics are sufficiently cooled. The peak in the SNR is an due to the diffraction limit for a 1 meter aperture at 1 micron and thus the signal is spread out over pixels smaller than the PSF. The peak of the SNR is indicative of an optimally matched spectrometer FOV. A larger aperture with adaptive optics on the ground or a larger space based telescope would peak at smaller pixel sizes. This plot is indicative of the performance of a single pixel high R spectrometer. An IFU could also be used to more optimally both spatially and spectrally search.

7.4 Near term future facilities

In addition to the existing ground and space based assets we will soon have wide field ground based capability with the LSST in the visible and near IR and excellent, though very narrow FOV, space based capability with JWST out to 28 microns. In addition we will have the ground based 30 m class telescopes again with narrow FOV. All of these will be available in the next decade if all goes as planned. All of the above analysis applies to the ground based LSST and 30m class telescopes and with the expanding IFU and related spectroscopy this gives excellent follow up capability to possible detection with wide field instruments like the LSST among others. The observation strategy for an effective would need to be modified for optimum use in the case discussed here.

JWST allows for a qualitatively new capability as the wavelength range is greatly extended compared to ground based assets. With spectroscopic capability this allows for unique opportunities though the narrow FOV is a problem for blind search strategies. JWST also offers the possibility of greater redshift space coverage for a given (though unknown) transmit wavelength.

7.5 – Civilizations with comparable transmit and receive capabilities

As mentioned our civilization currently the equivalent of about 1.5. Rapid progress to civilization class 4 is feasible within 50 years if the will existed to do so. Since the basic technology we propose is bidirectional and can operate in both a transmit and receive mode, we now ask what the quantitative consequences of this are. We apply the same methodology as above for existing small ground and space based telescopes but focus on space based deployment. The bottom line is that detection across the entire horizon is feasible with the usual caveat of being in the relevant band for detection.

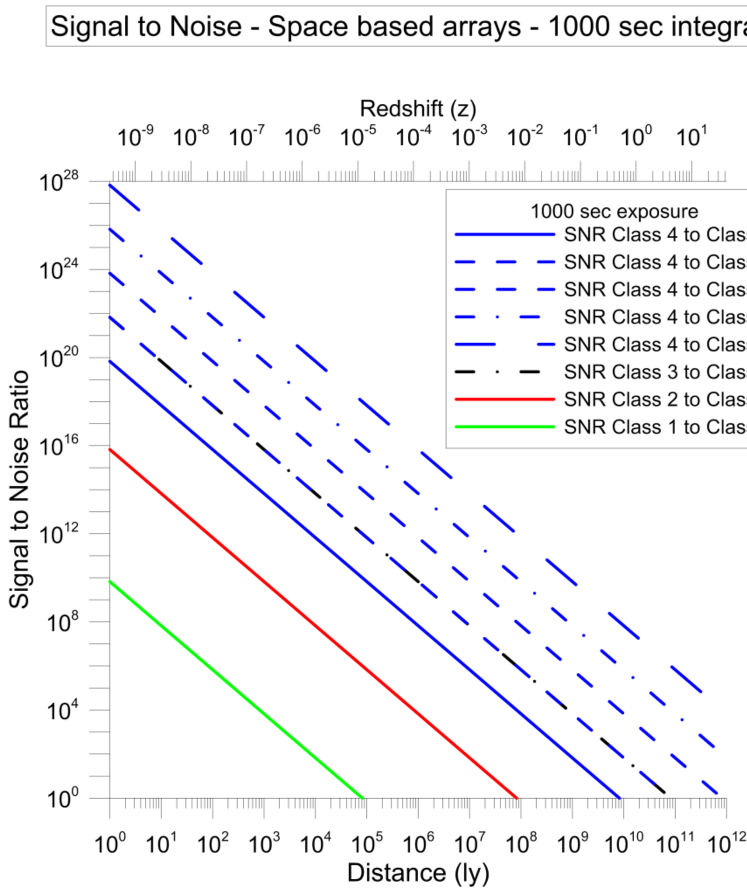

Figure 26 – SNR for diffraction limited space based arrays of various civilization classes vs distance for a single 1000 sec integration. The first class is the transmitter and the second is the receiver (Earth). Space background is assumed to be 10 γ/s-m^2-μm-sq-arcsec. Telescopes are assumed to be ideal and the detector is assumed to be photon counting. The receive bandwidth is 1nm wide. 10^{12} ly (~ 300 Gpc) corresponds to a redshift z~20.

7.6 – Blind searches and blind transmission – optimizing strategies

A major question in all searches is "why would "they" transmit towards us"? The equivalent for us is "why would we "look" at them"? In the case of "both sides" within our galaxy we already have preferred directions towards known exoplanets, though these appear to be ubiquitous through our own galaxy and presumably others. "We" could look towards known higher probability candidates based on presumed habitability for life and "they" could do the same. Since we are on the very beginnings of searching for exoplanets we can imagine a more advanced civilization would have vastly more knowledge of likely targets to transmit to. As we go beyond our own local realm and begin looking at extragalactic targets "we" could look towards all nearby galaxies. "They" could do the same. None of these are "blind" in the sense of "no logical" survey. As we go to high redshift targets we have little to guide us at our current level of knowledge. We could look towards galaxies with age distributions we deem more probable for the formation of life as one example. In our case using the DE-STAR phased array as the transmitter we can send out multiple beams or time share between beams to optimize chances for detection. This is a probability "game" for which we do not know the probabilities explicitly. The reality is we have little quantitative information to use so we enter the realm of blind searches.

The flux at the Earth from a civilization class S at distance L is F (γ/s-m^2) = $\xi P/(L\ \theta)^2 = \xi P/L^2\ \Omega$ where θ and Ω are the transmitted beam divergence angle and solid angle respectively

and $\xi=(hc/\lambda)^{-1}$. Here P(w) = $F_E\ \varepsilon_c\ 10^{2S}$ and $\theta = 2\ \lambda/d$ where d(m)=10^S with $\theta = 2\ \lambda 10^{-S}$ and

$\Omega = \theta^2 = (2\ \lambda/d)^2 = 4\ \lambda^2 10^{-2S}$ where F_E is the solar insolation at the top of the Earth's atmosphere or F_E ~ 1400 w/m^2 . Hence

F (γ/s-m^2) = $\xi P/L^2\ \Omega = \xi F_E\ \varepsilon_c\ 10^{2S}\ /(L^2\ 4\ \lambda^2 10^{-2S}\ ) = \xi F_E\ \varepsilon_c\ 10^{4S}\ /(4L^2\lambda^2) = (hc)^{-1}\ F_E\ \varepsilon_c\ 10^{4S}\ /(4L^2\lambda)$. We can immediately see why going to shorter wavelengths (for constant transmission power and array size) increases the photon flux (two powers of λ from diffraction and one power (inverse) from photon energy. The received flux in w/m^2 is $F_E\ \varepsilon_c\ 10^{4S}\ /(4L^2\lambda^2)$. This is useful in comparing microwave to optical/IR SETI where we see the forward gain of the optical system is vastly greater than the equivalent sized microwave system. One could argue that microwave systems are much easier to build in larger apertures than optical ones to counter this and indeed we have very large microwave telescope but only 10m class optical telescopes. If we assume the transmission comes from a phased array (our baseline) then the power can be distributed into (up to) as many beams as there are array elements. If we assume the transmitted beam is split into N beams (one of which is incident on the Earth) then we have ($\Omega_N = N\ \Omega$ is the split beam solid angle) and the new received flux F_N is:

F_N (γ/s-m^2) = $\xi P/N/(L^2\ \Omega_N) = \xi P/(N^2\ L^2\ \Omega) = F/N^2 = \xi F_E\ \varepsilon_c\ 10^{4S}\ /(4L^2\lambda^2)/N^2$. This obviously reduces the received flux but increases the transmitted solid angle Ω_N as there are N of these beams. This increases the probability of a "blind transmission" reception in terms of number of beam but at reduced flux. Depending on the type of search strategy on the received side these can essentially cancel out. This depends on the time gating of the reception strategy. Time multiplexing on the transmit side (beam switching not data encoding) is another strategy for transmission. A phased array is ideal for rapid beam switching. The same phased array transmission system is also a phased array receiver but we do not assume this at our current level of detection strategy.

7.7 – Optical beam dwell time

An important issue to ponder is how long would a transmitted beam be visible for IF the beam was NOT tracking us. We can make an estimate of this as follows. Assume the distance to the transmitter is L and from the point of view of the transmitter we will assume an Earth transverse speed of v_T. The full width beam size for a civilization class S is $\theta = 2\ \lambda/d$ where d(m)=10^S with $\theta = 2\ \lambda 10^{-S}$ and thus the spot size "s" at the Earth is $s = L\ \theta = 2\ L\ \lambda 10^{-S}$. The dwell time (Earth crossing time) $\tau = s/v_T = 2\ L\ \lambda 10^{-S}\ /\ v_T$. Typical transverse speeds at large distances are in the 100-1000 km/s range. This includes a typical galactic rotation speed. For reference the Earths orbital speed around the Sun is about 30 km/s and the Earths orbital speed around the galaxy is about 300 km/s. As seen in the accompanying figure the dwell time is typically long compared to our assumed putative integration time of 1000 seconds except for short distances and large civilization class. However in the latter cases the SNR would be extremely large even at spot dwell times much shorter than the 1000 sec integration time. For simplicity we assume a Euclidean geometry.

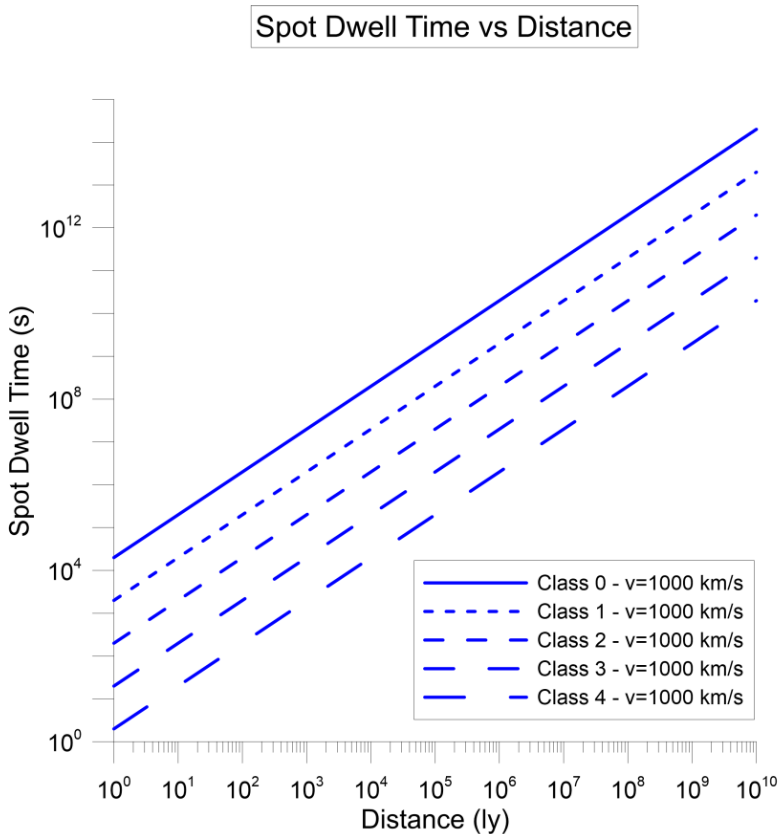

Figure 27 – Spot dwell time vs distance and class with an assumed commoving (relative to radial) transverse speed of 1000 km/s.

7.8 – The idea of "Naturalness"

One could argue on the basis of "natural wavelength windows" that one approach is "better" or more "likely" than the other. But there is no real "logic here as we have no idea what is logical to another civilization. Anyone who has observed SETI programs knows that we search with whatever our latest technology available is. As mentioned, our technological phase has only been an extremely small fraction of humanities existence, let alone life on Earth. A "reasonable" question is to ask what happens if we allow technology to mature to some modest fraction of human existence (say 50%) and then we readily see that instead of considering the last 100 years of feasible SETI ideas we might consider 1 million years of technological advancement. While we can project a roadmap into the next decade or so we certainly have extremely little predictive power into hundreds, let alone millions of years. We have to be honest and fall back to "what can we do now". What is new now is that we can now search for another similarly advanced civilization across the entire universe. This IS new to us. What is an assumption , of course, is that electromagnetic communications has any relevance on times scales that are millions of years and in particular that electromagnetic communications (which includes beacons) should have anything to do with wavelengths near human vision. We could simply "throw up our arms and give up" but this is not our nature. We proceed to explore within the limits of reasonable resource use.

7.9 – Communications between civilizations

The idea that any form of electromagnetic signal would be used as a form of communications is one that we are used to from our everyday lives. A major issue occurs when we extend this to long range communications where long range is measured in units of the distance between stars or galaxies. Here the time of flight (years to millions or billions of years) becomes a major point of discussion. We are used to communications being "full duplex" namely that "send and receive" or "speak and listen" happen with a delay that is very short compared to our lifetime. Even in our solar system the communication are "half duplex" in that we transmit and then must wait a significant period of time to receive a response. The idea that civilizations that are widely spaced would communicate in "real time" with each other with any form of electromagnetic signal thus seems highly illogical. As we do not have any faster way of communications (no Tachyons yet) we have a philosophical and scientific quandary as to why distant civilization would in fact use any form of "light speed" communications system except as a beacon or as a one way streaming of information, much like television - ie non interactive.

Beaming vs Communications - A more logical scenario seems to be one where civilizations search for other civilization by "beaming" out their existence and waiting for a response over long periods of time. In essence that is what the entire SETI effort has been focused on, except we generally simply listen. Thus the idea that we will "listen in" on the communication between civilizations seems unlikely whereas the idea of civilization that pro actively broadcast their existence, such as a firefly does, seems more logical. However in all of this "logic" is very much an anthropomorphic construct.

8. ACTIVE VS PASSIVE

In general SETI (with a few and controversial exceptions) has been carried out in a completely passive mode – ie we listen and do not speak. Perhaps we learned this as children or perhaps it is born out of fear from science fiction stories and movies. In general we have both a curiosity and a fear of the unknown. This is a natural survival instinct. There is also a completely rational part to listening vs speaking – namely the finite speed of light. When we speak (transmit) it will take a minimum of 4 years to reach the nearest stellar system (Alpha or Proxima Centauri), 1000 years to reach the Kepler planets, more than 2 million years to reach the near large galaxy (Andromeda) and close to 100 million years to reach the nearest galaxy clusters. With the exception of the nearest stars, these time scales are far beyond a human lifetime and perhaps more importantly they greatly exceed of time scale for "radical technology evolution". Another issue is that all stars and galaxies have a proper (transverse) velocity relative to our line of sight. This is often of order $\beta \sim 10^{-3}$. This means that if we observe a distant star or galaxy and want to transmit to it then its proper motion will have moved it from our initially targeting of it. It will have moved by an angle of approx β (in radians). This is an enormous angle relative to the beam size for even a modest system where the (full) beam size is $\theta = 2\ \lambda 10^{-S}$. Even for an S=1 civilization (less than us) and $\lambda = 1\mu$ we have $\theta = 2\mu$rad which is much smaller than a typical proper motion β. In order to hit the target we would have to have detailed knowledge of the dynamics and integrated gravitational field as well as gravitational lensing along the way. This is not a trivial task and one where civilizations may resort to beam broadening or multi beam transmission to increase detection probability. Depending on the detection temporal strategy these transmission strategies may not increase the detection probability. It is a complex mix of SNR for a given civilization transmission class and civilization reception class.

9. CONCLUSIONS

We have now reached the point in human technological evolution to project own presence across the entire universe. The question is “are there other civilizations for which this is also true”? If so are they now signaling us? We have shown that even our current technology is capable of being detected across the entire horizon if we chose to do so and that we are on an extraordinarily rapid ascent phase in this technology. We have shown that even modest directed energy systems can be “seen” as the brightest objects in the universe within a narrow laser linewidth. We have outlined logical search strategies that search for signatures of an exceeding large number of candidates on cosmological scales, including searches at high redshift, that can help us search for the answer to the question of “are we alone”. This can be done with very modest resource allocations.

ACKNOWLEDGEMENTS

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