

# Synchronized SETI - The Case for “Opposition”

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## ABSTRACT

If the signals that are being sought in SETI programs do exist but are very brief, for example because they are produced intermittently to conserve energy, then it is essential to know when these signals will arrive at the Earth. Different types of synchronization schemes are possible which vary in the relative amount of effort which is required by the transmitter and the receiver. Here the case is made for a scheme which is extremely simple for the receiver: make observations of a target when it is at maximum angular distance from the Sun (i.e. “opposition”). This strategy requires the transmitter to have accurate knowledge of the distance and proper motion of the Sun and the orbit of the Earth. It is anticipated that within about the next 10 to 20 years it will be possible to directly detect nearby extra-solar planets of approximately terrestrial mass. As any extraterrestrial transmitters are expected to have significantly more advanced technology it is therefore not unreasonable to expect that these transmitters would be able to detect the presence of the Earth and measure its orbit at even greater distances. In addition to the simplicity to the receiver of implementing this strategy it has the advantage that opposition is typically the time when observations are easiest to make anyway. A number of all-sky surveys that have already been performed naturally contain tiny “opposition surveys” within them. A full all-sky opposition survey would require extensive time to complete with a single moderate field of view telescope but different types of arrays might be employed instead including some systems already under construction.

*Subject headings:* interstellar communication; SETI; extrasolar planets

## 1. Introduction

Essentially all of the current SETI (Search for ExtraTerrestrial Intelligence) observing programs make only brief observations of any particular part of the sky. This means that transmitters with low duty cycles are very unlikely to be detected. However, it has been proposed by a number of authors

that some type of synchronization of transmitter and receiver can result in huge energy savings to the transmitter by restricting transmissions to certain short times which can nevertheless be determined by a receiver utilizing the same synchronization scheme. One synchronization strategy, which requires substantial effort by both the transmitter and the receiver is to use some type of external astrophysical event as a synchronizer. The transmitter immediately transmits when a noteworthy event occurs and the receiver looks for the signal after the calculated time delay. The calculation of this delay requires the receiver to have the ability to both detect and localize the astrophysical event and also precisely measure the distance to a potential transmitter. In an earlier paper (Corbet, 1999) it was proposed that for this strategy gamma-ray bursts are the best of the known potential synchronizers that are available primarily because of their large apparent luminosities and very brief durations. Earlier suggestions involving for example supernovae (Tang, 1976) and novae (McLaughlin, 1977; Makovetskii, 1980) have also been made.

In this paper it is proposed that another timing scheme may also be used which requires little work on the part of the receiver but substantially more effort by the transmitter. This scheme uses a very local (to the receiver) astrophysical event and is simply that potential SETI targets should be observed when they have their maximum angular distance from the Sun as seen from the Earth, i.e. in the terminology often used to describe planetary positions, they are at “opposition.” Although the angles involved here may be substantially less than  $180^\circ$  (but more than  $90^\circ$ ) the term “opposition” is used for convenience. This technique requires that the transmitter must not only be able to detect the presence of the Earth but also be able to measure its orbit, distance, and proper motion sufficiently accurately for the signal to arrive at the correct time. This scheme would make a beacon relatively easy for the receiver to find while at the same time conserving energy use by the transmitter.

## 2. Why Send Synchronized Low Duty Cycle Signals?

While an omnidirectional transmitter is the simplest to consider, and may well be appropriate for at least some types of “leakage” radiation, this scheme is very inefficient and so is not likely to be desirable for a beacon transmission. If the transmitter can utilize one or more narrow beams then large increases in efficiency can be achieved. However, if beaming is used it will not be possible to send to all desired targets continuously if the number of beams that can be produced simultaneously is less than the number of targets. Restrictions on transmission duty cycle can also result if a system is used for more than just interstellar transmission, for example the system might also be used for astronomical observations.

The use of continuous transmission may also be expensive in terms of energy consumption. One way to consider this is to compare the relative costs of transmitting a signal to accelerating an interstellar probe such as proposed by Bracewell (1960). This comparison, while simplistic, is independent of the amount of energy available in that there are energy costs associated with both these means of exploration. For illustration, if the Arecibo 1 MW planetary radar is operated

continuously then this corresponds to the same energy costs as accelerating 1kg masses to 1% of the speed of light approximately every 50 days. If a beacon is operated continuously for a long period of time then the total energy expenditure could be extremely large (e.g. Bracewell, 1996). Hence it may well be desirable to use the energy-saving technique of making only low duty cycle transmissions. Further, no matter what average power budget is available to the transmitting civilization, it may be possible to generate more intense signals by concentrating that power into low duty cycle signals. The detectable range of transmissions for a particular receiver sensitivity would thus be increased.

Another factor that may lead to the use of short duty cycle in a long running transmission program is the “psychological” factor that, the longer a program is continued without success, the less resources a civilization may be willing to devote to it. In this case techniques that would both save energy costs and use less time with transmission facilities that could be used for other purposes would become more important.

In addition to speculation about how an extraterrestrial transmitter may be operated, other considerations suggest that searching for low duty cycle signals should be done. These are (i) the experimental lack of strong persistent artificial radio emitters and (ii) the small number of deliberate terrestrial signals that have been sent have been extremely brief.

Searches for emission at around 1.4 GHz have covered essentially the entire sky and no persistent source has been found (see review by Tarter, 2001). While this may simply mean that extraterrestrial transmissions were too faint to be detected in these surveys, or that transmissions are not being made near this frequency, an alternative explanation may be that transmissions exist but only have low duty cycles. Weak evidence for the existence of such low duty cycle signals may come from the non-persistent candidate signals seen with Big Ear (Kraus, 1979; Gray & Marvel, 2001) and META (Horowitz & Sagan, 1993; Lazio et al., 2002).

The few deliberate transmissions that have been made from the Earth have been beamed in only one direction at a time and had extremely short transmission durations. A message sent from Arecibo in 1974 in the direction of the globular cluster M13 lasted only 169 s (The Staff at the NAIC, 1974). Although somewhat longer, the “Cosmic Call” made in 1999 (Dutil & Dumas, 1998) still only sent four transmissions, each transmission of four hour duration, to nearby stars using the Evpatoria 70 m antenna (Zaitsev & Ignatov, 1999).

The clear disadvantage of low duty cycle transmissions is that initial searches may not detect such signals. If the transmitter is only sending brief signals to a particular target it is thus advantageous to make use of one or more synchronization schemes. Without synchronization it will be very unlikely that the potential recipient will detect the signal. Although unsynchronized signals might be detected by a receiver monitoring the entire sky the entire time, such a system may not necessarily be employed by the potential recipient and, even if it is, may be of reduced sensitivity compared to a receiver with a narrow field of view.

The use of low duty cycle signaling does not necessarily exclude the presence of an additional

continuous signal. A transmitting civilization might plausibly choose to combine both continuous low intensity signals with brief more intense signals. The lower-intensity signals will be accessible to receivers with sufficient sensitivity while the low duty cycle signals will be accessible to less sensitive receivers as long as observations are made at the correct time. For a transmitting civilization that presumably wishes to have its signals detected it may well to choose a mixture of techniques including both continuous and short duty cycle transmissions and for the short duty cycle signals to perhaps use a variety of synchronization techniques. This combination of different strategies would increase the overall chance of at least one type of transmission being detected.

### 3. Background to Opposition

The concept of observing targets during opposition is related, to some extent, to previously published work. Most of this related work either notes the requirements on very tightly beamed transmissions or proposes synchronization using binary systems other than the orbit of the Earth around the Sun.

For transmission to nearby targets using short wavelengths (e.g. optical) which results in very narrow beams it has been recognized for some time that information on the orbit of a target planet is required (e.g. Shklovskii & Sagan, 1966; Kingsley, 1993). Otherwise, for nearby targets, a narrow beam aimed at a star may not illuminate a planet unless the beam is deliberately defocussed.<sup>1</sup>

Fillipova et al. (1991) argued that even if transmitters are using radio wavelengths they would still employ very narrow beams. These authors proposed that the transmitter would therefore aim a continuous signal directly at the target star. The potential receiver should thus observe stars close to the ecliptic plane at the time of opposition when its planet would pass through this beam. This scheme does have some problems as it assumes that the transmitter is not capable of detecting the presence of planets around the target star. The resulting time spent transmitting while the target planet is not in the path of the signal beam is thus wasteful of energy.

Pace & Walker (1974) proposed transmission to binary stars at observation of a particular binary phase of the recipient and, in the opposite direction, search for transmission from a binary star system at a particular phase. Pace (1979) extended this scheme to communication between single stars by utilizing binary systems in angular proximity to the line between the transmitter and receiver. In a similar way, Singer (1982) proposed that a transmitter could time the arrival of a signal at the Solar System to coincide with a particular phase of the orbit of Jupiter with respect to the transmitter. The orbit of Jupiter was chosen as this has the largest influence on the motion of the Sun. Singer (1980) proposed that the four phases of maximum and minimum displacement of the Sun/Jupiter system as viewed from the transmitting star should be utilized.

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<sup>1</sup>Note that in proposing observations of anti-Sun ecliptic longitude no particular wavelength regime is suggested and this technique can be used at radio, optical, or other wavelengths.

In addition to the more general considerations listed above, it is noted that in 1924 an attempt was organized by David Todd, an associate of Percival Lowell, to listen for artificial radio signals from Mars during the time of opposition (Dick, 1996). This, apart from the much smaller distance involved which makes signal travel time much less important, is very close to the proposal to look for transmissions from around other stars at opposition.

#### 4. Proposal

It is proposed that SETI observations should be made, either of individual targets or a general sky region, for a time period which includes the *exact* moment when that target or region is at its maximum angular distance from the Sun as observed from the Earth. The justification for this is: (i) the scheme provides a simple way for the receiver to achieve synchronization - the transmitter can be expected to want to make it as easy as possible for its signal to be found, (ii) advances in technology should soon demonstrate feasibility through the detection and characterization of terrestrial mass extra-solar planets, and (iii) for an orbit-based synchronization scheme if the Earth is the desired target of the ETI's transmissions (because it is the only planet in the solar system habitable zone; Kasting, Whitmire & Reynolds, 1993) then the parameters of the Earth's orbit are much more natural to use than those of another planet or an external binary star system.

The scheme proposed here is analogous to that presented by Pace & Walker (1974) but is an extension to use the Sun/Earth system itself as the binary system. While Singer (1982) argued for synchronization using Jupiter's orbit, as this is the major perturbation to the proper motion of the Sun, we are now at the stage where, even with current technology, we will soon be able to detect nearby terrestrial planets - this is discussed in more detail in the next section. In principle, a binary system has a number of phases which might be identified as important. For example, alignment, maximum angular separation as seen by the transmitter, and, for an eccentric orbit, apastron and periastron may also be used. Thus, with Singer's Jovian technique and the Pace-Walker binary scheme, for example, there is a lack of one specific orbital phase which is definitely preferred. However, in the case of using the Earth's orbit it appears clear that the time of opposition is most suitable. For the receiver this orbital phase gives the minimum contamination from the emission from the Sun. At this time the receiver and target are also, by a miniscule amount, closest to each other which is arguably a "psychological" factor to justify this choice of phase.

Note that synchronizing transmissions to the Earth's orbit does not necessarily imply that the signals can only be detected by equipment on the Earth itself. If the beam size of the transmission is sufficiently large then the signal may be detected, for example, by spacecraft located elsewhere in the Solar System. The Earth's orbit is simply being used as a local synchronizing astrophysical event that may be regarded as important by a civilization with ties to that planet. It has been proposed before that beams would be made sufficiently broad, perhaps a few astronomical units at the target, in order to illuminate the entire habitable region around a planet (e.g. Townes, 1993) but this suggestion is based on an assumption that the transmitter would not know the location of

the target planet or not be able to accurately predict its location when the signal arrives. If the presence and orbit of a target planet are known then, in principle, the ultimate limiting size of the beam might be as small as the size of the planet. However, this is not a requirement of the strategy proposed here and the transmitter may need to decide between a very narrow beam, which would be as small as possible centered on the target planet, and a broader less intense beam which could illuminate observatories far from the Earth.

## 5. Feasibility of Synchronization to Orbital Phase

### 5.1. General Considerations

If transmissions are made once per target year then the efficiency of the opposition technique depends on how brief a signal can be made compared to the length of the target planet's year. In order for the signal to arrive at the desired orbital phase the transmitter must know precisely: (i) the orbital period and phase of the target (e.g. the Earth), (ii) the distance to the target, (iii) the proper motion and rate of change of the distance to the target, and (iv) if necessary, the rate of change of the orbital period. We can gain some insight into the feasibility of this scheme by considering current technology and that presently under development. It should be kept in mind, however, that it is usually expected that any civilization that we make contact with will have significantly more advanced technology. This is because we ourselves only recently acquired the ability to signal across interstellar distances and, unless the lifetimes of communicating civilizations are very short, it is statistically unlikely that we would make contact with another similarly young civilization (Shklovskii & Sagan, 1966). It is therefore not unreasonable to assume that the transmitting civilization has much better technology for detecting and measuring the parameters of terrestrial planets.

### 5.2. Planet Finding Missions

Although numerous extra-solar giant planets are now known to exist (e.g. Marcy & Butler, 1998; Naef et al., 2001), with the exception of the objects around the pulsar B1257+12 (Wolszczan & Frail, 1992; Konacki, Maciejewski, & Wolszczan, 2000) no terrestrial mass planets have yet been found. However, this lack of such planets may be ascribed to the insensitivity of the technique used so far (high precision optical radial velocity measurements) and there are several missions under development which it is anticipated will find terrestrial mass objects. An overview of the basic techniques to be employed and some of the missions under consideration in the search for Earth-like planets is given by Woolf & Angel (1998). In NASA's program, for example, the Space Interferometer Mission (SIM), currently proposed to launch in 2009, is expected to have the capability of finding planets with masses not that much greater than the Earth around nearby stars by measuring stellar parallaxes to precisions of micro-arcseconds. Following on from SIM may be

the Terrestrial Planet Finder (TPF; Beichman, Woolf & Lindensmith, 1999) proposed for launch in 2012. By using nulling interferometry (Bracewell, 1978) in the infrared or a visible light coronagraph the TPF should be able to directly observe planets around stars up to 15 pc away with sizes as small as the Earth. The European Space Agency (ESA) is also considering missions with similar objectives. ESA’s GAIA mission (e.g. Gilmore et al., 1998) will perform high precision astrometry and the Darwin mission (e.g. Penny et al., 1998) is being investigated for later launch, perhaps in or after 2015. As proposed for the TPF, Darwin may also perform nulling interferometry in the infrared with the primary aim of detecting Earth-like planets. Following on from these missions, if the substantial technology demands can be met, may be a “Planet Imager” mission.<sup>2</sup> A “Planet Imager” would have sufficient resolution that an Earth-like planet could be imaged with multiple pixels and might require arrays of TPF-like interferometers separated by distances of thousands of kilometers. For the special case of terrestrial size planets viewed close to their orbital plane, the Kepler Mission (Koch et al., 1998; Borucki, Koch, & Jenkins, 2001), currently scheduled for launch in 2006, should be able to detect these systems at much greater distances by the photometric detection of planetary transits.

From a consideration of the missions currently being constructed and designed it is clear that primarily through space-based interferometry our terrestrial planet detection abilities will soon enormously increase. With their high precision astrometry these missions will also provide significantly improved distance estimates. In addition to the expected significantly higher technology expected for an alien transmitter, if multiple ETIs exist and are in communication with each other then, by sharing star catalog data, they can obtain vastly improved distance, proper motion, and velocity information. Their parallax baselines would then be measured in parsecs rather than astronomical units and, for the opposition technique, it is the precision with which the transmitter, not the receiver, can measure the distance which is relevant. For determining proper and radial motion of the target the expected larger age of any transmitter should also enable it to be able to obtain very precise measurements. It is emphasized again that the discussion of Earth’s current technology level for detecting terrestrial planets is simply to demonstrate that the proposed strategy is likely to be feasible.

### 5.3. Specifics

The minimum duration of the transmitted message ( $t_m$ ) depends on how well the transmitter knows the parameters of the system transmitted to. For example, consider a planet at a distance  $D$  from the transmitter, a mean radial velocity of  $v$ , an orbital period around its star of  $P_{orb}$ , and a proper motion of  $\mu$ . The associated measurement errors on these parameters being given by  $\delta D$ ,  $\delta v$ ,  $\delta P_{orb}$ , and  $\delta \mu$ . The signal travel time  $T$  is simply  $D/c$  but, for changes in the system, the relevant timescale is  $2T$ , the combination of light travel time from the receiver to the transmitter

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<sup>2</sup>See <http://origins.jpl.nasa.gov/missions/missions.html>

plus the signal travel time from the transmitter to the receiver. The first order constraints arise from the uncertainties in the distance to the star and the orbital period and phase. The distance uncertainty simply yields:

$$t_m > \delta D/c \quad (1)$$

During the duration  $2T$  there will be  $2T/P_{orb}$  orbital cycles yielding:

$$t_m > (\delta P_{orb}/P_{orb})(2D/c) \quad (2)$$

The signal duration must also be greater than the uncertainty in the orbital phase,  $\phi$ . i.e.:

$$t_m > \delta\phi P_{orb} \quad (3)$$

Second order effects arise from the radial velocity between the transmitter and receiver and the proper motion. The radial velocity changes the relative distance during twice the signal travel time:

$$t_m > \delta v 2D/c^2 \quad (4)$$

The uncertainty in the change in alignment caused by the proper motion gives a constraint which is the time taken for the receiving planet to move it its orbit sufficiently to bring about alignment again. For the worst case situation where the proper motion is entirely in the target's orbital plane:

$$t_m > (\delta\mu/360)P_{orb}(2D/c) \quad (5)$$

where  $\mu$  is measured in degrees per time unit.

For illustration we may see what constraints result from the levels of precision that are available with technology that is currently available or is expected to soon become available.

**Equation 1):** With micro-arcsecond level parallax errors, such as aimed for with SIM and GAIA, rather small signal arrival errors could be achieved for the nearest stars. For example, the errors are about half an hour at 5 pc ( $\sim 15$  ly) and about 3 days at 50pc ( $\sim 150$  ly).

**Equations 2) & 3):** No extra-solar terrestrial mass planets are yet known around normal stars and so no orbital periods have yet been measured for such systems. Consider, however, the case of the gas giant planet 47 UMa b which has a  $1089\pm 3$  day orbital period measured from 13 years of data (Fischer et al., 2002) and is at a distance of 14.1 pc (45.9 ly). These parameters yield an arrival time error of about 90 days. While this is large, the size of this error, even without any improvement in the measurement precision, decreases directly as the length of observations increases. For example, a 1,000 year baseline alone reduces the error to less than one day. For 47 UMa b the current phase uncertainty given by Fischer et al. (2002) is about 34 days which could again be reduced by a larger data set or more precise measurements. Even without improvement the 90 day arrival time uncertainty is  $\sim 10\%$  of the orbital period yielding a factor of 10 efficiency gain over a continuous transmission. For terrestrial mass planets orbital periods may be determined in the relatively near future, not by radial velocity measurement, but by astrometry of the parent star (SIM/GAIA) or astrometry of the planet itself (TPF/Darwin and perhaps the Planet Imager).

**Equation 4):** If a star has a radial velocity of, for example,  $10 \text{ km s}^{-1}$  then, at 5 pc and 50 pc the change in the star’s distance over twice the light travel time would be about 7 light-hours and 3 light-days respectively. If  $3 \text{ m s}^{-1}$  precision radial velocity measurements are available (e.g. Butler et al., 1996) then the distance changes can be predicted to about 10 and 100 light-seconds respectively. The signal arrival time errors caused by velocity errors are thus smaller than the effects of the distance errors predicted by Equation 1).

**Equation 5):** For an example of the effects of proper motion on alignment again consider the case of 47 UMa b. The proper motion of the parent star measured with Hipparcos is about  $320 \pm 1$  milli-arcseconds  $\text{yr}^{-1}$ . This yields a corresponding minimum signal duration of  $t_m > 1.8$  hours. With the availability of micro-arcsecond  $\text{yr}^{-1}$  precision proper motions this would then shrink by a factor of one thousand.

For the nearest stars even current/near future Earth technology gives interestingly small signal arrival time errors from all parameters apart from the effects of the uncertainty in the orbital period. However, this figure could be reduced simply by extended observation durations. It thus appears feasible that an extraterrestrial transmitter could use the opposition technique for at least nearby stars. The major unknown is the maximum distance at which this technique could be used which depends on the level of technology available to the transmitter for finding, and measuring the orbits of, terrestrial mass planets.

It is noted that the high precision stellar proper motion measurements available with a SIM/GAIA type system enable very fine beams to be utilized by a transmitter. It was earlier argued by some authors such as Oliver (1993) that uncertainties in the proper motion place strong constraints on the minimum size of a beam that could be employed. However, with proper motion measured to micro-arcseconds  $\text{yr}^{-1}$  the corresponding error on the angular motion of a star at 50 pc during twice the light travel time is about 0.3 milli-arcseconds ( $\sim 1.6 \times 10^{-9}$  radians). Constraints on beam width due to stellar proper motion uncertainties are thus extremely weak and the primary requirement for a narrow beam instead becomes a knowledge of the orbit of the target planet.

## 6. Alternative Simplified Transmission Strategy

For an Earth-based transmitter it will be for some time challenging to undertake the type of signaling proposed here. Certainly the number of known extra-solar terrestrial planets will be much smaller than the number of stars that it might be worthwhile considering transmitting to. Instead, a related but simpler scheme could be employed if desired. This would be to simply transmit at the time of opposition of a target star as seen from the Earth. In this case the detection of the signal, if the potential receiver is not constantly monitoring for transmissions from the Earth, relies on the receiver knowing the orbit of the Earth. The receiver will need to take into account the relative proper motion of the two stellar systems during the signal travel time as this would change

the apparent time of opposition. This technique shares some qualities of the suggestion by Shostak (1997) to look for leakage from internal communication in binary star systems.

## 7. Opposition Coverage in Current All-Sky Surveys

Many all-sky SETI surveys such as META/BETA (Horowitz & Sagan, 1993; Leigh & Horowitz, 2000) operate with a transit telescope at a fixed hour angle. Complete coverage of the observable sky is achieved by moving the telescope in declination at most once per day. Thus at local midnight (for a telescope set to an hour angle of zero) objects on the ecliptic longitude line running through the center of the field of view will be at “opposition.” These types of surveys have thus already automatically performed some synchronized opposition observations. However, the coverage of opposition is very small compared to the total amount of sky surveyed.

For simplicity in obtaining a very crude estimate of the amount of opposition sky surveyed, as exact values are not important here, the offset between the ecliptic and equatorial coordinate systems is ignored. Consider, for example, a detector with a “rectangular” field of view (FOV)  $\theta^\circ \times \psi^\circ$  in longitude and latitude respectively then, at a declination of  $\delta$ , approximately  $\theta/(360 \cos(\delta))$  of a  $360^\circ$  scan would contain observations of the anti-Sun ecliptic longitude. So for a  $0.5^\circ \times 0.5^\circ$  detector (comparable to Project META’s circular  $0.5^\circ$  beam at 21 cm), and observations made for  $-30^\circ < \delta < +60^\circ$ , this FOV yields an anti-solar coverage of roughly  $\sim 0.2\%$  or about three days from 5 years of observations. However, this figure is just the amount of time spent with observations containing opposition data in the FOV and not the fraction of data which is anti-solar.

To calculate the amount of opposition data consider that, as the FOV crosses the anti-Sun line, this line is itself slowly moving at slightly less than one degree per day. The time taken for the detector to scan across the line is  $\theta/(360 \cos(\delta))$  days. The anti-solar longitude will move about  $(360/365) \theta/(360 \cos(\delta))$  degrees during this time and the area of sky that is anti-solar during a single scan is thus about  $\theta\psi/(360 \cos(\delta))$  degrees<sup>2</sup>. For a  $0.5^\circ \times 0.5^\circ$  FOV detector at the equator this is thus about  $7 \times 10^{-4}$  degrees<sup>2</sup> in one scan compared to up to  $\sim 180$  degrees<sup>2</sup> total scanned (some of the potential observation time will typically not be usable when the telescope points too close to the Sun). In the approximately 180 steps required to survey  $90^\circ$  of declination then about 0.15 degrees<sup>2</sup> of anti-Sun sky would be observed. So, for example, in covering the observable sky five times there would thus be about 0.5 degrees<sup>2</sup> of exactly anti-solar sky surveyed. Similarly, for the planned Harvard all-sky optical survey (Howard, Horowitz, & Coldwell, 2000) which will have a  $0.2^\circ$  (Right Ascension)  $\times$   $1.6^\circ$  (declination) FOV, the reduced size in longitude yields a roughly 0.05% fractional time coverage but this is compensated for by the larger size of the FOV in latitude.

The very small size of these opposition “micro-surveys” compared to the total sky coverage illustrates the importance, even for an all-sky survey, of finding the correct synchronization scheme if such is being employed by the transmitter. So far no all-sky survey has resulted in a clear detection of a signal but existing data sets might be used to investigate whether there is any excess

of candidate signals for the anti-solar observations compared to the remainder of the dataset. For future observations it might be advantageous to either store the raw data from anti-solar pointings or use a lower threshold for candidate signals from this region and then compare the number of candidates with other parts of the sky. Note that the “wow” signal reported from survey observations made with the Ohio State University (OSU) Big Ear telescope did not occur when the signal location was anti-solar but more than 30 degrees from this longitude (Gray & Marvel, 2001).

## **8. Proposed Opposition Searches**

### **8.1. General Considerations**

For the receiver the coordinates of the anti-Sun ecliptic longitude on the sky are easily calculated. For any particular time find the position of the Sun in ecliptic coordinates (including the eccentricity of the Earth’s orbit), the line of potential target positions is then those for which the ecliptic longitude is  $180^\circ$  from the Sun and the ecliptic latitude goes from  $+$  to  $-90^\circ$ . The coordinates of this line can then be converted to equatorial coordinates if desired. For observing particular targets the equatorial coordinates of a target at the estimated epoch of observations can be translated to ecliptic coordinates, and the time when the Sun will be at that ecliptic longitude  $+180^\circ$  can be calculated.

### **8.2. Targeted Opposition Searches**

In targeted SETI programs “opposition” observations may have durations as short as desired as long as they include the exact time of opposition. Signals sent by a competent transmitter using this technique will be long enough to be guaranteed to include this time. However, for a single ground-based observatory, or satellite in low Earth orbit, it will in general not be possible to obtain observations at exact opposition for all desired targets in the course of one year. It may thus be profitable to employ multiple telescopes located at different longitudes on the Earth (as well as in both the Northern and Southern hemispheres). If the transmission duration is sufficiently long that observation at the exact time of opposition is not required, then multiple observatories may not be required. However, it is impossible to know how accurately the transmitter knows the parameters of the Earth/Sun system which determines the minimum transmission duration with this technique.

### **8.3. All-Sky Opposition Surveys**

A full opposition survey would observe all areas of the sky when they are anti-solar at least once. An individual telescope might track the anti-Sun ecliptic longitude for as long as possible at a selected ecliptic latitude, perhaps moving to observations at a higher latitude when the original

target field falls below the horizon. The size of the field of view of the telescope in longitude probably need not be very large as long as the telescope is tracking the anti-solar longitude as this dimension only gives the length of time during which a signal would be detected. Since the anti-Sun ecliptic longitude is moving at less than one degree per day, a  $0.5^\circ$  field of view for example can give observation times for post-opposition longitudes of greater than half a day if the “leading edge” of the field of view is near the opposition line. Additionally, if a signal is detected in real time then the sky survey would be suspended for extended observations of the region from which the signal is coming. The coverage in latitude, however, gives a direct reduction in the time required to complete a full survey with all times of exact opposition covered. This type of survey with a limited field of view detector would be very slow as it takes a complete year to survey a  $360^\circ$  strip on the sky at a particular latitude. This is unlike the meridian all-sky surveys where a  $360^\circ$  sky strip is completed within a single day. A  $0.5^\circ$  field of view telescope would thus take 180 years for an opposition survey covering  $90^\circ$  in latitude.

A survey based on the assumption that a signal would have a duration of a particular minimum time could allow a telescope to move in ecliptic latitude between its observation limits while remaining pointed at the drifting opposition longitude. This telescope might then detect signals that had a duration longer than the time taken to scan in latitude. It would naturally be necessary to be able to both collect data and maintain reasonable knowledge of the telescope’s pointing direction during this “nodding” motion.

Neither scheme (nodding or staring) using a single telescope of limited field of view is ideal for an all-sky survey. Staring takes a long time to complete a survey and nodding might miss extremely brief signals. Instead it may be advantageous to make use of the techniques considered for all-time all-sky surveys. Such projects, whose ultimate goal is to continuously monitor the entire sky, could thus have as an intermediate less ambitious goal monitoring the anti-Sun line. Two of these projects are the similarly named Project Argus from the SETI League (Shuch, 1997) and the Argus Telescope being developed at Ohio State University (Dixon, 1995). While both projects have the ultimate aim of continuously observing the entire sky at radio wavelengths it will be challenging for either team to achieve this goal.

The SETI League project aims to cover the entire sky by using many small diameter radio telescopes. The problem here is the large number of dishes required, 5000 will be needed for complete coverage but, by the middle of 2002, only 115 had been reported as operating. The OSU telescope has a design which employs an antenna array whose elements are combined via software to form beams that would cover the entire sky visible from a single site. The limitation with this technique is the enormous computing power that is required to cover the entire sky with both good spatial and spectral resolution when a large number of elements, required for good sensitivity, is employed. By restricting either of these projects to just monitoring the anti-Sun range of ecliptic latitudes the difficulties would be much reduced. Either telescopes (SETI League) or software formed beams (OSU) could monitor just this line to the exclusion of most of the rest of the sky. The number of telescopes/beams required is determined by the beam size along the latitude line.

The small telescopes employed by the SETI League have fields of view of a few degrees across and so the number of telescopes required for an opposition survey to be completed in the course of a few years does not seem unreasonable (even though not all SETI League telescopes are steerable which is required to track the anti-Sun line). For an OSU type telescope for a full survey of even one hemisphere to be completed within a single year would require multiple versions of this telescope at different longitudes on the Earth. However, it is of course not a requirement that such a survey is completed within a single year.

In principle another system that could be employed to give a very large field of view would be if the separate components of the Allen Telescope Array (ATA, formerly 1hT; Welch & Dreher, 2000) were operated and pointed individually instead of operating as a coordinated array. However, in contrast to the OSU and Project SETI systems, operating the ATA in a mode suited to a rapid opposition survey results in a substantial decrease in sensitivity. For it to be worthwhile to split an array such as the ATA into smaller units the power transmitted by the sender at the time of opposition compared to other times must be sufficiently greater than the relative reduction in sensitivity of the detector. However, this power difference cannot be known in advance and, if transmissions are only sent at the time of opposition then observing at this time is essential.

At optical wavelengths a telescope of the OSU type with software formed beams cannot be made and so one or more telescopes of large field of view are required. One possibility may be to use a system incorporating a Luneburg lens (also known as a “Luneberg” lens; Luneberg, 1944) which in principle may have up to a  $2\pi$  steradian field of view.<sup>3</sup> A system which is already continuously optically monitoring a large fraction of the nighttime sky for astronomical purposes is the CONCAM project (Nemiroff & Rafert, 1999) which utilizes CCD cameras together with fish-eye lenses. However, the sensitivity and time resolution of CONCAM are presently rather low and so unlikely to be useful for SETI studies.

## 9. Conclusion

With only somewhat more advanced technology than we currently possess, an extraterrestrial transmitter could plausibly send signals timed to arrive at a particular phase of the Earth’s orbit. The natural phase for this is when the Earth is nearest to the apparent position of the transmitter. Targeted searches timed to coincide with this phase seem feasible. All-sky searches are also possible but, if complete exact opposition observations are to be achieved in a reasonable amount of time, then one or more telescopes capable of providing extensive ecliptic latitude coverage are required. In general, if synchronization techniques are to be used in a targeted SETI program then it is still advocated that the external astrophysical synchronization technique (e.g. Corbet, 1999

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<sup>3</sup>A single Luneburg lens may itself have a  $4\pi$  steradian field of view but the presence of detectors on the lens obstructs that part of the lens.

and references therein) should also be considered as well as the opposition technique. Using, for example, gamma-ray bursts as external synchronizers enables all transmissions to be made at least as short as the brief burst timescale whereas opposition transmissions require precise astronomical measurements of the target and the signal arrival time accuracy decreases with increasing distance<sup>4</sup>. The external astrophysical synchronizer technique is only well suited for targeted and not all-sky searches. However, the external synchronizer technique could be used by an extraterrestrial transmitter with approximately our current level of technology. In contrast, the opposition technique is most productive if a transmitter has substantially more advanced technology. The opposition technique permits a complete all-sky or targeted survey to be done within a predetermined period of time whereas with the external astrophysical synchronizer, with events occurring at random, it is not possible to predict when a particular target would be observable.

A technique that would combine part of the philosophy of both of these synchronization techniques would be for the transmitter to send a message when it was at *its* closest point to the target. The receiver would then calculate the expected arrival time. This strategy is, however, only currently advocated for Earth-based transmission rather than observing programs - for observing programs it is not even possible yet, if we are only interested in terrestrial mass extra-solar planets, as none have yet been detected.

I thank an anonymous referee for useful comments including the suggestion of using Luneburg lenses at optical wavelengths.

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<sup>4</sup>With an external synchronizer the effect of larger distances is to require longer observing times rather than transmission durations.

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