ADVANCING THE SEARCH FOR EXTRATERRESTRIAL INTELLIGENCE

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Executive Summary

Fifty years ago Giuseppe Cocconi and Philip Morrison [1] ended their *Nature* paper with the sentence "The probability of success is difficult to estimate, but if we never search, the chance of success is zero", and thereby launched a new exploratory science known as SETI – the search for extraterrestrial intelligence. Today SETI falls under the umbrella of astrobiology, a suite of cross-disciplinary sciences attempting to understand the origin, nature, and distribution of life in the cosmos. Astrobiology enjoys a substantial enthusiasm among researchers despite the fact that no compelling evidence for life beyond Earth has yet been found. New technologies and observatories offer extraordinary potential for major astrobiological finds and young scientists are wagering with their careers.

Few topics in astronomy or astrobiology generate as much interest and excitement as SETI. It is still not possible to estimate with any accuracy the chances of success; but the discovery of extrasolar planets and the enormous diversity of newly-recognized extremophiles give the cosmos the appearance of being more bio-friendly than it did five decades ago. Exponential gains in computational capabilities, new observing facilities designed and constructed specifically for SETI observing, and new receiver technologies that open up new wavelength regimes can be combined in the coming decade to significantly improve the speed and scope of search efforts, thereby boosting the possibility of success. The consequences of contact with life beyond Earth would profoundly affect humanity. However, even in the absence of a successful detection, the resulting new equipment and techniques will have useful applications in other areas of astronomy, and indeed in science and technology generally.

Two of the most difficult questions of astrobiology are addressed directly by SETI.

- ***Is the origin of life unique, rare, or commonplace?***
- ***Is the emergence of intelligence an unlikely eccentricity of our own evolution or an expected product in any sufficiently rich habitat?***

Goals for the Coming Decade

The search space is vast, so we should focus efforts on programs offering great improvement in sensitivity and number of targets surveyed, or probing untested but plausible wavelengths, celestial locations (e.g., ecliptic), and signaling schemes. During the next decade, university programs and dedicated observatories will create hardware/software/firmware to:

1. Expand the number of stars targeted for deliberate observations from the thousands to the millions, with sensitivity over a frequency range of 1-10 GHz, which would be adequate to detect the strongest terrestrial transmitters to a distance of 1000 light-years.
2. Increase the sky coverage and sensitivity of SETI surveys over 1-3 GHz, with the goal of exploring ~10 billion distant stars by covering the whole sky and concentrating on the central region of the galactic plane; seeking transmitters whose power might be ~ 10^4 times as strong as the Arecibo planetary radar.
3. Repeatedly observe the northern sky with dedicated optical SETI facilities that can survey deeply for signals equivalent to the intentional transmission of today's pulsed, petawatt lasers from distances of up to 1000 light years.
4. Extend the optical searches from the visible into the near IR, where absorption by interstellar dust is substantially reduced and the transmitter range is greatly extended.
5. Host a global community of open source developers, working on stored datasets, to invent and improve efficient detection algorithms for more complex classes of weak signals with higher dimensionality, and expand the opportunities for all volunteers.

Scientific Context for Advancing the Search for Extraterrestrial Intelligence

A variety of studies over the past decades have shown that the habitats and many of the building blocks for life, and potentially intelligent life, are likely to be abundant in the Galaxy.

Extrasolar Planets

The past decade has seen an explosion in the number of extrasolar planets and extrasolar planetary systems, with the current census approaching 350 extrasolar planets. This number is expected to increase into the thousands as a result of the observations undertaken by the Corot and Kepler missions. Further, the Extrasolar Planet Task Force has outlined a strategy, employing a suite of approaches over the next 5–15 years, designed to provide a robust estimate for the number of potentially habitable extrasolar planets in the solar neighborhood.[2]

Biology and Chemistry

The origin of life on Earth is not yet understood, but it did not take long. Diamond-graphite inclusions in 4.25 billion year old zircon minerals from the Jack Hills in Western Australia display a light carbon isotope ratio that may provide the earliest evidence of life [3] only a few hundred million years after the formation of the planet. Even if this controversial claim turns out to be wrong, the biological $^{12}C/^{13}C$ signature is established in 3.7 billion year old rock from Isua in Western Greenland [4]. Today microbial life thrives in extreme ranges of temperature, pressure, pH, salinity, and survives intense radiation, desiccation, complete darkness, and vacuum exposure [5]. These extremophiles suggest that life might be able to make a living on other bodies within the solar system or orbiting other stars. Recent evidence for contemporary sub-surface water and possible biogenic methane on Mars is tantalizing [6]. The chemistry of the interstellar medium is overwhelmingly organic, and a combination of endogenous synthesis and exogenous delivery by asteroids and comets likely supply the prebiotic building blocks for life (as we know it) [7] lending support to the claim that "Life is a cosmic imperative."[8]

The Past as Prologue

SETI observing, in its modern incarnation, began with Frank Drake's modest search for microwave signals from two nearby star systems using an 85-foot antenna. Searches during the ensuing half-century have not elicited a single verified signal from an extraterrestrial transmitter. The failure of SETI to find its quarry has led many to question the fundamentals of this small-scale research effort. But this is a criticism with little merit: while surveys have shown that the sky is not littered with either strong, persistent narrow-band signals at the lower end of the terrestrial microwave window (running from 1 to 10 GHz), nor intense optical pulses, most of the cosmos remains unplumbed over a wide spectral range. Project Phoenix [9], the most comprehensive targeted SETI search ever conducted, could carefully examine only ~750 nearby star systems for extremely narrow radio beacons over a 2 GHz range. Optical SETI experiments have deliberately observed only a few thousand stellar targets and broad area coverage with limited sensitivity and duty cycle: see archive of searches [10].

An analogy of approximately the right numerical scale would be an attempt to decide whether the Earth's oceans were home to any fish, by examining only a single glass of water scooped at random from the sea. It would not be impossible for this experiment to have a successful outcome as the smallest fish (~ 1mm in size) and some of its larger relatives could be captured in the glass and discovered by the naked eye; but that's an improbable outcome. In other words, despite its long history, the amount of phase space sampled in SETI experiments remains extraordinarily small. This is not for lack of ingenuity, or effort, but rather a lack of continuous access to appropriate observational tools. This situation began to change in the last decade and is poised to change dramatically in the coming decade. Two and three orders-of-magnitude improvement in the depth and breadth of SETI searches will take place. Consequently, if the SETI strategy for testing the existence of extraterrestrial intelligence is valid, it's not unreasonable to expect a signal-detection within the lifetime of the readers of this report.

Telescope Speed

Historically, SETI experiments have focused on radio signals, for two reasons. First, generating radio signals requires only simple technology, and, second, radio signals can cross the Galaxy with very little absorption. Two search strategies have been used: (1) targeted observations of individual star systems or other specific astronomical objects (e.g., globular clusters or the galactic center), and (2) surveys, either of the entire sky or of parts of the galactic plane. The typical speeds of these experiments are low: in targeted searches, approximately one stellar system is examined per week. All-sky reconnaissance could take on order of a year to complete. In addition, it's worth noting that the dwell times – the length of observation in any direction at a given frequency – is only seconds to minutes. Consequently, even if galactic transmitting sites are numerous, the transmissions themselves must be highly persistent. If they are not directed towards Earth with high duty cycle, there is little chance that our brief scrutiny would coincide with the arrival of a signal. An increase in the speed of SETI searches ameliorates this difficulty for both types of experiment.

In the radio regime, multiple receivers in the focal plane, such as the multi-beam receivers now on the Arecibo and Parkes radio telescopes, provide an order of magnitude improvement. Phased array focal plane receivers now under development for the Square Kilometer Array could speed up these existing antennas by another order of magnitude, at least over a limited range of radio frequencies. In addition, early phases of the SKA (~10%) could be available for SETI observations before the end of the decade.[11].

Another way to achieve a multiplexing advantage to speed up SETI searches is being demonstrated by the Allen Telescope Array (ATA), now under construction as a joint project between the SETI Institute and the University of California, Berkeley's Radio Astronomy Lab. By phasing up the array to observe as many as sixteen pencil beams (each targeted on a different star) within the array's large field of view (enabled by the small 6m array antennas) and by simultaneously using two polarizations and four frequency bands selected from the 10 GHz of available spectrum, the speed of searching increases. Since the SETI equipment on the ATA will do this at the same time that the array is conducting large radio surveys that are key to finding answers to more traditional astronomical questions, substantial and prolonged access to the sky is expected. The primary SETI project for the ATA will be a survey of one million stellar targets over the range of 1 to 10 GHz with sensitivity adequate to detect an Arecibo radar out to 300 pc. There will also be an initial experiment to scrutinize 155 exoplanetary systems currently known to be accessible to this instrument, and repeated surveys of 20 square degrees along the galactic plane, capable of detecting transmitters of $4x10^{17}$ W EIRP (20,000 times Arecibo).

In the optical regime, filtering in the time domain eliminates the stellar background photons and allows detection of nanosecond pulses from a distant laser. Targeted searches are ongoing at Leuschner [12] and Lick [13] observatories. The introduction of two-dimensional detectors, such as the array of 64-pixel photomultipliers array now being used on the Harvard all-sky optical search [14], accelerates survey speed by more than an order-of-magnitude. These detectors currently have a trigger threshold of between 20 and 100 photons per m^2 per nanosecond pulse, and could detect a 4.7 MJoule pulse (Helios class laser) beamed by a 10 m antenna out to a distance of a few hundred pc. Existing systems have typically used inexpensive photomultiplier tubes and could be improved in sensitivity by a factor of 3 to 5 with no additional technology development, given adequate funding.

Signal Processing Speed

As the rate at which data are acquired (telescope speed) increases, so too must the rate at which those data are examined for evidence of engineered signals. In the coming decade this will be done in three ways: 1) building customized signal detectors from faster hardware and firmware components that are easier to assemble as reconfigurable computing engines [15], 2) supplanting older generations of custom signal detection hardware with software-only signal processing running on commodity servers, and 3) where appropriate, enlisting the global, opensource community of developers and signal processing experts. The last is an elaboration and extension of the extremely successful service-computing model pioneered by UC Berkeley's SETI@home that should facilitate discovery and coding of SETI detection algorithms for more complex, higher-dimensional classes of signals to be developed and applied to stored data using cloud computing resources.

In Figure 1, these improvements in radio searching are illustrated for a single metric of speed: the number of simultaneous channels used in major radio SETI experiments. The improvement is exponential and, on average, follows Moore's Law. In fact, SETI search speed can exceed this rate of betterment since multiple parameters (for example, number of channels and number of beams on the sky) can each improve at the Moore's Law rate. There have also been improvements in optical photon detection technologies, from single diodes to linear arrays, to two dimensional arrays and multi-pixel bolometers along with an increase in the area on the sky that is sensed by each individual pixel.

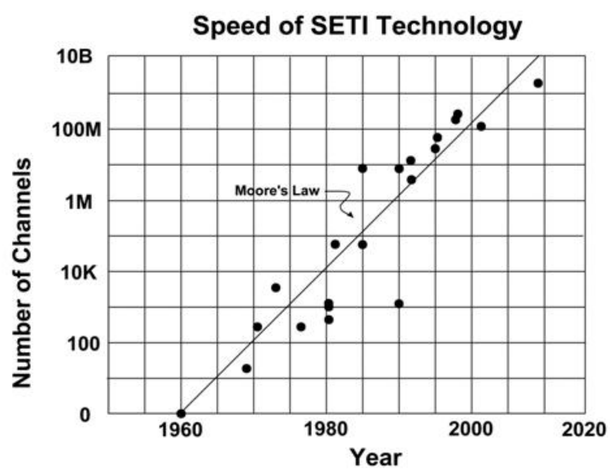

Fig. 1 – Moore's Law in spectral channels

Signal Types

To date, most SETI searches have been optimized for finding obviously-engineered signals characterized by extreme frequency compression or extreme time compression, thus avoiding confusion with astrophysical emitters. In the radio regime, SETI has traditionally sought narrow-band signal components, usually 1 Hz or less (the interstellar medium will typically disperse any signal to at least 0.1 Hz). This choice was made on the basis of straightforward consideration of the physics of propagation, but also the fact that a narrow-band signal maximizes the signal-to-noise at the receiving end for any fixed transmitter power. It's also the case that narrow-band signals are easy prey for radio spectrometers thanks to the N log N scaling of the Fast Fourier Transform.

Recently, short (microsecond) radio pulses have joined the list of signals being sought as part of the University of California, Berkeley's Astropulse program [16]. Such pulses might be a suitable "beacon" for any society intentionally trying to draw attention to the presence of a transmitter. Short pulses would make sense for any transmitting effort that tries to reach large numbers of targets with a reasonable expenditure of energy. Future SETI efforts might be carried out as "blind" commensal experiments with routine pulsar searches.

SETI researchers in Italy have developed mathematical techniques using the Karhunen-Loeve Transform that allow searches for broad bandwidth signals, and have also developed signal processing hardware to implement the transform [17]. In general, although narrow-band (monochromatic) "tones" comprise a complete basis set for describing all types of radio signals, there are an infinite number of other bases by means of which communication can take place. If extraterrestrial beacons operate using these other modes, simple Fourier components are not the optimal matched filter for their reception. The opportunities afforded by powerful digital computing platforms will soon broaden our ability to search for these other transmission modes involving signals of higher dimensionality and with the same processing costs as for the straightforward Fourier analyses of the past.

The major advance anticipated in the next decade for OSETI searches is the improvement in speed brought about by multiple-pixel detectors, as noted above. These new pixelated bolometers, photomultiplier tubes, and other photon-counting devices will enable fast sky surveys for pulsed optical/IR signals with large instantaneous sky coverage.

During the coming decade, there may also be ways to increase the sensitivity of OSETI searches by finding opportunities to perform non-interfering observations on much larger telescopes, perhaps in the 10m class, because imaging quality optics are not required. In the past, there have been commensal searches that piggyback on high-resolution spectral studies of stars, looking for unnatural continuous emission at the bottom of strong absorption lines, and the initial OSETI observations at Harvard were done during radial velocity searches for exoplanets. Some thought has been given to creating fast triggers for the photomultiplier arrays on the large, high energy Gamma-ray arrays, such as VERITAS, to discriminate coincident, single-pixel events on the sky from detector noise events. OSETI observations might be conducted with large solar concentrator mirrors on commercial power plants during the night.

In the next decade there is an exciting potential for expanding the search into new territory by replicating the detection strategies of OSETI at wavelengths in the IR. For a given total pulse energy, the number of photons contained in the pulse, and the number of those photons that traverse the ISM, without being absorbed, increases as the wavelength increases from optical to IR. Solid state photomultipliers can work out to 30 µm, avalanche photo diodes and photomultiplier tubes with IR sensitive photo-cathodes work in the near IR. These devices have medium to excellent quantum efficiencies and are beginning to be affordable, although they do require cryogenic cooling, thus increasing cost and complexity. Further in the future MKID microwave resonators (arrays of bolometers yielding $10^{2\text{-}3}$ pixels) could offer a really attractive, fast survey potential. It is easy to imagine a natural progression where the IR detectors replace the initial OSETI detectors, and OSETI searches find ways to move onto bigger pieces of glass during the next decade.

The SETI community is poised to significantly broaden the type of signals to which its experiments are sensitive. But the same holds true for the astronomical community. There is a possibility that a detection confirming the existence of sentient beings elsewhere will be made serendipitously during the course of more traditional astronomical observations. Therefore, we should support a rich and diverse program of explorations of the sky and of our own solar-system, while training our students to be curious about any anomalies that turn up in their data, in the spirit of Jocelyn Bell.

Adequacy of the Sample

Traditional targeted SETI searches examine star systems deemed likely to include habitable planets, prioritized according to distance and other habitability criteria. Careful enumeration of large numbers of these stars is essential to the type of commensal observing that will be conducted on the Allen Telescope Array, for example, or eventually on larger imaging instruments such as the planned Square Kilometer Array. Using data from the Hipparcos and Tycho-2 catalogs, a list of ~250,000 such star systems has been culled, and these so-called "habstars" will be the initial quarry for the large-scale targeted searches of the coming two decades [18] This will extend our scrutiny of all suitable stellar systems to a distance of 600 parsecs. Currently the NOMAD catalog is being scrutinized to find additional target stars, the successful completion of the GAIA astrometric mission in the middle of the decade, and an improved census of nearby M dwarfs will provide millions of target stars for future observations.

Two-dimensional optical detectors, and wide-field radio telescopes increase the speed with which SETI can examine extended objects or engage in restricted surveys. Such targets might include stellar clusters, the region near the galactic center, the solar anticenter direction, or entire galaxies. While of limited practicality during SETI's first half-century, they are now feasible.

Conclusion

Since the first SETI search almost five decades ago, the detection of extrasolar planets and of microbial life thriving in the most extreme terrestrial environments have given a suggestively bio-friendly mien to the cosmos. Investigations into the evolution of intelligence on Earth has hinted (but not yet proven) that, rather than being an improbable response to a niche evolutionary opportunity, intelligence might be a common product on worlds with a highly diverse biota. [19].

However, we still cannot predict whether or when SETI will be successful. Assuming that electromagnetic signals are the most easily detectable signature of another civilization, we need to examine a multi-dimensional volume: space (three dimensions), time, frequency, polarization (two possibilities), and modulation (a continuum of possibilities). This needs to be done with sensitivity adequate to detect the signals above any astrophysical background noise.

This has been true since SETI began. What the next decade will offer is the availability of nearly continuous access to the sky, a consequence of commensal observing; multiplexing of observed targets and frequency bands; a continuing growth in instantaneous processing bandwidth; access to the IR portion of the spectrum; and greatly enhanced computational capacity permitting searches for a broader class of signals. At the same time, the increase in knowledge about extrasolar planets is permitting a straightforward refinement of SETI targets.

Funding for SETI in the United States has come largely from private sources since 1993. Given its inherently uncertain nature, it will undoubtedly remain a relatively small-scale endeavor in the larger enterprise that is astronomical research. But the importance of the questions it seeks to answer encourages our continued efforts.

It has taken SETI nearly a half century to collect and examine a single 'glass' of the cosmic ocean. In the next two decades, given funding adequate to support observatories and observers, this tally will increase by three orders of magnitude, in multiple dimensions of the search. That is a sample size that many SETI practitioners estimate is finally sufficient to realistically test the premise that what has happened on our world has happened on many others.

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