SETI turns 50: five decades of progress in the search for extraterrestrial intelligence

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ABSTRACT

The 1959 Nature article by Giuseppe Cocconi and Phil Morrison[1] provided the theoretical underpinnings for SETI, accompanied in 1960 by Project Ozma[2], the first radio search for signals by Frank Drake at the National Radio Astronomy Observatory (NRAO). Well over 100 search programs have been conducted since that time, primarily at radio and optical wavelengths, (see www.seti.org/searcharchives) without any successful signal detection. Some have suggested that this means humans are alone in the cosmos. But that is far too strong a conclusion to draw from far too small an observational sampling. Instead of concluding that intelligent life on Earth is unique, it is more appropriate to note that in 50 years our ability to search for electromagnetic signals has improved by at least 14 orders of magnitude and that these improvements are still occurring at an exponential rate. At the SETI Institute we are in the process of re-inventing the way we search in order to fully utilize these technological enhancements. We are now building the setiQuest community and we intend to get the world involved in making our searches better. We need to find ways to harness the intelligence of all Earthlings in order to better seek out extraterrestrial intelligence. If we do it right, we just might succeed, and we might also change how we see ourselves, and make our own world a better place.

Keywords: SETI, setiQuest, search for extraterrestrial intelligence, Drake Equation, open source

1. INTRODUCTION

Though Frank Drake was the first scientist to use a radio telescope to search for signs of extraterrestrial intelligence, optical telescopes had been employed for this purpose for hundreds of years, most notoriously at the Flagstaff observatory built by Percival Lowell to study what he claimed were the massive canal-construction projects of the dying race of Martians[3]. Lowell's "canals", his wishful thinking, and his over-interpretation of poor quality data had a rather unfortunate impact on the credibility of SETI science. So it is appropriate that we mark a more recent birthday for SETI. Drake's Project Ozma was the first critical, scientific exploration undertaken to answer the ancient question "Are we alone?"

1.1 The embryonic age of SETI

In 1961, the US Academy of Sciences sponsored a meeting at the NRAO Green Bank Observatory in West Virginia to explore the topic of SETI. The agenda for that meeting became the well-known Drake Equation[4], which still serves today to organize our ignorance about the factors that might be necessary for detectable, technological civilizations to co-exist with us in the Milky Way Galaxy. This NAS meeting started a tradition of decennial SETI conferences jointly sponsored by the US and USSR Academies of Sciences that continued until a few weeks before the dissolution of the Soviet Union in 1991. During this period, small search programs were carried out in Australia and The Netherlands, and the Ohio State University Radio Observatory began the first (and longest) sky survey at the neutral hydrogen 21 cm frequency proposed by Cocconi and Morrison, selecting a restframe defined by the center of the Galaxy to select the actual observing frequency (see http://www.seti.org/searcharchive).

For more than a decade and a half following Project Ozma, the former Soviet Union dominated this young science in the number of searches, the variety of search strategies, and the claims of success[5]. In 1965, overly-enthusiastic observers from the FSU, shared their speculations with *Tass* reporters, eventually causing the editor of the *New York Times* to report the detection of a variable radio source thought to be due to ETI. In fact, the astronomers had detected

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synchrotron self-absorption modifying the spectrum of the quasar CTA-102[6], thereby producing an emission profile that resembled what Nikolai Kardashev had postulated for an advanced technological civilization[7].

1.2 The NASAonic age of SETI

Dr. John Billingham from the NASA Ames Biotechnology and Life Sciences Divisions got NASA into the SETI business starting in 1970 by sponsoring a series of high profile seminars. That was followed the next year by a summer study jointly sponsored by NASA Ames and Stanford University and co-led by Billingham and Dr. Bernard M. Oliver, then the Director of HP Labs. The Cyclops Report[8], details the results of that study, including the rationale for a radio search, a strawman design for a massive phased array, and an exhaustive tutorial on square-law detection, false alarm rates, and other signal processing basics related to the recognition of engineered, narrowband radio signals. At NASA Ames, Billingham opened the Interstellar Communication Study Group as part of the life sciences burgeoning interest in what was then called exobiology. Over time, studies turned into plans and then into the first NASA-supported SETI search with the NRAO Green Bank 300 Ft. antenna. Mark I VLBI tape recorders were used as bit buckets to capture 1-bit sampled data onto hundreds of reels of magnetic tape for later processing with the CDC 7600 computer at Ames[9]. As the digital electronics revolution made possible the development of near-real-time, custom-built signal detection equipment that could be transported to existing large radio telescopes around the world, the Ames Study Group expanded and morphed into the SETI Project Office. The employees of this office spent considerable time and effort creating a series of documents to squeeze this new field into NASA's institutional structure; first within the Life Sciences and then within Astrophysics and Space Sciences. The Jet Propulsion Laboratory also became active in SETI, first as a competing program and then in concert with NASA-Ames. With a steady stream of refereed, scientific papers carefully documenting negative results from observations conducted by a growing number of research groups in the US and Europe, plus review articles charting the progress of, and potential for, a systematic scientific exploration, the legitimacy of the SETI endeavor gradually enhanced within the scientific community (finally overcoming the stigma of Lowell's fanciful publications). Of note, the National Research Council's astronomy and astrophysics decadal reviews for the 70's, 80's, and 90's each awarded SETI cautious recommendations for small-scale programs.

As SETI activities within NASA multiplied and became more visible, they began attracting negative attention from various members of Congress. After a Golden Fleece Award from Senator Proxmire in 1978 and several cycles of negative and positive annual line-item budget requests, SETI was re-instated as a NASA program in FY83 and moved forward, with only minor Congressional skirmishes and name changes, towards a 10-year, coordinated observing project. The Microwave Observing Project (renamed the High Resolution Microwave Survey, HRMS) involved a Sky Survey (managed by JPL utilizing 34 m telescopes within NASA's Deep Space Network) and a Targeted Search (managed by Ames Research Center utilizing large scientific radio telescopes around the world). Both prongs of the search strategy rested on significant technological developments in digital signal processing and fast Fourier transforms. JPL built a wideband spectrum analyzer (WBSA) with 2^{21} (~2 million) channels as a prototype of a system that was intended to grow to 32 million channels covering 320 MHz of bandwidth with 20 Hz resolution to be used on DSS 34m antennas in Goldstone, CA, Madrid Spain and Tidbinbilla Australia for observing the entire sky from 1 to 10 GHz[10]. The SETI Project Office at Ames worked with Stanford and other nearby universities as well as Silicon Engines (a local start-up) to build a multi-channel spectrum analyzer (MCSA) with ~28 million channels of 0.7 Hz resolution covering 10 MHz of bandwidth, dual-polarization, with pattern recognition software capable of recognizing drifting CW and pulsed signals in near-real time. Like the WBSA, this hardware was expected to grow by a factor of 6 over the first few years of the 10-year program in order to complete a targeted search of 1000 nearby, solar-type stars over the frequency range of 1 to 3 GHz[11]. To accommodate an observing protocol that based the Targeted Search System (TSS) at the NRAO Green Bank 140 ft. telescope for the bulk of the time, with periodic observing campaigns to Arecibo Observatory in Puerto Rico, Nançay Observatory in France, and Parkes Observatory in Australia, the TSS was packaged up in its own tractor-trailer, customized to fit snuggly into a military cargo plane.

On October 12th 1992 (marking the 500th anniversary of Columbus's discovery of the New World) NASA's HRMS was launched simultaneously at the Goldstone Deep Space Communications Complex in the Mohave Desert and at the Arecibo Observatory in Puerto Rico. Both sets of equipment worked as intended, but a valuable lesson was learned for the Targeted Search; one telescope was not enough to work efficiently in the radio frequency interference-laden (RFI) environs of Puerto Rico. One year later, NASA's SETI program was terminated by Senator Richard Bryan from Nevada. This time there was no revival. Bryan had attempted to eliminate funding for SETI from NASA's FY93 budget, but he was out-maneuvered by his colleague Senator Jake Garn from Utah. When the FY94 NASA budget came to the floor of the Senate for a vote, Garn had left office, and Bryan skillfully inserted an 11th hour amendment stripping the funds. Bryan let NASA know that the same fate would await any future-year funding for SETI. The NASAonic era was over, almost exactly one year from the day that HRMS had launched for its 10-year mission of exploration.

1.2 The philanthropic age of SETI

During the 1980s as NASA was experiencing a roller coaster ride of Congressional funding, two non-profit organizations were created that would ultimately be critical to the survival of SETI observing programs following the cancellation of the NASA HRMS. In 1980, partly as a result of his interactions on the subject of SETI with Senator Proxmire from Wisconsin, Carl Sagan joined with Bruce Murray (then Director of JPL) and Louis Friedman to incorporate The Planetary Society (TPS) with the goal "of inspiring the people of Earth to explore other worlds, understand our own, and seek life elsewhere." This organization has consistently raised public awareness and lobbied for a variety of space exploration projects and for SETI. Over the years, TPS has provided funding for UC Berkeley-based SETI observing programs (SERENDIP, SETI@home, and OSETI), observing programs at Harvard University (META, BETA, OSETI, and OSETI Sky Survey), and the Southern SETI project of the Argentinean Institute for Astronomy[12]. In 1984 Oliver contracted with Tom Pierson (then at SFSU Foundation) to perform a study of various organizational models that might permit the NASA SETI Project Office to stretch the modest funds available for SETI. The goal was to bypass the outlandishly large indirect cost rates being charged by local universities on grants and cooperative agreements that were funding their soft-money faculty working at Ames on the Targeted Search. The non-profit SETI Institute was the outcome of that study. Dr. Jill Tarter (then at UC Berkeley) wrote a broad scientific charter for the SETI Institute, becoming its first employee after Pierson filed the incorporation papers and became its CEO. The key to success was setting an indirect cost rate that reflected the true, low cost of providing a scientific home for researchers wishing to "explore, understand and explain the origin, nature, and prevalence of life in the universe." The first NASA cooperative agreement was awarded in 1985, and the funds that were no longer needed to cover bloated indirect costs were made available for actually constructing long-planned prototype signal detection systems. The SETI Institute continued to support NASA's SETI Project Office, but it also attracted researchers from the field of exobiology and then astrobiology. Cost-effective management has allowed the SETI Institute to grow into one of the largest astrobiology research facilities in the world, a fact often obscured by its name.

Following Congressional termination in 1993, the SETI Institute immediately began raising private, philanthropic funds to rescue and continue the Targeted Search portion of the HRMS, giving the new project the ironic name of Project Phoenix. Because the HRMS Sky Survey was completely dependent on NASA's DSN antennas, it was impossible to recast that strategy, and SETI work at JPL wound down during FY94. In an effort to maintain a sky survey strategy for SETI searching, a third non-profit was incorporated in 1994, the grassroots SETI League "dedicated to privatizing the electromagnetic Search for Extra-Terrestrial Intelligence". Its financial backing came from Richard Factor (President of Eventide), and Dr. H. Paul Shuch became its Executive Director. They launched Project Argus in an attempt to organize radio amateurs, and others around the globe, to acquire decommissioned antennas (e.g. backyard TVRO dishes), equip them with low cost electronics and PC-based signal detection software, to form a coordinated network of thousands of telescopes constantly surveying the radio sky for SETI signals. Membership peaked at about 1500 in 62 countries, but the number of functioning Argus stations has never gotten much beyond 150, far from the goal needed for full sky coverage. The organization continues today with a strong public outreach and education focus.

So bruising was the Bryan amendment, that SETI became the four-letter-S-word that could not be spoken at NASA Headquarters. NASA funding remained unavailable until Dr. Alan Stern, the Associate Administrator of the Science Mission Directorate, added language into the 2008 general NASA Research Announcement specifically inviting "Investigations to identify and characterize signal characteristics and/or observable properties of extrasolar planets which may distinguish planetary systems with intelligent life." Ironically, in the years immediately following the HRMS termination, extrasolar planets were first detected, and astrobiology then became a larger and larger portion of the space science program. NASA's mission statement even began to include the slogan "Are we alone?" although their funded work to answer this question was confined to searches for microbial life on other worlds. With the thaw in NASA's attitude, JPL is once again planning for SETI surveys, although now limited to the galactic plane where the bulk of the stars in our Galaxy reside and taking place at the Goldstone Apple Valley Radio Telescope, outside-the-gates of the DSN. Because of the Moore's Law growth of computing capacity, this survey will cover a much larger range of frequencies (from 2 to 23 GHz) than planned for HRMS. There was another disconcerting fallout from NASA's political skirmishes over SETI. In 1994 the NSF inserted language in its guidelines for proposals that specifically excluded funding for SETI research. This language wasn't removed until 2000, and only after Lamar Smith, a sympathetic Congressional Representative from Texas, exerted his influence.

Under the leadership of Barney Oliver, the SETI Institute's fundraising efforts met with immediate success. Silicon Valley icons such as David Packard, Bill Hewlett, and Gordon Moore joined Oliver and became SETI supporters, stepping in to redress what they felt was the foolishness of Congress. Paul Allen (Microsoft co-founder) was the next to offer his support. With the potential of additional private funds to back Project Phoenix, transfers of government furnished equipment and rental agreements for the observing time on the Parkes and Green Bank telescopes and re-affirmation of the previously-approved Arecibo SETI observing plan were negotiated. Without access to military cargo planes, the TSS along with a newly-developed FUDD or follow up detection device (intended for use at a second, distant telescope to form a pseudo-interferometer) shipped to Australia on a container ship to start six months of observations at the Parkes and Mopra Observatories in 1995. Although Oliver got to celebrate the conclusion of the tactically successful Australian deployment with the other major donors, he passed away shortly thereafter, leaving a very generous bequest to the SETI Institute to keep the search alive.

After its return from Australia, the TSS was refurbished and shipped to the Green Bank 140 Ft. antenna, and the FUDD went to Woodbury Georgia where an old AT&T ground station had been transformed into a radio telescope in a joint project with Georgia Tech students and faculty. Observations in West Virginia and Georgia continued from 1996 to 1998. The final phase of the Targeted Search took place at Arecibo Observatory in conjunction with the Lovell Telescope at Jodrell Bank Observatory in the UK during a series of observing campaigns lasting from 1998 through 2004. During that time, the original TSS, built from full-custom hardware, was upgraded and replaced by a series of rack-mounted PCs each containing two custom accelerator cards, and its massive RAIDs were replaced with modern disk technologies. Unimaginatively, this TSS replacement was called the new search system (NSS). During its nine-year observing program, Project Phoenix observed 800 stars, out to distances of 240 light years, over a frequency range of 1200 to 3000 MHz, with sensitivity sufficient to detect 20th century Earth-analog technologies[13]. No repeatable evidence of extraterrestrial technologies in the form of narrowband radio signals was found.

As the 20th century was coming to a close, the SETI Institute held a series of workshops from 1997 to 1999 to determine the best way to continue SETI exploration during the first two decades of the 21st century. Many workshops had been held on the subject of SETI since it's inception in 1960, but these were noteworthy because for the first time technologists from the Silicon Valley were included in the mix of astronomers and radio engineers already involved in SETI programs. That made a profound difference in the outcome. The Silicon Valley cohort was able to convince the remaining workshop participants to bet on Moore's Law; to make future plans that required computing complexity and capacity not yet available, confident that when needed they would be. The results of those workshops have been published in *SETI 2020*[14], containing three recommendations:

- Build the One Hectare Radio Telescope (1hT) to carry out targeted searches of candidate stars and surveys in the galactic plane at frequencies from 1 to 10 GHz,
- Commence infrared/optical searches (OSETI) for signals using direct photon detection techniques, and
- Begin prototyping an omnidirectional SETI system (OSS) designed to search for strong, low-duty cycle microwave signals at frequencies from 1 to 3 GHz.

The first recommendation reaffirmed the efficacy of radio signals for the purpose of transmitting information over interstellar distances. It recognized that systematic searches could not proceed at any reasonable pace without a dedicated facility, and further that instrumental and computational technologies now permitted an affordable observatory to be built as a large number of small dishes, while achieving a world-class sensitivity and speed.

In the early 1960's, Nobel Laureate Charles Townes (inventor of the maser-laser) suggested searches for fast optical pulses[15]. The second recommendation in *SETI 2020* recognized that the fast, photon-counting photodiodes needed to implement such optical searches were finally available and affordable. Indeed, before the workshop series concluded, two OSETI facilities were operating on existing telescopes at the Leuschner Observatory at UC Berkeley[16] and the Oak Ridge Observatory at Harvard[17].

Since the SETI 2020 workshops there has been only minimal progress made on the third recommendation for a fly's eye instrument. The Argus system, which was started at Ohio State University with funding from the SETI Institute and then moved to Virginia Tech, uses inexpensive arrays of simple spiral antennas[18]. The limiting technology for OSS is not the receivers, but the enormous computing power required to form individual beams across the sky and explore each with spectrometers having thousands to millions of spectral channels. *SETI 2020* estimated that starting with a 2 x 2 array of receivers, and growing in steps of 4 in array size and bandwidth, an array of 64x64 elements with 4 GHz of bandwidth requiring ~10^{16} ops might be achievable and affordable by 2020.

In 1994, David Gedye at Microsoft had a great idea about filling the vacuum left by termination of the NASA SETI program. He suggested allowing individuals to use spare cycles on their personal computers to process SETI data collected from radio telescopes. Prof. Woodruff Sullivan from University of Washington put Gedye in contact with Dan Werthimer at UC Berkeley Space Science Laboratory, who was then running the third generation SERENDIP III (a SETI detector that piggy-backed on routine astronomical observations), and David Anderson, a UC Berkeley computer scientist who was a specialist in the relatively little-known field of distributed computing. This team eventually gained funding and support from TPS, Paramount Pictures, Starwave, and some of the same Silicon Valley technologists participating in the SETI 2020 workshops. In 1999 they launched SETI@home[19] based on data recorded with SERENDIP IV at Arecibo Observatory. SETI@home did not invent distributed computing, but it was so wildly successful that it really put this computing modality on the map. A decade later this innovative search has randomly explored the sky visible from Arecibo several times, and has now been upgraded to continue working with data recorded directly from ALFA, the new 7-beam feed system there. While the heavy-lift Fourier transforms and pattern-recognition computations are done on volunteers' CPUs in a distributed network, candidate signal detection actually takes place at Berkeley after the millions of reported signals are sent there every day. Known RFI is removed and the surviving, characterized signals from a given sky direction are compared with the results found when that same piece of sky was observed on other occasions. Over time, a list of the most probable candidates is built up and dedicated observing campaigns try to reacquire them; to date without success. More than 5 million people from every country have downloaded this screen saver and at any moment there are perhaps 50,000 active volunteers making their computers available to the search. Early on, the idea of competitive teams with a leader board was introduced and that appears to have been a very important motivator for continued participation. TPS has remained the primary fundraiser for this effort, although starting in 2002 the NSF began funding a transformation to a generalized platform for distributed computing and grid computing called BOINC. Today SETI@home is only one of dozens of projects that allow more than 300,000 volunteers to provide service computing in support of their favorite scientific and social research areas.

2. PURPOSE-BUILT OBSERVATORIES FOR SETI

SETI 2020 recommended that a radio telescope with 10^4 square meters (1 hectare) be built as an array from a large number of small dishes (LNSD) so that SETI and traditional radio astronomy could be carried out commensally. The report further recommended that optical SETI signal detectors be added to existing telescopes to conduct targeted searches of stars within 1000 light years. The first decade of the 21st century has seen the implementation of both these recommendations and more.

2.1 The Allen Telescope Array

Following the conclusion of the SETI 2020 workshops, the SETI Institute signed a memorandum of understanding with the University of California Berkeley Radio Astronomy Laboratory (RAL) to develop and design a dual-purpose array for conducting SETI and traditional radio astronomy 24 x 7. During the SETI 2020 workshops, Dr. Sandy Weinreb from JPL introduced his MMIC low noise amplifier capable of working across the entire 1 to 10 GHz terrestrial microwave window favored by SETI, and Prof. Jack Welch from the RAL designed a frequency independent feed to match the LNA. The partnership between the SETI Institute and the RAL seemed an obvious match; the former had a strong background in building signal detectors, and the latter had a distinguished history of building arrays, a faculty with a strong interest in cm wavelength radio astronomy, and a site in northern California that would become available when the existing BIMA mm array was moved to a higher site in southern California and joined with telescopes from Cal Tech's Owens Valley Observatory to form the CARMA array for higher frequency mm astronomy. The One Hectare Radio Telescope (1hT) officially became the Allen Telescope Array (ATA), when Paul Allen agreed to fund the technology development phase of the project in 2000. At the successful completion of the technology development phase, Paul Allen agreed to fund the first phase of construction in 2003 and a search began for partners to finish out the array to its final size. The US Naval Observatory provided funding for additional telescopes and early operations. The array now consists of 42 antennas, and the search for partners to build it out to its full 350-antenna configuration is ongoing.

The ATA[20] is located near Mt. Lassen Volcanic National Park at the Hat Creek Radio Observatory. The array will eventually consist of 350 antennas, each 6.1 m in diameter, and have the equivalent collecting area of a single dish that is

114 m in diameter. It is being built as the first LNSD array with the antennas connected by a vast network of computing. Because the individual dishes are small, the array observes a very large patch of the sky at any moment - about the size of 7 full moons across at a frequency of 1 GHz. Specifically, he full-width half-max field of view is 3.5°/f (in GHz). Since the 350 antennas will be spread across the Hat Creek Valley, with the largest separation of any two antennas being 900 m, the array will have the spatial resolution that is finer than the huge Arecibo telescope by a factor of three. All of the receiving electronics are housed within a pyramidal structure between the secondary and primary mirrors. A system of four log-periodic feed arms act as aerials to capture radio waves of both (linear) polarizations that are reflected and focused by the antenna surfaces. These feed arms are sensitive to long wavelengths (low frequencies) at the large end and short wavelengths (high frequencies) as the small end; the instantaneous frequency coverage is 0.5 to 10 GHz (see Figure 1). A pair of wideband LNAs designed by Sandy Weinreb are mounted inside a vacuum dewar and cryogenically cooled to 70K by a small refrigerator at the base of the pyramid; the LNAs amplify the entire frequency range. A post-amplifier and optical transmitter send the full bandwidth analog datastream along buried, single mode fibers to the processing building in the center of the array. Today the data are digitized by ADCs having a bandwidth of only 104 MHz, within two years these should be replaced by ADCs with 600 MHz bandwidth, and over the working lifetime of the observatory more and more of the analog data will be accessed instantaneously.

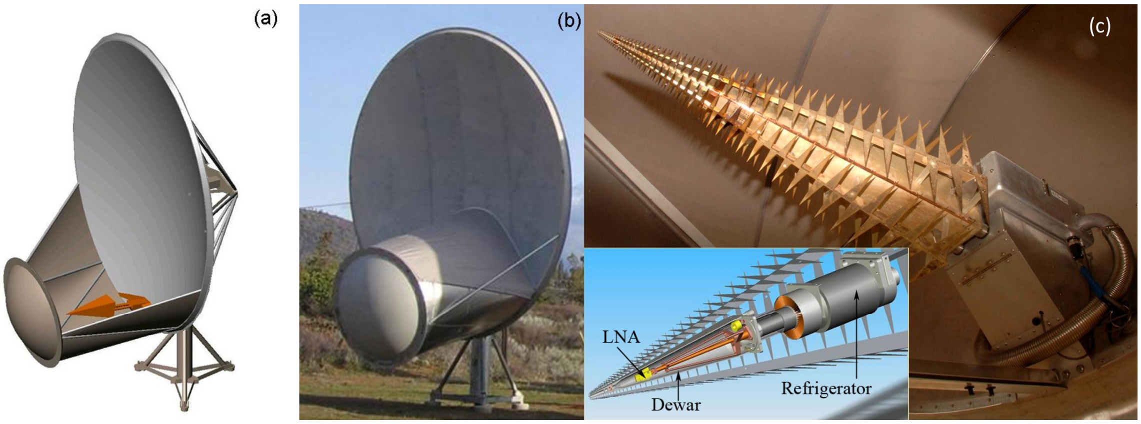

Figure 1 – The ATA uses a clear-aperture, offset Gregorian design. (a) schematic of 6.1m offset parabolic primary, 2.4 m hyperbolic secondary, metallic shroud, and pyramidal feed/receiver. (b) picture of ATA antenna enclosed by radome cover. (c) the cryogenic feed/receiver system with cutaway showing vacuum dewar and refrigerator.

In the processing building there are four LOs that mix with the incoming analog data before it is digitized to create four independently tunable data paths that then feed multiple signal processing backends. The result is that radio maps of large areas of he sky can be constructed for astronomical surveys utilizing spectral-imaging correlators at the same time that beamformers permit selection of individual sky pixels to enable SETI observations of multiple, individual target stars lying within the same area of the sky. SETI signal detection today utilizes a modified version of the NSS from Project Phoenix (see Figure 2), but that will soon be replaced with software detectors installed on COTs servers. Over the next decade between 1-10 million nearby stars will be explored across the naturally quiet terrestrial microwave window for signals that are no stronger than Earth's most powerful radar. In a complementary observing mode, a survey of billions of distant stars within 20 square degrees surrounding the direction of the galactic center are being probed for extremely powerful transmitters.

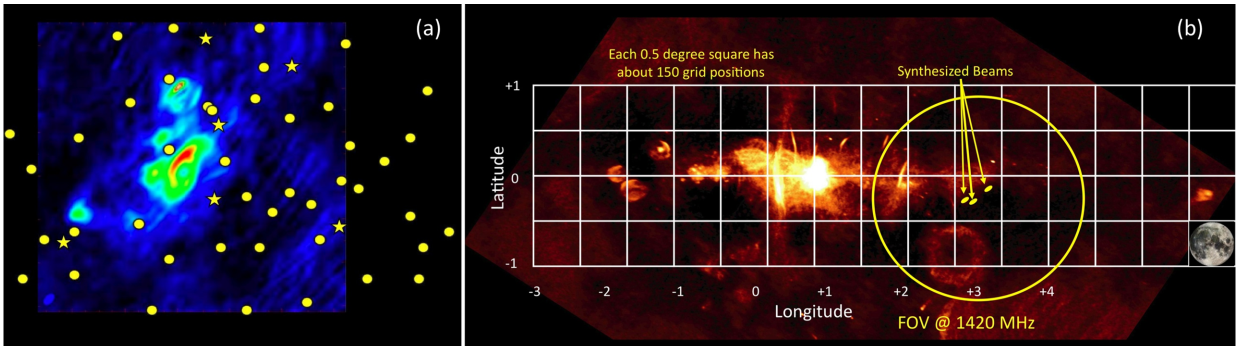

Figure 2 – ATA Observing. (a) 50 stellar SETI targets selected from catalogs prepared by Turnbull and Tarter[21,22] are observed pair-wise using beamformers and 100 million-channel spectrometers at the same time that the neutral hydrogen gas in the M81-M82 system is mapped using imaging correlators. (b) 20 square degrees surrounding the galactic center are explored using a grid of 3518 pointing centers for SETI signal processors at the same time that correlation spectrometers search for transient astronomical signals.

2.2 OSETI Sky Survey

As already noted, before the SETI 2020 workshops ended, OSETI detectors had been built and targeted search observing projects had begun using older, 1m class telescopes at UC Berkeley's Leuschner Observatory, and Harvard's Oak Ridge Observatory. Soon thereafter OSETI search programs were initiated at Princeton University Observatory[23] (at times in conjunction with Harvard), UC Santa Cruz's Lick Observatory[24], and a privately funded observatory in Campbelltown NSW, Australia[25]. The Princeton, Lick, and Harvard targeted programs have now ended after having each observed several thousand stars, looking for nanosecond pulses from distant lasers. Although there is no known natural background of such short pulses to confuse the observations (the equivalent of RFI), high-energy particles interacting with the detector, and discharge events in the photodiodes produce an unacceptably high false alarm rate. The solution is to use two, or even three photodiodes in coincidence, in order to drive down the false alarm rate exponentially. As with the radio searches, no repeatable, pulsed optical signals have yet been found.

The SETI 2020 workshop did not anticipate the rate at which the technology of fast photodiode detectors would improve; expanding first to linear and then to large, square arrays. These arrays are the key to sky surveys, and have now enabled a dedicated OSETI observatory to be built on the grounds of the Oak Ridge Observatory in Harvard, Massachusetts. This all-sky OSETI survey[26] observing facility was constructed by students and faculty at Harvard University to survey of the 60% of the northern sky visible from there. The telescope is housed in a building featuring a roll-back roof and a removable section in the south-facing wall to accommodate drift scans with only a single axis of rotation. Because the system does not require image quality optics, the 72" primary and 36" secondary mirrors have been manufactured inexpensively by fusing glass over a spherical form and then polishing. The detection system is based on eight pairs of 64-pixel Hamamatsu fast photodiodes, and custom electronics to permit real-time pixel by pixel intercomparison for coincidence detection to eliminate false positives. This new telescope searches for powerful laser transmitters by conducting meridian transit scans of the sky in 1.6°x 0.2° strips (with a dwell time, due to the Earth's rotation, of about one minute). The sky visible from that site can be scanned in approximately 150 clear nights. Significant effort and ingenuity went into making the telescope fully operable from remote locations. The first scan of the sky has been completed and twelve areas of the sky with interesting results have been followed up using the 10m Whipple Telescope, without any further confirmation. Another survey is now underway with upgraded electronics. The survey sensitivity should be adequate to detect laser pulses from the analog of a Helios-class laser being transmitted through a 10 m telescope up to a distance of 1000 ly.

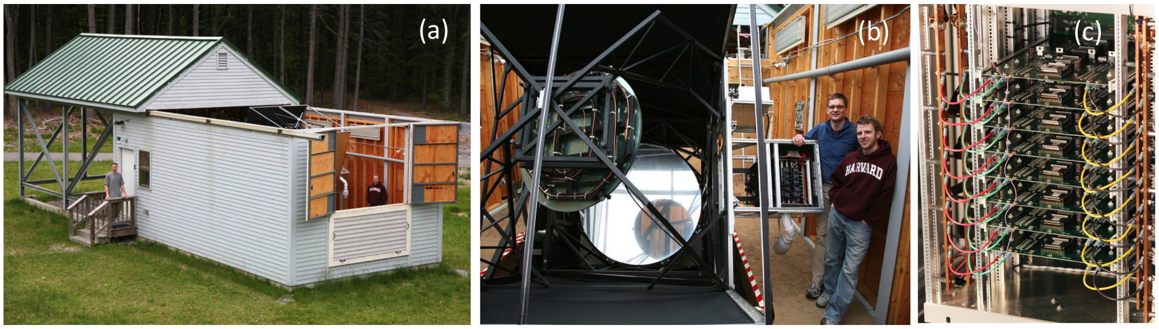

Figure 3 – The Harvard OSETI Sky Survey Observatory. (a) the inexpensive facility features a roll-back roof with a section of the south-facing wall that can be removed to accommodate drift scans. (b) the 72" primary and 36" secondary mirrors, the detector housing and two of the student builders. (c) detector arrays of photodiodes.

3. THE NEXT PHASE OF EXPLORATION

After 50 years without detecting a signal at radio or optical wavelengths, is it time to give up and conclude that we are (at least practically) alone in the universe? No, that is far too strong a conclusion based on far too little data.

Just how much of the cosmic haystack have we explored to date? Start by assuming that electromagnetic signals are indeed the correct manifestation of extraterrestrial technologies for which to search. The electromagnetic cosmic haystack itself is at least 9-dimensional (3-space, time, 2-polarizations, frequency, modulation, required sensitivity). There are ~10^{11} stars in the Milky Way, not all of them have planetary systems, but some that do probably have more than one habitable planet, so lets take 10^{11} stars as a good measure of the 3 spatial dimensions to be searched. Radio searches have typically covered both polarizations, so that isn't a factor. In the radio spectrum there are 9 billion 1-Hz channels within the 1 to 10 GHz terrestrial microwave window, so roughly $10^{11+10} = 10^{21}$ combinations of star-Hz to search. How many modulation schemes might we have to explore? The Cyclops Report considered only circularly polarized, narrowband signals because these propagate nearly undistorted through the interstellar medium. But such signals are information poor and can be masked by local RFI. Modern communication theory suggests that with adequate compute power it would be possible to search through a large number of modulation schemes for complex signals with a large number of degrees of freedom, primarily very broadband signals. It might also be necessary correct for the interstellar distortion (mainly dispersion) that broadband signals suffer, although there may turn out to be techniques such as autocorrelation[27] to directly detect the distorted signal. As a rough guess, perhaps a search of 100 different modulation schemes, and 100 different dispersion measures for a total of 10^4 trials. That brings us to something like 10^{25} star-Hz-modulations for this portion of the haystack. Project Phoenix searched 10^{12} star-Hz for a single modulation type of narrowband signals, and the ATA has already searched a comparable amount, for a total of $2\text{x}10^{12}$ star-Hz-modulations. Thus far, the ratio of searched space to haystack space is $2\text{x}10^{-13}$. What about required sensitivity and time? A comprehensive search of the haystack that would make a null result significant would be one that would detect the equivalent of our own 21st century technology throughout the galaxy. The current galactic center survey with the ATA requires a transmitter to be 20,000 times as strong as our current most powerful transmitter (the Arecibo planetary radar with an EIRP of $2\text{x}10^{13}$ W EIRP), meaning that our searches to date are only 10^{-17} of the 8-dimensional portion of the 9-dimensional haystack, and we haven't yet factored in time. The duty cycle of the signal is unknown, but if it is a deliberate signal it should be fairly high because the sender wishes it to be received. To date all our searches have required that this duty cycle be unity so that it is detectable with one or a few looks and persists for confirmation; that is to say we have had little or no sensitivity to transient signals, or to signals that undergo strong fading through the interstellar medium. However, this is a small factor compared to the temporal issue of longevity; arbitrarily we set the duty cycle to 1/2. In the 10 billion year history of the Milky Way, the technology has to be transmitting at a time when we are searching. The probability of this is crudely $L/10^{10}$ years, where L is the longevity of the transmitter. Although our terrestrial history indicates that the technologies themselves outlast the civilizations of technologists, L is often thought of as the longevity of the technological civilization, and we know nothing about it. We use our own example to set a lower limit of 100 years. However, in our galactic neighborhood, most stars are older than the Sun with an average age of ~7 billion years. If elsewhere the evolutionary timescale to reach technological capability is comparable to our own 4 billion years, then L could be as long as $3\text{x}10^9$ years. Using these two limits means that the fraction of the 9-

dimensional cosmic haystack searched to date lies between $5x10^{-26}$ and $1.5x10^{-18}$, with a geometric mean of $2.5x10^{-22}$. Coincidentally, the Earth's oceans hold $1.4x10^{18}$ m^3 of water, or $6x10^{21}$ cups of water. So our search of the 9-dimensional haystack is equivalent to sampling about 1.6 cups of water from the Earth's oceans. If you were looking for fish instead of extraterrestrial intelligence, I don't think that you would conclude that there are no fish in the ocean after this meager sampling!

So what should SETI do? To continue the analogy, we can build bigger glasses and dip them faster to sample the ocean at a more rapid rate. Indeed that is what we have done over the past 50 years due to the digital revolution and improvements in the analog components of our telescopes. Compared to Frank Drake's project Ozma with one radio channel, scanning 400 kHz of the spectrum, having a detection sensitivity set by a system temperature of 350K and the collecting area of an 85 foot (26 m) antenna, plus a single event-above-threshold average, today's searches with the ATA-42 are almost 15 orders of magnitude more capable. Our spectrum analyzers now have $3x10^7$ channels and are used to scan 9 GHz of the spectrum, the ATA has a system temperature of 40K and the equivalent collecting area of a 40 m antenna, plus a processing gain of 10, and the ability to observe 3 stars simultaneously. The analog components of the system are fairly close to optimal, with perhaps another factor of 1.3 improvement possible due to lower system temperatures in the future. Funding will permit growth of the collecting area of the ATA by another factor of 10. In addition, Moore's Law will continue to improve the speed and processing power of the digital components, allowing for more channels, and multiplexing more stars at once. We should certainly plan on doing more of what we've been doing as well as exploring more of the frequency and modulation space within the haystack. We should keep abreast of new technologies and physics that might provide us with new tools to look in entirely different ways. And most assuredly, we should stop doing this all by ourselves. We need to take a lesson from SETI@home and invite the world to participate, this time giving them the opportunity to contribute creatively to change what and how we do our searches.

3.1 Expanding OSETI

There are two obvious avenues for improving OSETI searches; move the detectors onto larger pieces of glass, and extend their frequency range into the infrared where scattering and absorption by interstellar dust is reduced, thereby extending the range of the searches. Since OSETI does not require image quality optics, opportunities might exist for repurposing or sharing large collecting areas built for other purposes.

Holder and collaborators[28] have used archival data and conducted some OSETI trial observations with the large 10m Whipple telescope built for the detection of Cherenkov radiation from gamma-rays interacting with the atmosphere. In its intended-use mode, the observing software on the Whipple ignores point-source events registered by the focal plane array of photomultiplier tubes because it is looking for the light from extended air showers, and these localized events represent a significant noise background from cosmic rays. By demanding symmetry and coincidence with known stellar positions on the sky, it may be possible to identify any OSETI signals among these discarded cosmic-ray background events. The two large Cherenkov radiation telescopes of the MAGIC[29] collaboration have implemented a single pixel trigger for OSETI events. Even better would be a triggering system based on the simultaneous detection of single pixel events among multiple telescopes within a gamma-ray detector array (e.g. VERITAS) that correspond to the same sky location. Another potential for repurposing large optical collecting areas for OSETI has been demonstrated by the STACEE experiment[30] using 64 of the 212 heliostat mirrors in the National Solar Thermal Test Facility. Gamma-ray astronomers are using such solar-power arrays at night for detection of Cherenkov air showers using photomultiplier tubes with nano-second time responses. These systems could be used to independently confirm reported OSETI signal detections or to track stellar candidates in a targeted observing program.

3.2 The Square Kilometre Array

The international radio astronomy community is currently planning and designing the Square Kilometre Array (SKA)[31], an LNSD array that will have 100 times the collecting area of the ATA-350 and extend over continental baselines up to 3000 km. The array will be constructed from dishes ~10-15m in diameter to provide a large field of view and will generate many simultaneous beams on the sky, enabling SETI observations to be conducted commensally with the other key science projects. There will also be dense and sparse low frequency arrays with very large collecting areas that will sample frequencies lower than those that have typically been used for SETI. Low frequency SETI observations are just beginning with LOFAR stations in The Netherlands and Europe[32]. Two SKA prototype dish arrays are now being constructed at the potential observatory sites in Western Australia[33], and South Africa[34]. The final site selection decision is expected in 2012, with construction starting in the coming decade and full operation perhaps as early as 2024 (dependent upon funding). The factor of 100 improvement in sensitivity promised by the SKA translates into a reach throughout the galaxy that is 10 times farther than our current explorations.

3.3 Getting the World Involved

In February of 2009, the first author of this article was given the opportunity to make a wish to change the world, which the TED organization (Technology, Entertainment, and Design) and its parent body, the Sapling Foundation, committed to help enable. That wish: "I wish that you would empower Earthlings everywhere to become active participants in the ultimate search for cosmic company" is now entering its initial phase of fulfillment with the launch of the setiQuest community[35]. The motivation behind that particular wish is the extraordinary power that SETI has to encourage individuals to reconsider their place in, and their intimate connection with, the universe. The discussion and pursuit of SETI programs have the effect of holding up a mirror to the planet; encouraging all who participate to adopt a more cosmic perspective, to internalize the commonality of all human Earthlings, and ultimately to trivialize the differences among them. SETI, by its very nature, ought to be a global pursuit. Detection of evidence of another distant technology will change everything, for all of us. The current state of digital and social-networking technologies may now enable a new level of globalization.

setiQuest currently provides opportunities for members of its community to participate in four different activities associated with setiObs (the radio searches being conducted at the ATA): setiCode, setiData, setiCloud, and setiCitizen. setiCode allows open source software developers to work with our existing observing code base as it gets published over the next year; taking from it those pieces they may find useful for other purposes and adding features that will improve its efficiency and ease of use. We hope they will also create ways to provide more visibility into the real-time setiObs searches and offer the world new ways of easily checking in on our progress. The global community of communications engineers and students with technical understanding of digital signal processing can participate in setiCloud. They will be able to help us expand the types of signals that setiObs can recognize. Existing algorithms are well suited to a class of radio signals characterized by extreme frequency compression, but are not a good match to complex signals of higher dimensionality. The cost of computing is now becoming sufficiently low to take on the challenge of near-real-time, complex signal detection. Large volumes of hosted storage (for raw, time-series data from the ATA) along with significant cloud-computing resources have been provided to support the setiQuest community. setiCloud enables DSP-savvy community members to produce clever, sensitive, signal-detection algorithms optimized for the detection of broadband, complex signals. Eventually these algorithms must achieve the efficiency required for implementation as part of the near-real-time setiObs. Those community members who are curious about what information radio data from the sky above Hat Creek Observatory might contain are invited to explore terabyte datasets, specifically recorded each week for setiData, and stored in the cloud. These data can be searched for signals, or mined for other purposes. The final group of setiQuest community members is everybody else; the crowd. These are the people whose engagement is so important, because this is how the world will change. setiCitizen is the slowest community to be implemented. Plans call for use of a combination of social-networking and gaming technologies to build a vibrant, passionate, and strongly-connected community that can help us find signals we are now not processing. The vast majority of these signals will be interference due to terrestrial technologies, but buried within them there might just be one from an extraterrestrial technology. These citizen scientists will help us by participating in the near-real-time search using their brains, their eyes, and perhaps even their ears as pattern-recognition tools to augment already-implemented algorithms. If we succeed in this technically-challenging implementation, members of the setiCitizen community will ultimately get to determine whether the next ATA observation should follow up on a signal they have discovered, They help us by exploring portions of the spectrum we are now ignoring, and they help themselves by connecting to one another and using the SETI framework to better appreciate their human sameness, when contrasted with any independently-evolved technological civilization elsewhere.

Figure 4 summarizes the various threads and opportunities within the setiQuest community. There are opportunities for individuals to participate as open source code developers, as signal detection algorithm developers, as citizen scientists, as data miners, and as volunteers to help us build the infrastructure needed to enable all of setiQuest.

To date, activities intended to open SETI searches to participation by the world at large have revolved around the radio searches being conducted with the Allen Telescope Array. It is not yet known whether similar open participation might be possible for any of the OSETI projects now being conducted. The Berkeley OSETI program is planning a new search called OSPOSH[36] that will make use of an FPGA-based, reconfigurable computing backend. As this processing hardware will be developed as part of an open-hardware development standard, it should be possible for individuals with the appropriate skillsets to contribute to its future improvement.

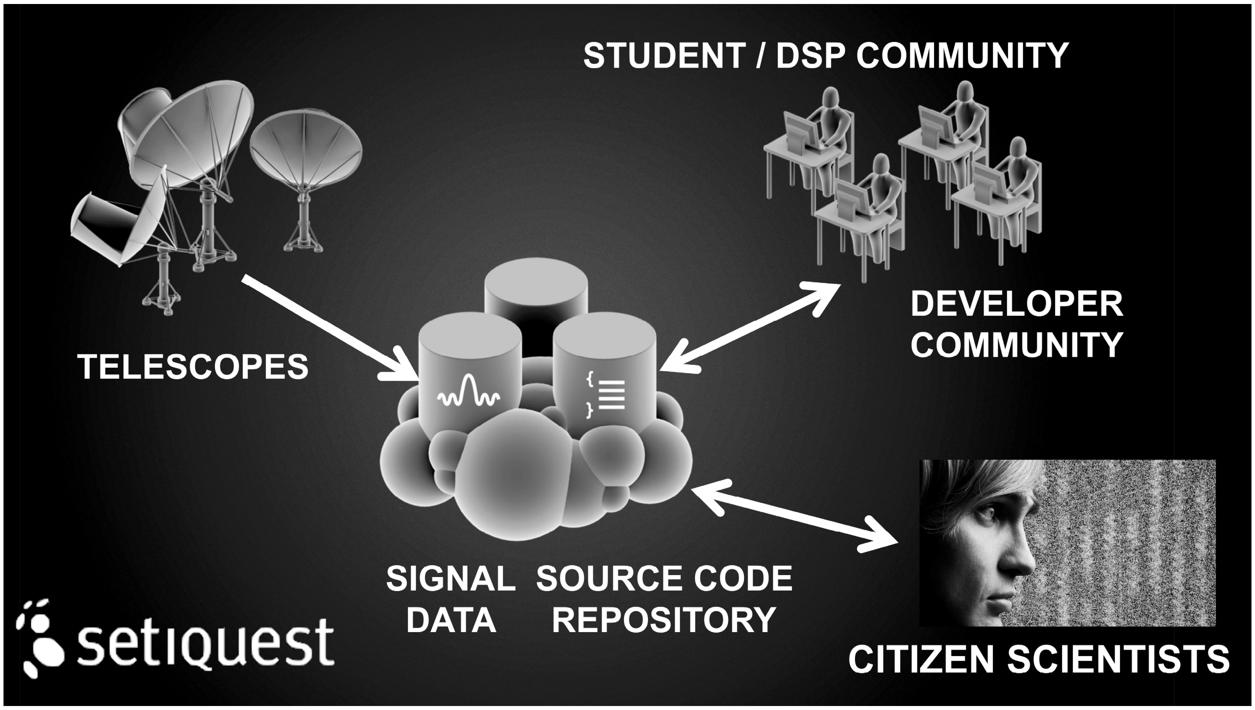

Figure 4 – Data from the ATA will be stored in the cloud or served in real time to allow a global community of citizen scientists, open source code developers, and digital signal processing experts, who can develop new detection algorithms, to participate in setiQuest; improving SETI searches at the ATA and helping to change the world.

4. CONCLUSIONS

The past 50 years of SETI explorations have been marked by extraordinary technological progress. More than a hundred individual search projects have been, or are being, conducted; the vast majority at radio wavelengths, but more recently the optical portion of the spectrum is being utilized as well. Although no evidence of another technological civilization has been found, the multi-dimensional phase space that might contain a signal has been so poorly investigated that it is premature to draw any conclusions about the prevalence or absence of intelligent life elsewhere. Purpose-built, SETI observatories at radio and optical wavelengths now exist, and opportunities for participating with larger, future instruments are being explored. Improvements in analog hardware and digital processing will continue to conflate and yield exponential enhancements in search capabilities, so that the tools being used become commensurate with the size of the space to be explored. At 50 years of age SETI is on the threshold of re-inventing itself; breaking away from its historic methodology of isolated researchers interrogating the skies with custom-built hardware, and opening the search to participation by global volunteers with specific technological skills, and the larger community of motivated citizen scientists. The key to this transition is the migration from unique custom signal processors to COTs servers and open source software.

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