

The History of SETI at the Hat Creek Radio Observatory

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Abstract. Since the first SETI search in 1960, observations have encountered an exponentially growing problem with radio frequency interference (RFI) generated by our own communication, entertainment, and military technologies. The signal processing equipment that is used for SETI has gotten much faster and more capable, yet the fraction of the possible search space that has been explored remains very small. More than 100 searches have been reported in the literature. Tarter (2001) has summarized the various search strategies and the SETI Institute maintains an updated search archive at <http://www.seti.org/searcharchive>. The Allen Telescope Array (ATA) at Hat Creek Radio Observatory will be the first instrument designed with SETI as a goal, and its speed and flexibility will permit a significant exploration of our local region of the Milky Way Galaxy, targeting ~ 1 million stars for weak signals, as well as surveying for stronger signals from ~ 40 billion distant stars, located in the direction of the galactic center and the surrounding 20 square degrees. Just as Jack Welch has been responsible for many of the innovations in the ATA and the SETI observations it will soon undertake, he has been the key to enabling SETI at the Hat Creek Radio Observatory for the past three decades.

1. Origins of SETI

In 1959, Cocconi and Morrison (1959) published the first scientific paper on the search for extraterrestrial intelligence (SETI) suggesting that radio telescopes might be capable of detecting signals transmitted over interstellar distances by other technological civilizations. They called particular attention to the λ 21cm (1420-MHz) line of neutral hydrogen, the most abundant element in the universe. Frank Drake reached the same conclusions independently, and in the early spring of 1960, he conducted the first radio SETI observations (Drake 1961). He used a single-channel receiver with a bandwidth of 1 Hz that he tuned over several hundred Hertz of the spectrum in the vicinity of 1420 MHz, while observing two nearby solar-type stars, Tau Ceti, and Epsilon Eridani. Several hundred hours of time on the 85-ft Tatel telescope located at the NRAO in Green Bank, West Virginia were devoted to these observations. This first search was brief; nevertheless, it encountered nearly all of the inherent challenges that have characterized radio SETI projects for the past 45 years. There was no successful detection of an extraterrestrial signal, but signals were detected. These signals were the result of terrestrial technologies and required proactive procedures by the observer in order to discriminate between radio frequency interference and ETI. The signal processing equipment required for SETI observations was different from the traditional equipment used in radio astronomy observations. The amount of exploration possible in the finite amount of observing time available

on the telescope was far less than required for a systematic search, and forced the adoption of certain constraining hypotheses to limit the scope of the exploration to match the time available.

2. Interstellar Water

In 1968, when Jack Welch, Charles Townes and student Al Cheung discovered the first polyatomic molecules of interstellar ammonia and then water in 1968/69 using the 6-m dish at Hat Creek Radio Observatory (HCRO; Cheung et al. 1969), Jack immediately realized the implications of abundant cosmic water for supporting life on other worlds. The newspaper headlines dealing with this discovery make it clear that the experimenters got this message across to the media, e.g., “*Sound of life in the Universe heard at Hat Creek*” (Redding Record-Searchlight, 1968).

Today NASA’s astrobiology program has been pursuing a strategy of “follow the water” in its search for clues of possible life (past or present) on Mars and the moons of Jupiter and Saturn. Back in 1968, Jack already understood that the ubiquity of water throughout the cosmos meant that the odds were increased for finding life among the stars, and that the universe might well be bio-friendly.

3. Visionary *Cyclops Report*

In the summer of 1971, under the auspices of the American Society for Engineering Education, NASA Ames Research Center and Stanford University sponsored a notable ten week-long summer study. John Billingham from the Life Sciences Division at NASA Ames, and Barney Oliver, then Director of Hewlett Packard Laboratory, were the study leaders. The goal of that study was to design an instrument for the detection of extraterrestrial intelligence. The resulting *Cyclops Report* (Oliver & Billingham 1972) described an array of some 1600 antennas, each 100-m in diameter, and phased up into a single beam (equivalent to a monolithic, clear aperture antenna with a diameter of 4 km). The participants in the summer study suggested that a search of the nearest million solar-type stars (within a distance of ~ 1000 light years) should commence with one 100-m antenna, and be repeated with increasing sensitivity by adding antennas to the array. The final size of the array was determined by the arbitrary requirement to be able to detect a 10^9 W equivalent radiated isotropic power (EIRP) beacon from the most distant of the stellar targets. Such a deliberate beacon was something the participants expected from a technologically advanced civilization. Note that today: (1) our most powerful transmitter, the Arecibo radar, produces 2×10^{13} W (EIRP) but only into a narrow, high-gain beam; (2) low-power (~ 1 W EIRP) cell phones (unknown to the study participants) are nearly ubiquitous isotropic radiators; and (3) we operate no intentional beacons for interstellar communication (though many of our directed, terrestrial broadcast signals do leak off the planet and advertise our presence with modest power $\sim 10^5$ W (EIRP)). The *Cyclops Report* was extraordinarily well written (e.g., the chapters on signal detection theory are still excellent teaching tools), and was aggressively persuasive. One of its more compelling messages, at least to me when I was a graduate student at the time, was that—after thousands

of generations of humans seeking answers from priests and philosophers to the ancient question: “Are we alone?”—the technology of the second-half of the twentieth century finally provided the current generation of humans at least one opportunity to pursue an observationally based, scientific answer.

4. SERENDIP

The *Cyclops Report* was widely circulated, and read by many astronomers. Thus, it wasn’t very surprising that in 1975 Jack agreed, as HCRO Director, to let Stuart Bowyer, a fellow faculty member and X-ray astronomer, use the 85-ft antenna at Hat Creek to search for evidence of extraterrestrial intelligence. Bowyer’s innovative plan called for a “piggyback” (or commensal) observing protocol wherein data being collected by radio astronomers using the 85-ft could also be analyzed by separate SETI signal processing equipment in an attempt to uncover technological artifacts buried in the cosmic noise being gathered for other scientific analyses. Such commensal observing programs are possible because a radio telescope samples the wavefront (both amplitude and phase) of the incoming electromagnetic radiation, and thus multiple copies of the data can be created. Berkeley faculty and colleagues were using the 85-ft to study high velocity clouds of hydrogen, the structure of the magnetic field in the Milky Way Galaxy and active galactic nuclei with VLBI. Bowyer reasoned that by trading control over the pointing directions and frequency tunings of the 85-ft in return for continuous access to the sky, a serendipitous discovery of a distant technology might result during a more or less random (from the point of view of SETI observers) survey of the sky.

Jack’s support for this first SERENDIP (Search for Extraterrestrial Radio Emission from nearby Developed Intelligent Populations) project at Hat Creek extended to donations of old equipment, technical advice and his services as a pilot. Jack donated a mothballed PAR autocorrelator with 100 channels of spectral resolution from the Radio Astronomy Lab (RAL), and Bowyer obtained a (by then obsolete) PDP-8/S mini-computer from the Astronomy Department. It was this donated computer that started the author down the SETI path (as a first year graduate student I had learned to program the PDP-8/S in octal). Having done a theoretical thesis with Joe Silk, I had never taken a class in radio astronomy, so it was only after Bowyer recruited me to help with SETI that I met Jack Welch, the pilot. In an unsuccessful, but memorable attempt to influence Dr. John Billingham, who was by then heading NASA Ames’s newly established Interstellar Communications Study Group, and to win funding for the SERENDIP project, Jack flew Bowyer, Billingham, Mike Lampton (an extremely clever X-ray astronomer) and me to the Hat Creek site in a small airplane rented from a local flying club. The hoped-for funding never materialized, perhaps because we all abandoned John Billingham on the tarmac of the San Jose airport, racing to find bathroom facilities after our return flight. No check for SERENDIP was forthcoming from NASA.

Even without formal funding, SERENDIP slowly took form with encouragement and technical support from Jack and the addition of Gerry Zeitlin to the group. SERENDIP conducted its initial surveys with the 85-ft telescope at Hat Creek (Fig. 1) in 1979, and published its first paper in 1983 (Bowyer et al. 1983).

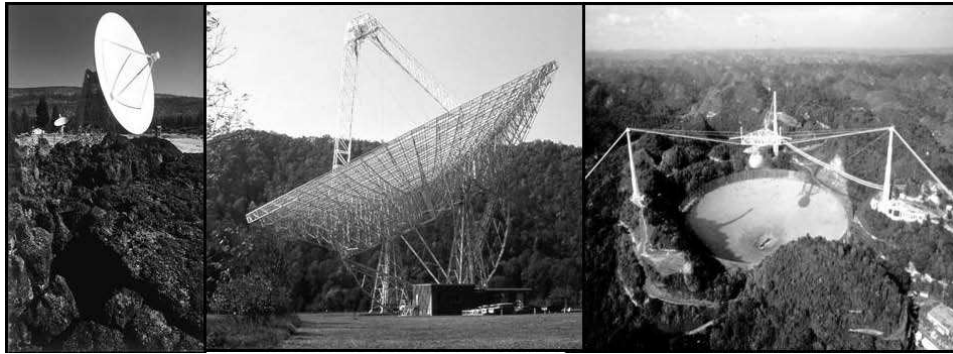


Figure 1. Left panel is a famous Ansel Adams portrait of the 85-ft dish at Hat Creek Radio Observatory, middle panel is the NRAO 300- ft antenna at Green Bank, West Virginia in better days (photo courtesy of NRAO), and right panel is the Arecibo Observatory in Puerto Rico with its upgraded Gregorian system (photo courtesy of Seth Shostak). SERENDIP systems have operated on all these antennas. The first two collapsed catastrophically; I hope that the same fate does not await Arecibo.

Later, SERENDIP spent some time at DSS 14 (NASA's 64-m DSN antenna at Goldstone) performing commensal searches while DSS 14 observed spacecraft. Dan Werthimer joined the team, and SERENDIP began a series of upgrades to versions II (deployed on the NRAO 300-ft antenna until it collapsed), and more recently, versions III, IV and V, at the Arecibo Observatory in Puerto Rico (Fig. 1). Today, SERENDIP V conducts a random sky survey and feeds part of its data to SETI@home, an extremely popular, distributed computing volunteer search effort. As SERENDIP has evolved from its original 100 channels of spectral resolution into the current system with 168 million channels, and as it has improved its sensitivity by migrating from an 85-ft antenna to the 1000-ft Arecibo dish, Jack Welch has remained an active advisor. Experimental and test equipment has traveled freely back and forth between the RAL and the SETI workspace in the Space Sciences Lab, while signal processing solutions viable in one realm have been adopted and adapted into the other.

On 1998 October 14 Jack Welch was named the Watson and Marilyn Alberts Professor for SETI at UC Berkeley in recognition of his continued interest in and support of SETI observations and instrument development, thus becoming the only endowed university chair-holder for SETI on the planet. This appointment was renewed in 2003. Jack thoroughly enjoys any opportunity to share his work with the Alberts (Fig. 2), who are both UCB alumni, and who have also been committed to, and volunteered with, SERENDIP in its later incarnations.

5. Allen Telescope Array

In addition to sponsoring SETI at Hat Creek, Jack has another SETI connection. Since its incorporation in 1984, he has served as a member of the Board of Trustees for the non-profit SETI Institute in Mountain View, CA acting at times as its Vice President. His advice has always been extremely useful to the SETI Institute, providing a thoughtful scientific appraisal that has served



Figure 2. Jack with Watson (R) and Marilyn (L) Alberts at the Jackfest, 2005 September.

to balance enthusiasms for the various schemes necessitated by the obligation to raise private funding to support the SETI enterprise. From 1997 to 1999 Jack was a leading participant in the SETI 2020 (Ekers et al. 2002) workshops that the SETI Institute held to plot a course for the next two decades of SETI research. The goal of the workshops was to reconsider the conclusions of the 1972 *Cyclops Report*, in light of nearly 30 years of technology development and discoveries about the workings of the cosmos. The workshops were attended by long-time SETI proponents, mostly astronomers, physicists and engineers, all of whom were well versed in the details of its signal processing challenges. In addition, a new cadre of younger technologists from the high-riding Silicon Valley were invited to participate, in order to keep a watchful eye out for unwarranted historical baggage during the deliberations, and to help with short-term predictions of technology trends. The SETI 2020 roadmap recommended three SETI endeavors for the next two decades, none of which had been conceived prior to the start of the workshops. The workshop participants suggested that the SETI Institute should: (1) implement its own dedicated SETI radio telescope with 10^4 m^2 of collecting area, constructed as an array of inexpensive dishes (the One Hectare Telescope, or 1hT); (2) take advantage of newly affordable fast photon counters to begin looking for short, broadband optical pulses using university-class $\sim 1\text{-m}$ telescopes (what is now called OSETI); and (3) prototype and build up gradually (as the necessary computational power becomes affordable) a radio fly's eye array capable of monitoring all the sky, all the time, over a significant portion of the microwave spectrum to search for transient SETI signals. These workshops laid the groundwork for a partnership between the SETI Institute and the UC Berkeley RAL and SETI's return to Hat Creek.

When Sandy Weinreb (at that time working at the University of Massachusetts, but now at Caltech/JPL) told the SETI 2020 workshop participants that he believed he could build a single, inexpensive, low noise MMIC amplifier that would work across decades of centimeter bandwidth, Jack Welch rose to the challenge and claimed that he could build a frequency-independent feed to collect all that bandwidth. Given these two innovative ideas, and a bit of empirical economic modeling, the workshop participants soon designed a world-class array consisting of 350 6-m antennas that they felt could be built far less expensively than any previous radio telescope, and could be dedicated to doing *both* traditional radio astronomy and SETI simultaneously. Nearly three decades after the Cyclops array was designed in another workshop, a world-class SETI telescope that was actually feasible and affordable was conceived. The 1hT became a reality and was renamed the Allen Telescope Array when the Paul G. Allen Foundation funded the technology development and early construction phases of the project at HCRO.

A small but powerful team has been working on the ATA since 2000, with John Dreher (who describes the ATA in detail elsewhere in this volume) acting as the first project manager/scientist for the technology development phase, followed by Dave DeBoer as project manager for the construction. The ATA is unquestionably the first of a new generation of cm-wavelength telescopes that both incorporates many novel ideas and strives to make use of COTS (Commercial Off The Shelf) components and commercial manufacturing practices to minimize costs. Jack's signature brown-colored engineering lab notebooks bulge with calculations for the ultrawideband log-periodic feed, comparisons of symmetric and off-axis telescope optics, and the benefits of a large metallic shroud, specifications for impedance matching lenses behind the window of the cryogenic dewar, schemes for antenna calibration, and estimates of heat-exchange through underground conduits. Many other clever individuals worked on these and other design features, but when there were differences of opinion, Jack's designs usually prevailed. This collaborative effort has produced nine separate innovations that have been granted, or are pending, US patents.

The ATA may have begun life as a SETI telescope in the SETI 2020 workshop, but it rapidly evolved into a cutting-edge instrument for multiple, concurrent explorations of the radio sky. A seven-element rapid prototyping array was dedicated in Orinda in 2000 April; the first major funding was granted in 2000 July; the first fringes were obtained on a three-element production test array at Hat Creek in 2002 December; funds for the first phase of construction and concurrently for the NSF-supported correlator were granted in 2003 July; the tent for antenna assembly was erected in January of 2005; and the first wide field image of M31 was made in the summer of 2005 using a prototype 4-element correlator. In 2006 the first 42 antennas of the ATA will begin functioning as an NSF-funded University Radio Observatory producing radio astronomy maps, searching the sky for transient sources, and surveying the inner galactic plane for signals from ETI. After lots of hard work and persistent attention to detail, we now know how to build the ATA, and all the tools to do so are in place and the production line is running. Completion of the 350-element array will be determined by the rate at which funds can be raised. The world is watching all of this activity, because the ATA is also a pathfinder for a proposed future

international facility that is expected to have 100 times the collecting area of the ATA, known as the Square Kilometre Array.

Jack advocated the use of the HCRO site for the ATA, opportunistically inheriting the infrastructure and knowledgeable staff there once the BIMA antennas had moved south to CARMA. Schedule slips meant a period of overlap on the site that taxed both projects, but the ATA is now beginning to reap the rewards of a remote and relatively radio quiet site removed from heavy commercial or military air-traffic routings. For the first time SETI observations will be reliably conducted at frequencies as low as 1 GHz. At a crucial moment, Jack also provided the diplomatic *bon mot* that insured the use of the Hat Creek site. During an environmental scoping hearing, conducted at the observatory by the US Forest Service as part of a required process to modify the use permit for the Federal land, Jack neatly defused some simmering objections to the project. In a pre-meeting conversation with Jack, one gentleman among the dozens of local residents attending the hearing, expressed his disapproval at spending money on SETI and radio astronomy instead of other more earthly requirements, such as feeding starving people in Africa. When it came time for Jack to present the rationale behind the research to be done with the ATA, Jack of course mentioned the expected (and unexpected) discoveries pertaining to the workings of the cosmos, and the potential for ending our cosmic isolation, but for the benefit of the skeptical gentleman, he emphasized that the ATA will provide the opportunity to educate generations of students who will go out to join the workforce of the 21st century, because education is the business of the university. The gentleman remained silent, and the scoping hearing ended in applause and enthusiastic support for the ATA!

We expect that the ATA will have the same sort of revolutionary impact on the field of radio astronomy that the Sloan Digital Sky Survey (SDSS; Loveday 2002) has had on the field of optical astronomy. Optical astronomers use the concept of “etendue,” which is the product of the effective collecting area of the telescope in m^2 and solid angle of subtended on the sky in square degrees, to express the speed at which the universe can be explored, and discoveries made. The SDSS has an etendue of ~ 6 -10, and the next generation of optical survey telescope, the LSST, is aiming for an etendue of ~ 300 . In contrast, the ATA has etendue values ranging from 24,500 to 430 (for the frequency range 0.5 GHz to 11.2 GHz. So if etendue is truly a valid measure of “discovery space,” then the ATA can be characterized as a radio astronomy discovery machine.

The great expansion of SETI search volume with the ATA will also greatly accelerate the pace of SETI searches (see Fig. 3). While there is no guarantee that this will yield a signal from ETI, the wisest statement about predicting success in SETI remains the last sentence of the seminal paper by Cocconi and Morrison: “The probability of success is difficult to estimate, but if we never search, the chance of success is zero.” The ATA is being built to search, and if it succeeds, it will be in no small measure due to the efforts of Jack Welch. Over the decades, the mode of searching has evolved and become significantly more sophisticated since the early SERENDIP observations, but at the core, it retains the commensal strategy pioneered at Hat Creek. The large primary field of view of the small dishes in the ATA array will be shared between the traditional astronomical observations and SETI search systems. The architecture of the ATA electronics permit SETI signal processing equipment to be attached to

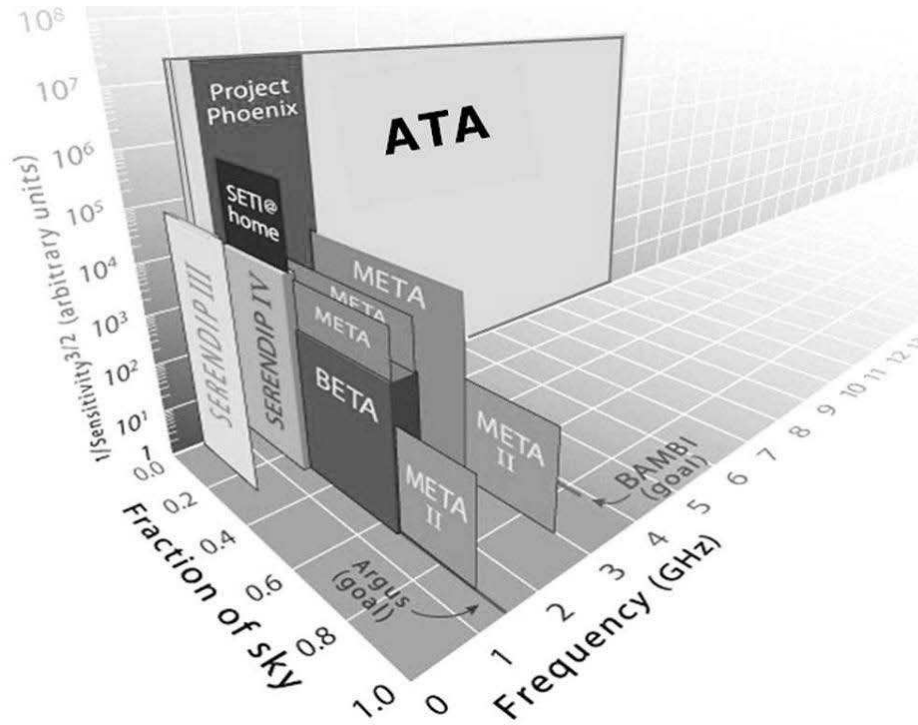


Figure 3. Exploration of the Cosmic Haystack. According to Harwit (1981), the frequency axis for the observable electromagnetic universe should extend from 10^5 Hz (the plasma frequency of the ISM) to 10^{29} Hz (pair production against the cosmic microwave background). The fraction of sky observed by the depicted searches represents two spatial dimensions of the Cosmic Haystack. The third spatial dimension and the unknown signal strength have been combined into the relative sensitivity of the vertical axis. Time, polarization, and modulation schemes have been omitted from this graph. Even so, it is obvious that not much phase space has been explored. The ATA will significantly expand the search volume.

as many as 16 dual-polarization, phased-array beams, whose positions can be selected anywhere within the primary field of view, and whose frequency can be any of two 100-MHz bands selected by SETI observers, and two 100-MHz bands selected by other radio astronomers within the range from 0.5 GHz to 11.2 GHz. Table 1 compares the original SERENDIP capabilities with two versions of SETI systems for the ATA: (1) the current generation of DSP inherited from the previous Phoenix Project at the SETI Institute based on rack-mounted PCs enhanced by two custom signal processing accelerator cards (Backus et al. 2002); and (2) the next generation SonATA system (SETI on the ATA) that is currently being prototyped as a “software only” implementation in a generic PC cluster environment. The table is one attempt at illustrating the enormous improvements in speed and our capacity to conduct SETI searches at Hat Creek, and doesn’t fully elaborate all the ATA innovations that have been built-in to enable this multiple, concurrent observing facility. SETI observations at Hat Creek have been keeping pace with, or outstripping, Moore’s Law ever since Jack Welch and the SERENDIP team entered the field thirty years ago.

Table 1. SETI at the Hat Creek Radio Observatory: THEN and NOW

	SERENDIP on the 85-ft antenna	Prelude SETI System on the ATA-350	SonATA System on the ATA-350
Effective Area (m ²)	264	6137	6137
System Temperature (K)	55	45	45
No. Channels	10 ²	2 × 10 ⁸	2.4 × 10 ⁹
Polarization	Single linear	Dual-circular	Dual-circular
No. IFs × Bandwidth (MHz)	1 × 0.1	3 × 30	16 × 100
Frequency Resolution (Hz)	1000	1	1
Number of Simultaneous Targets	1	3	≤16
Frequency Coverage (GHz)	0.922-0.32 1.415-1.425 1.607-1.617 1.855-1.865 ~5-5.01	1-10	1-10
Sensitivity (W m ⁻²)	5 × 10 ⁻²²	1 × 10 ⁻²⁵	1 × 10 ⁻²⁵

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