Searching for ET with Help from Four Million Volunteers: The SETI@home, SERENDIP, SEVENDIP, ASTROPULSE and SPOCK Seti Programs

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ABSTRACT

We summarize results from three radio and two optical SETI programs based at the University of California, Berkeley.

The ongoing SERENDIP IV sky survey searches for radio signals at the 300 meter Arecibo Observatory. SERENDIP IV uses a 168 million channel spectrum analyzer and a dedicated receiver to take data 24 hours a day, year round. The sky survey covers a 100 MHz band centered at the 21 cm line (1420 MHz) and declinations from -2 to +38 degrees.

SETI@home uses desktop computers of 5 million volunteers to analyze 50 Terabytes of at taken at Arecibo. The SETI@home sky survey is 10 times more sensitive than SERENDIP IV but it covers only a 2.5 MHz band, centered on 1420 MHz. SETI@home searches a much wider parameter space, including 14 octaves of signal bandwidth and 15 octaves of pulse period with Doppler drift corrections from -50 Hz/s to +50 Hz/s. SETI@home is the planet's largest supercomputer, averaging 45 Tflops. SETI@home participants have contributed over a million years of computing time so far.

The SEVENDIP optical pulse search looks for ns time scale pulses at visible wavelengths. It utilizes an automated 30 inch telescope, three ultra fast photo multiplier tubes and a coincidence detector. The target list includes F,G,K and M stars, globular cluster and galaxies.

The SPOCK optical SETI program searches for narrow band continuous signals using spectra taken by Marcy and his colleagues in their planet search at Keck observatory.

The ASTROPULSE project is the first SETI search for μs time scale pulses in the radio spectrum. Because short pulses are dispersed by the interstellar medium, and amount of dispersion is unknown, ASTROPULSE must search through thousands of possible dispersions. Substantial computing power is required to conduct this search, so the project will use volunteers and their personal computers to carry out the computation (using distributed computing similar to SETI@home). The ASTROPULSE software is being tested now, and we hope to begin this search early next year.

1. INTRODUCTION

At the University of California, Berkeley, we are conducting five SETI searches that are roughly orthogonal to each other in search space. These five searches are summarized in table 1.

Program Name	Timescale	Wavelength
SERENDIP	1 s	radio
SETI@home	ms	radio
ASTROPULSE	μs	radio
SEVENDIP	ns	optical
SPOCK	1000 s	optical

Table 1. SETI programs at the University of California, Berkeley

The SERENDIP IV sky survey covers a relatively broad range of radio frequencies, but not as thoroughly as SETI@home. The SETI@home sky survey is more sensitive and examines a much wider variety of signal types than SERENDIP, but only covers a narrow band centered on the 21 cm Hydrogen line (a "magic frequency"). The upcoming ASTROPULSE program is the first search for μs time scale radio pulses. The SEVENDIP optical pulse search is sensitive to low duty cycle ultra-short pulses (eg: pulsed lasers). The optical continuous search is sensitive to narrow band long duty cycle signals (eg: continuous visible lasers).

We describe each of these programs below.

2. OPTICAL SETI

There is no clear wavelength choice for SETI. Microwave, IR and visible wavelengths all have advantages and disadvantages, depending on what factors another civilization chooses to optimize (power, size, bandwidth, and/or beam size). Although optical photons require more energy to generate than radio photons, optical beam sizes are typically much smaller, and directed interstellar communication links can be more efficient[?,?,?].

2.1. SEVENDIP (Search for Extraterrestrial Visible Emissions from Nearby Developed Populations)

The SEVENDIP program at Berkeley searches for nanosecond time scale pulses, perhaps transmitted by a powerful pulsed laser operated by a distant civilization. The target list includes mostly nearby F,G,K and M stars, plus a few globular clusters and galaxies.

The pulse search utilizes Berkeley's 0.8 meter automated telescope at Leuschner observatory and specialized instrumentation to detect short pulses. A similar instrument has been developed at Harvard University[?].

The SEVENDIP instrument uses beam splitters to feed light from the telescope onto three high speed photomultiplier tubes[?]. These tubes have a rise time of 0.7 ns and are sensitive to 300 - 700 nm wavelengths. The three signals are fed to high speed amplifiers, fast discriminators, and a coincidence detector.

Three detectors are needed to reject "false alarms," which can be caused by radioactive decay and scintillation in the PMT glass, cosmic rays, and ion feedback. These false alarms can happen often in a single PMT, but almost never occur in three PMT's simultaneously.

We have built two of these three detector systems; one for our SETI observations at Leuschner Observatory and the other for an optical SETI program at Lick Observatory, directed by Remington Stone.

The Leuschner pulse search has examined 7200 stars so far, each star for one minute or more. The experiment's sensitivity is 1.5 $\times 10^{-17}$ W/m^2 for a 1 ns pulse, which corresponds to 1.5 $\times 10^{-28}$ W/m^2 average power if the pulse duty cycle is one nanosecond every 100 seconds.

2.2. SPOCK (Search for Other Civilizations at Keck)

The other optical SETI program at Berkeley is a search for high duty cycle coherent signals[?]. The optical spectra of 500 stars are searched for narrow "emission lines," with each star observed several times per year. Amy Reines and Geoff Marcy don't use dedicated observing time for this experiment; instead, they mine data taken by Marcy and his colleagues as part of their on-going search for extrasolar planets.

These planet search observations are taken at Lick, Keck, and the Anglo-Australian observatories. Thousands of echelle spectra with a resolution of 0.1 Angstroms are examined for emission lines that are at least 1% more intense than the normal stellar spectral energy distribution, based on previous spectra of the same star. Doppler shifting would move lines in wavelength, permitting this differential comparison approach. This analysis would reveal artificially generated emissions, such as those from a laser beams that are narrower in wavelength than thermally broadened natural emission lines.

3. THE SERENDIP V ARECIBO SKY SURVEY

The SERENDIP SETI program began 26 years ago; it is currently going through its fifth generation of instrumentation and has observed on 14 radio telescopes. During these twenty-six years, SERENDIP's sensitivity has improved by a factor of ten thousand and the number of channels has increased from one hundred to more than four billion[?,?].

The latest SERENDIP sky survey, SERENDIP V, will be commencing in late 2004 and will utilize the National Astronomy and Ionospheric Center's 305 meter radio telescope in Arecibo, Puerto Rico.

The newest iteration on SERENDIP instrumentation will make use of the new multi-beam receiver currently being installed at Arecibo. It will participate in a collaborative three year sky survey systematically covering 25% of the sky, concentrating within the galactic plane. Thereafter, reobservation will help to detect and remove the effects of source scintillaton[?] and short duty cycles, in addition to enabling more robust detection algorithms.

The sky surve will utilize a real-time 4 billion channel FFT spectrum analyzer to search all seven dual-polarization receivers for narrow band radio signals in a 300 MHz band centered at the 21 cm Hydrogen line (1420 MHz). The system has a 1 second integration time, 0.6 Hz resolution, and a sensitivity of 10^{-24} W/m^2.

SERENDIP uses a dedicated flat feed and cryogenic receiver mounted on the carriage house of the Arecibo telescope. The feed provides a single linear polarization with a gain of 3K/Jy and a 0.1 degree beam width.

In addition to observations from the systematic sky survey, SERENDIP can make use of an alternate feed and receiver not used by other researchers. This custom SERENDIP receiver can conduct observations continuously and simultaneously with ongoing astronomy and atmospheric programs. Historically, SERENDIP has collected high quality data from the Arecibo telescope about 65% of the time, covering the sky visible to the telescope in about one year. A source typically stays in the beam between 12 and 24 seconds.

SERENDIP data analysis is described by Cobb, et al[?]. Information on signals whose power exceeds 16 times the mean noise power are logged along with baseline power, telescope coordinates, time and frequency. This data is transmitted to Berkeley in real time; then, radio frequency interference (RFI) rejection algorithms are applied to the data, off-line, at UC Berkeley. After the RFI is rejected, computers search for candidate signals. SERENDIP's candidate detection algorithms are sensitive to several types of signals, which, individually or combined, may trigger an event to be noted for further study. These algorithms test for beam pattern matching, linear drift rates, regularly spaced pulses, multiple frequencies (particularly those periodic in frequency), and coincidence with nearby stars, globular clusters, or extra-solar planetary systems. Every few months, the entire data base is scanned for multiple detections – "signals" that are detected again when the telescope revisits the same sky coordinates. We test how well these multiple detections fit a barycentric reference frame. We also apply another test that allows much higher frequency separation, which is necessary if transmitters are not corrected for their planet's rotation and revolution.

Potential candidates are scored and ranked by the probability of noise causing that particular detection. In cases where multiple detections have been made, a joint probability is assessed. These joint probabilities are used for comparing candidates against each other and generating a prioritized candidate list for re-observation.

SERENDIP systems are also used by our colleagues at the SETI Australia Center[?] and Seti Italia[?].

4. THE SETI@HOME SKY SURVEY

SETI@home data comes from the same piggyback receiver that SERENDIP uses at the Arecibo radio telescope. Whereas SERENDIP analyzes this data primarily using a special-purpose spectrum analyzer and supercomputer located at the telescope, SETI@home records the data, and then distributes the data through the internet to hundreds of thousands of personal computers. This approach provides a tremendous amount of computing power but limits the amount of data that can be handled. Hence SETI@home covers a relatively narrow frequency range (2.5 MHz) but searches for a wider range of signal types, and with improved sensitivity[?,?].

SETI@home was launched on May 17, 1999. SETI@home observations span a total of roughly four years, during which most of the sky is observed three times. In its 4.5 years of operation, SETI@home has attracted 5 million participants. Together the participants have contributed over a million years of computer time, making SETI@home the largest computation ever performed (a total of $2 \cdot 10^{21}$ floating point operations to date). SETI@home is also the largest supercomputer on our planet, currently averaging 69 Teraflops per second. Users are located in 226 countries, and about 50% of the users are from outside the U.S.

Although SETI@home has 1/40 the frequency coverage of SERENDIP IV, its sensitivity is roughly ten times better. The SETI@home search also covers a much richer variety of signal bandwidths, drift rates, and time scales than SERENDIP IV or any other SETI program to date.

Primary data analysis, done using distributed computing, computes power spectra and searches for "candidate" signals such as spikes, gaussians, and pulses. Secondary analysis, done on the project's own computers, rejects RFI and searches for repeated events within the database of candidate signals.

SETI@home covers a 2.5 MHz bandwidth centered at the 1420 MHz Hydrogen line. The 2.5 MHz band is recorded continuously on 35 Gbyte DLT IV tapes with one bit complex sampling. Tapes are mailed to UC Berkeley for analysis; the complete sky survey requires 1100 tapes to record a total of 39 terabytes of data.

SETI@home data tapes from the Arecibo telescope are divided into small "work units" as follows: the 2.5 MHz bandwidth data is first divided into 256 sub-bands; each work unit consists of 107 seconds of data from a given 9,765 Hz sub-band. Work units are then sent over the Internet to the client programs for the primary data analysis.

Because an extraterrestrial civilization's signal has unknown bandwidth and time scale, the client software searches for signals at 15 octave spaced bandwidths ranging from 0.075 Hz to 1220 Hz, and time scales from 0.8 ms to 13.4 seconds. The rest frame of the transmitter is also unknown (it may be on a planet that is rotating and revolving), so extraterrestrial signals are likely to be drifting in frequency with respect to the observatory's topocentric reference frame. Because the reference frame is unknown, the client software examines 14,000 different Doppler acceleration frames of rest (dubbed "chirp rates"), ranging from -50 Hz/sec to +50 Hz/sec.

At each chirp rate, peak searching is done by computing non-overlapping FFTs and their resulting power spectra. FFT lengths range from 8 to 131,072 in 15 octave steps. Peaks greater than 22 times the mean power are recorded and sent back to the SETI@home server for further analysis.

Besides searching for peaks in the multi-spectral-resolution data, SETI@home also searches for signals that match the telescope's Gaussian beam pattern. Gaussian beam fitting is computed at every frequency and every chirp rate at spectral resolutions ranging from 0.6 to 1220 Hz (temporal resolutions from 0.8 ms to 1.7 seconds). The beam fitting algorithm attempts to fit a Gaussian curve at each time and frequency in the multi-resolution spectral data.

Gaussian fits whose power exceeds 3.2 the mean noise power, and whose weighted chi-squared is less than 8.8 are reported by the client software to the server for secondary analysis.

SETI@home also searches for pulsed signals using a Fast Folding Algorithm[?] and an algorithm developed by the SETI Institute to search for three regularly-spaced pulses.

Most of the signals found by the client programs turn out to be terrestrial based radio frequency interference (RFI). We employ a substantial number of algorithms to reject the several types of RFI[?].

After the RFI is rejected, we search the remaining data set for multiple detections in any reference frame, giving higher weights to drifting or pulsed signals, those that repeat in the barycentric frame, that match the antenna beam pattern, or detections coincident with newly detected planets, nearby stars (from the Hipparcos catalog) or globular clusters. A list of the best candidate signals is available at `http://setiathome.berkeley.edu/Candidates/`. We have recently been allocated dedicated telescope time at Arecibo to conduct follow up observations of SETI@home's best candidates.

The SETI@home screen saver program is available for mac, windows and 45 versions of unix. Participants can download the client software at: `http://seti.berkeley.edu`.

In its few months of operation, SETI@home has performed the largest computation in history. While it is not clear if other research projects will have the same mass appeal as does SETI, this clearly shows the viability of distributed computing for other scientific problems.

5. ASTROPULSE

Radio SETI searches to date have concentrated on narrowband signals as opposed to a wideband signals such as a pulses. The ASTROPULSE project is the first SETI search for μs radio pulses. ASTROPULSE will detect pulse widths ranging from 1 μs to 1 ms. Such pulses might come from extraterrestrial civilizations, evaporating black holes, gamma ray bursters, certain supernovae, or pulsars. The ASTROPULSE program will mine the 50 Tbyte SETI@home data archive for serendipitous detections of such events.

One of the unique features of this search is that it is the first pulse search to use coherent de-dispersion in a "blind" fashion - we have no previous knowledge of a specific dispersion measure (DM) to examine. The reason this search has never been attempted before is due to the enormous computing power required. We are able to afford this by implementing a distributed computing scheme, similar to SETI@home.

Radio pulses travelling through the interstellar medium (ISM) become dispersed, or spread out in time. Due to plasma interactions, electromagnetic waves of different frequencies travel at different speeds through the ISM, with higher frequency waves travelling faster. This effect becomes more pronounced for high bandwidth signals, such as pulses. By contrast, narrowband signals will only experience a slight smearing. For frequencies much greater than the plasma frequency of the ISM, dispersion vanishes, and is not an issue in optical SETI. (Pulsed optical SETI doesn't need to take dispersion into account).

Since dispersion is a coherent effect (preserving the phase of the signal), it can be corrected for, and the full strength of the signal can be recovered. The way to do this is to properly phase shift each frequency component in such a way as to make the original pulse line back up in time. This essentially amounts to a convolution by an appropriate chirp function. This needs to be done for each DM to be examined. Even implemented with FFT convolution, the computation will scale roughly as $O(N^2 \log N)$. At our bandwidth of 2.5 MHz, we calculate that to analyze the data in real time would require a computing power of 0.5 TeraFLOPs. The computing problem is eminently parallel in nature. Similar to SETI@home, ASTROPULSE will use volunteers and their personal computers to carry out the computation. ASTROPULSE will use a general purpose distributed computing system we are developing dubbed BOINC (Berkeley Open Infrastructure for Network Computing). The ASTROPULSE and BOINC software are being tested now, and we hope to begin this new search early next year.

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