The Berkeley Radio and Optical SETI Program: SETI@home, SERENDIP, and SEVENDIP

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ABSTRACT

We present results from two radio and two optical SETI programs at the University of California, Berkeley:

The SERENDIP IV sky survey searches for narrow band radio signals at the 305 meter Arecibo Observatory in Puerto Rico. The program uses a 168 million channel spectrum analyser, running in "piggyback" mode, using a dedicated receiver to take data 24 hours a day, year round.

SETI@home is Berkeley's most recent SETI project. SETI@home uses desktop computers of over a million volunteers to analyse 40 Terabytes of data from Arecibo Observatory. SETI@home is the largest supercomputer on the planet, currently averaging 20 Teraflops.

The SEVENDIP optical program searches for nS timescale pulses at visible wavelengths. The target list includes nearby F,G,K and M stars, plus a few globular cluster and galaxies. The pulse search utilizes Berkeley's 30 inch automated telescope at Leuschner Observatory.

Another Berkeley optical SETI program searches for narrow band coherent signals in high resolution stellar spectra taken by Marcy and his colleagues as part of their on-going search for planets at Lick, Keck, and the Anglo-Australian observatories.

1. INTRODUCTION

At the University of California, Berkeley, we are conducting four SETI searches that are roughly orthogonal to each other in search space. 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 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).

All four Berkeley SETI programs are ongoing - 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[7,12,13].

2.1. SEVENDIP I (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 a two detector instrument built for optical SETI in 1997. A similar instrument has been developed at Harvard University[6].

A block diagram of the SEVENDIP I system is shown in Figure 1. The instrument uses a beam splitter to feed light from the telescope onto a pair of high speed photomultiplier tubes. These tubes have a rise time of 0.7 nS and are sensitive to 300 - 650 nm wavelengths. The signals are fed to a pair of high speed amplifiers, a pair of fast discriminators, and a coincidence detector.

Two detectors are needed to reject "false alarms," which can be caused by radio active 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 both PMT's simultaneously.

The pulse search has examined about 700 stars so far, each star for two minutes or more. The experiment's sensitivity is 1.5E-17 W/m^2 for a 1 nS pulse, which corresponds to 1.5E-28 W/m^2 average power if the pulse duty cycle is on one nanosecond every 100 seconds.

2.2. SEVENDIP II

We recently developed an improved instrument to replace the two detector search system[14]. In the new system, the light is split three ways onto three detectors, so that each detector receives 1/3 of the telescope light.

With three detectors, the false alarm rate is reduced substantially. Reduced false alarm rate is important when observing bright stars where the count rates and coincident detections are high.

A two detector system has a false alarm rate given by

$$\mathrm{Rate}_{12} = \mathrm{rate}_1 \cdot \mathrm{rate}_2 \cdot \mathrm{t} \tag{1}$$

where rate_1 and rate_2 are the count rates of the two detectors and t is the pulse width of the detector and electronics (~1 nS).

A three detector system has a false alarm rate given by

$$\mathrm{Rate}_{123} = \mathrm{rate}_1 \cdot \mathrm{rate}_2 \cdot \mathrm{rate}_3 \cdot \mathrm{t}^2 \tag{2}$$

A two detector beam-splitter system needs an average of three photons to detect a coincidence (assuming no losses in the beam splitter and 100% quantum efficiency). A three detector system is less sensitive than a two detector system, needing an average of 5.5 photons for triple coincident detection. However, for dim stars, we use the instrument to detect a coincidence on any pair of the three detectors. In this mode, the system is slightly more sensitive than the two detector system, needing an average of 2.5 detected photons for a double coincidence. We have built a pair of these new three detector systems; one for our seti observations at Leuschner Observatory and the other for a new optical seti program at Lick Observatory, directed by Remington Stone.

2.3. Coherent Optical Search

The other optical SETI program at Berkeley is a search for high duty cycle coherent signals. The optical spectra of 1000 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 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 IV ARECIBO SKY SURVEY

The SERENDIP SETI program began 20 years ago; it has gone through four generations of instrumentation and has observed on 14 radio telescopes. During these twenty 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 one hundred million[15,2].

The latest SERENDIP sky survey, SERENDIP IV, began in September 1998. Observations are ongoing and will be completed in 2003. The survey utilizes the National Astronomy and Ionospheric Center's 305 meter radio telescope in Arecibo, Puerto Rico.

The Serendip IV survey sky coverage to date is shown in Figure 2. The survey will thoroughly cover 25% of the sky (declinations from +3 to +33 degrees) and has moderate coverage from -2 to +3 and +33 to +38 degrees. Each of the one million beams is observed an average of five times during the five year survey. Multiple observations are needed because sources may scintillate[4] or have short duty cycles, and many of our robust detection algorithms require multiple detections.

The sky survey utilizes a real time 168 million channel FFT spectrum analyzer to search for narrow band radio signals in a 100 MHz band centered at the 21 cm Hydrogen line (1420 MHz). The system has a 1.7 second integration time, 0.6 Hz resolution, and a sensitivity of 10^{-24} W/m^2.

SERENDIP IV 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. System temperature is 45K.

Because the feed and receiver are not used by other researchers, SERENDIP can conduct observations continuously and simultaneously with ongoing astronomy and atmospheric programs. Serendip collects 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 IV data analysis is described by Cobb, et al[3]. 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 algorithm's 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, regular 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[10], Seti Italia[8], and Ohio State University[5].

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 analyser 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[1,11].

SETI@home was launched on May 17, 1999. SETI@home observations will span a total of roughly three years, during which most of the sky will be observed three times. In its 1.75 years of operation, SETI@home has attracted 2.5 million participants. Together the participants have contributed over 500,000 years of computer time, making SETI@home the largest computation ever performed (a total of $6 \cdot 10^{20}$ floating point operations to date). SETI@home is also the largest supercomputer on our planet, currently averaging 20 Teraflops. 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 two 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 mSec 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[9] 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[3].

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 Gliese catalog) or globular clusters. We compare candidates signals with SERENDIP IV data, and will follow up interesting candidates with dedicated observations.

The SETI@home screen saver program is available for mac, windows and 45 versions of unix. Particpants 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. ACKNOWLEDGMENTS

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6. FIGURES

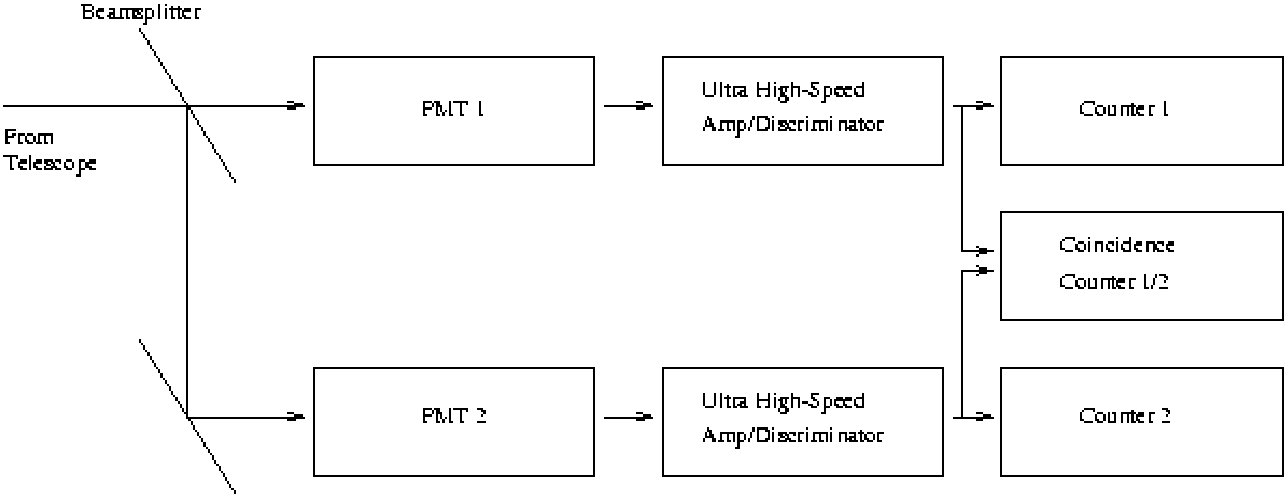

Figure 1. Block Diagram of the SEVENDIP I Optical SETI Pulse Detector. SEVENDIP II uses three detectors in coincidence.

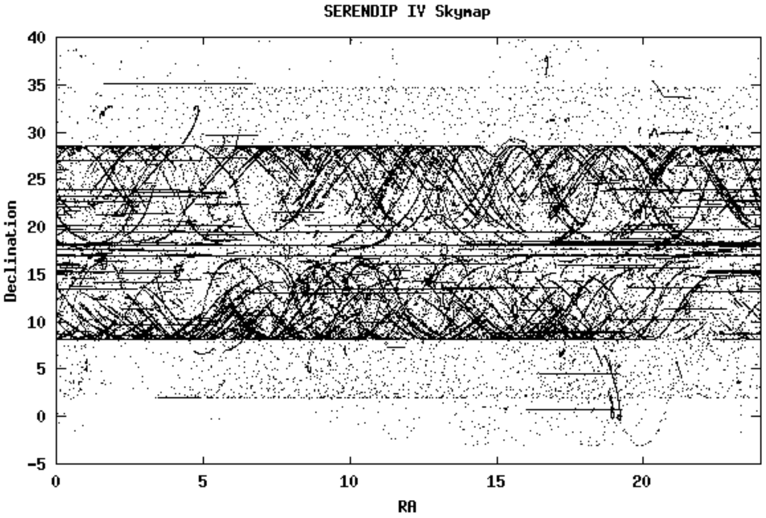

Figure 2. The SERENDIP IV Arecibo Sky Survey - Sky Coverage from September 1998 through October 1999.

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