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FORTY TRILLION SIGNALS FROM SERENDIP: THE BERKELEY SETI PROGRAM

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ABSTRACT The SERENDIP search for extraterrestrial intelligence (SETI) project is a search for narrow band radio signals from extraterrestrial civilizations. SERENDIP is an acronym for the Search for Extraterrestrial Radio Emissions from Nearby Developed Intelligent Populations. The SERENDIP SETI search paradigm is based on a piggyback data acquisition system and an off-line data analysis system. Piggyback observing restricts frequency and pointing control; however, given that no one knows where to look or at what frequency an ETI signal may be broadcast, piggyback observing has high scientific merit. In addition, the plethora of postulated search volume limits systematic SETI searches to relatively small scales. In piggyback mode SERENDIP systems run autonomously acquiring vast quantities of high-quality data at low cost. To date, SERENDIP systems have observed more search volume ($frequency\ coverage \times sky\ coverage \times sensitivity^{-3/2}$) than all previous searches combined.

INTRODUCTION

Figure 1 illustrates the progress of SERENDIP instrumentation systems since the inception of SERENDIP I in the late 1970s. The first piggyback search was conducted in 1975 with the SERENDIP I instrument, a 100 channel autocorrelator with a 100 second integration period and a 1 kHz frequency resolution. SERENDIP I operated at Hat Creek Observatory from 1979 to 1982.

In 1986 the second generation SERENDIP instrument, SERENDIP II, began search operations on the 300 foot telescope at the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia. SERENDIP II incorporated a wholly new design based on a 65,536 point complex fast

Fourier transformation (FFT). SERENDIP II integrated for one second, and had a 1 Hz frequency resolution. With SERENDIP II, the Berkeley SETI team observed almost continuously at NRAO from 1986 to 1988 until the unfortunate collapse of the 300 foot telescope in November of 1988. SERENDIP II analyzed about 3.2 10^{12} spectral bins. The SERENDIP II instrument has since been used by NASA to conduct radio frequency interference (RFI) surveys at selected observing sites for the High Resolution Microwave Survey program. The SERENDIP I and II programs are discussed more fully in Bowyer *et al.* (1993).

OBSERVATIONS

SERENDIP III, the latest SERENDIP system, is currently conducting the first SETI sky survey at 430 MHz using the National Astronomy and Ionosphere Center's radio observatory in Arecibo, Puerto Rico. Arecibo's 1,000 foot aperture makes it the most sensitive radio telescope in the world. On 15 April, 1992 the SERENDIP SETI team began their third large scale search program with the SERENDIP III instrument.

SERENDIP III is a 4 million channel spectrum analyzer with a 1.7 second integration period and a 0.6 Hz frequency resolution (2.5 MHz instantaneous band coverage). In order to cover the receiver's entire 12 MHz intermediate frequency (IF) signal, SERENDIP III mixes the IF with a signal generated by a local oscillator (LO). By stepping the LO signal, SERENDIP III processes the entire IF in 2.4 MHz steps taking about 8.5 seconds to complete a single IF sweep.

SERENDIP III's 0.6 Hz frequency bin size is wide enough to encompass Doppler frequency drifts caused by the Earth's motions (0.1 Hz $\sec^{-1}$ GHz^{-1}) plus reasonable accelerations of the transmitter's reference frame. Signals will not chirp between more than two frequency bins, thus making it unnecessary to guess at which "magic" frames of reference our galactic neighbors are transmitting.

SERENDIP III utilizes an innovative technique to achieve rapid sky coverage and excellent RFI rejection. Figure 2 illustrates the Arecibo feed arrangement. SERENDIP III observes on the 430 MHz line feed system on carriage house one while other radio astronomical programs observe with a high frequency receiver on carriage house two. While the primary observer tracks a target, the 430 MHz receiver (radially opposing the high frequency receiver) slews in the opposite direction across the sky at twice sidereal rate. In this observing mode, a point source can be observed for about 20 seconds, enough time to allow multiple detections of an ET signal.

The rapid slew of the 430 MHz receiver system allows SERENDIP to discriminate between spurious RFI signals, background noise, and ETI signals. Signals that persist over multiple pointings of the telescope beam are later rejected as interference.

Figure 3 shows a sky track in galactic coordinates of a typical three hour observing run. By randomly pointing the 430 MHz feed, SERENDIP

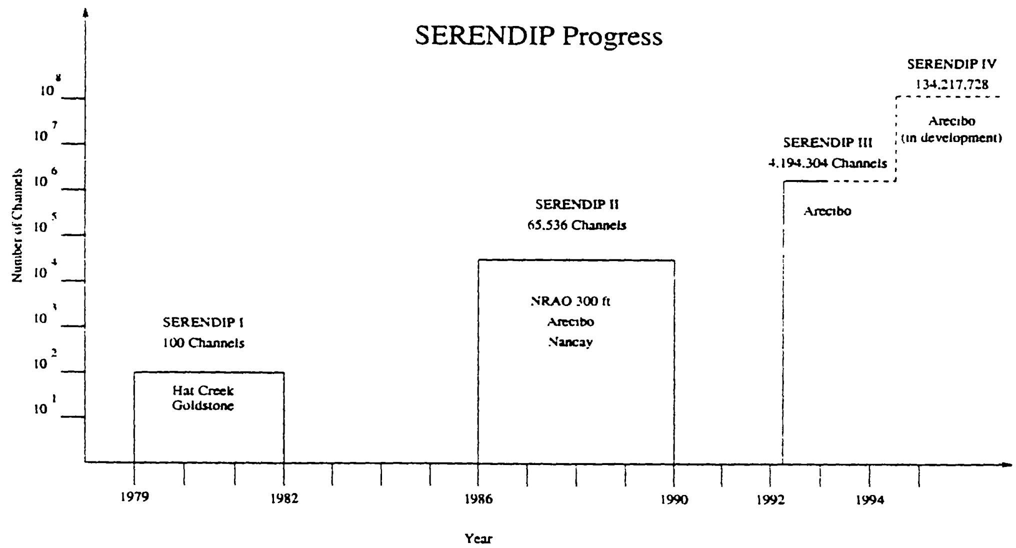

Figure 1: SERENDIP progress. Since the first SERENDIP system was installed at Hat Creek Observatory in 1975, SERENDIP instruments have grown exponentially in the number of channels by a factor of e each year.

observes most of the sky, slowly covering the entire visible sky. To compensate for the effects of interstellar scintillation which can affect signal amplitudes by several orders of magnitude over a time scale of hours (see Cordes *et al.* 1993), SERENDIP plans to observe 50% of the sky at least five times before completeing its current survey near 430 MHz. Table 1 summarizes SERENDIP's sky coverage to date.

Table 1. SERENDIP Sky Coverage as of August, 1993

Percent of Observable Sky	Observed at Least
89%	1 time
71%	2 times
53%	3 times
25%	4 times
18%	5 times

All SERENDIP systems employ real-time signal processing and data acquisition, and off-line data analysis. The off line data analysis is conducted at UC Berkeley. Data are filtered and analyzed for ETI signals. The

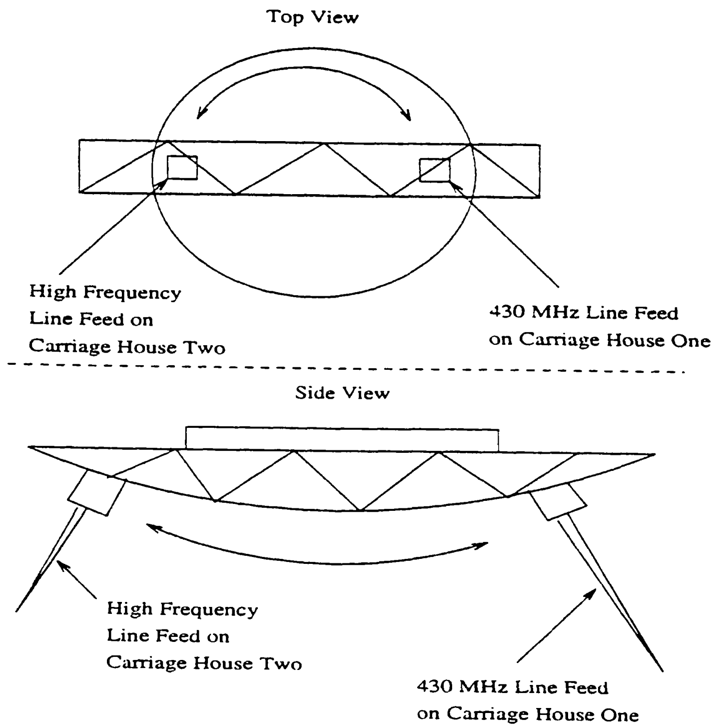

Figure 2: The Arecibo feed arrangement is ideal for piggyback SETI. About 80% of the time astronomers use the high frequency feed system to track objects across the sky. SERENDIP tags along on the 430 MHz feed system slewing across the sky in the opposite direction at twice the sidereal rate.

data analysis system, called SIREN, an acronym for SERENDIP Interference Rejection and ETI Notification, is discussed fully by Donnelly *et al.* , this volume. Instrumentation is described by Werthimer *et al.* , this volume.

RESULTS

In the first 16 months of observing at Arecibo, SERENDIP III surveyed about 90% of the Arecibo visible sky (28% of the whole sky) at a sensitivity of $2\ 10^{-25}$ watts meter^{-2} and analyzed $40\ 10^{13}$ spectral channels in over 4,500 hours of observing. In this time SERENDIP III logged information on over 160 million signals having power above 17 times the mean spectral power. Of the 160 million detections, 99% have been categorized as interference from local or near-space sources. The remaining 1.5 million events have been analyzed by the SIREN system for ETI signals. One hundred and sixty four interesting coordinates have been logged thus far for further investigation.

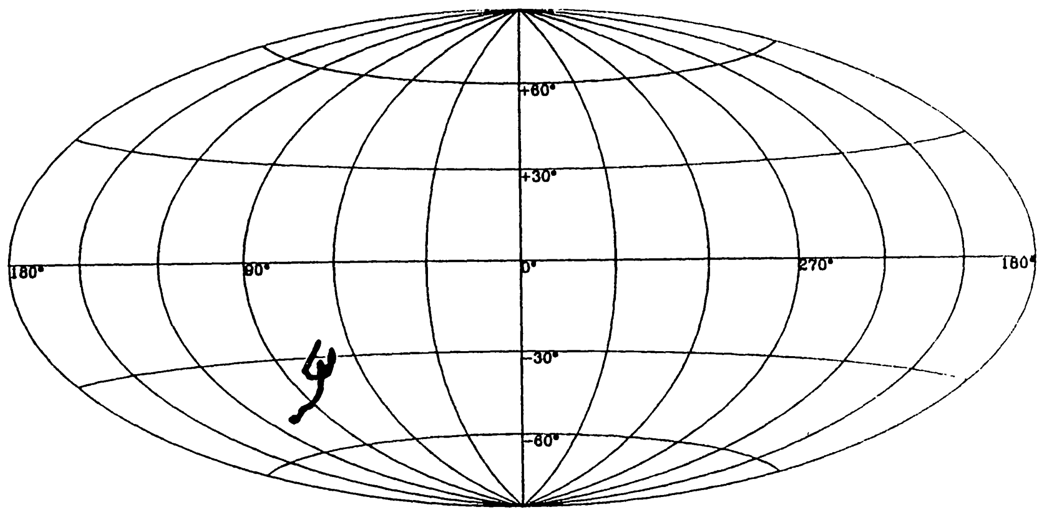

Figure 3: Galactic map of a typical three hour observing run. SERENDIP observes from carriage house one while the scheduled astronomers observe on carriage house two.

Signal selection criteria include: 1) signals with linear frequency drifts over short time scales, 2) point-source signals matching the telescope's characteristic beam profile, and 3) signals that are detected on different days. The current list of 164 candidate signals were all detected under the third selection criterion. Random statistics over spatial and frequency bins for the SERENDIP accumulative data set and selection criteria predict approximately 100 multiple detection candidates. Further investigation however revealed subtle detection clusterings in frequency, which can account for the additional 60 detections. Thus far, no signal has shown beam pattern point source characteristics above the 90% confidence threshold; data are currently being analyzed under the second selection criterion. Figure 4 shows the galactic coordinates of SERENDIP III's first 18 months of sky coverage.

Other SETI groups are using SERENDIP III systems in their search efforts as well. The SERENDIP III design is at the heart of the Harvard Billion channel Extraterrestrial Assay (BETA) system. BETA will replace the current Million channel Extraterrestrial Assay (META) systems now used by Harvard in Massachusetts and Argentina. Ohio State will be bringing a SERENDIP III system on line in mid-1994, and NASA utilized SERENDIP III at Arecibo to study RFI reflection effects off the lunar surface.

Working from the experience and success of SERENDIP III, the SERENDIP development team has completed the design and is building the next generation SERENDIP system, SERENDIP IV. The latter, based on the already proven SERENDIP III technology, will analyze 160 million channels simultaneously, and will execute 200 billion operations each second.

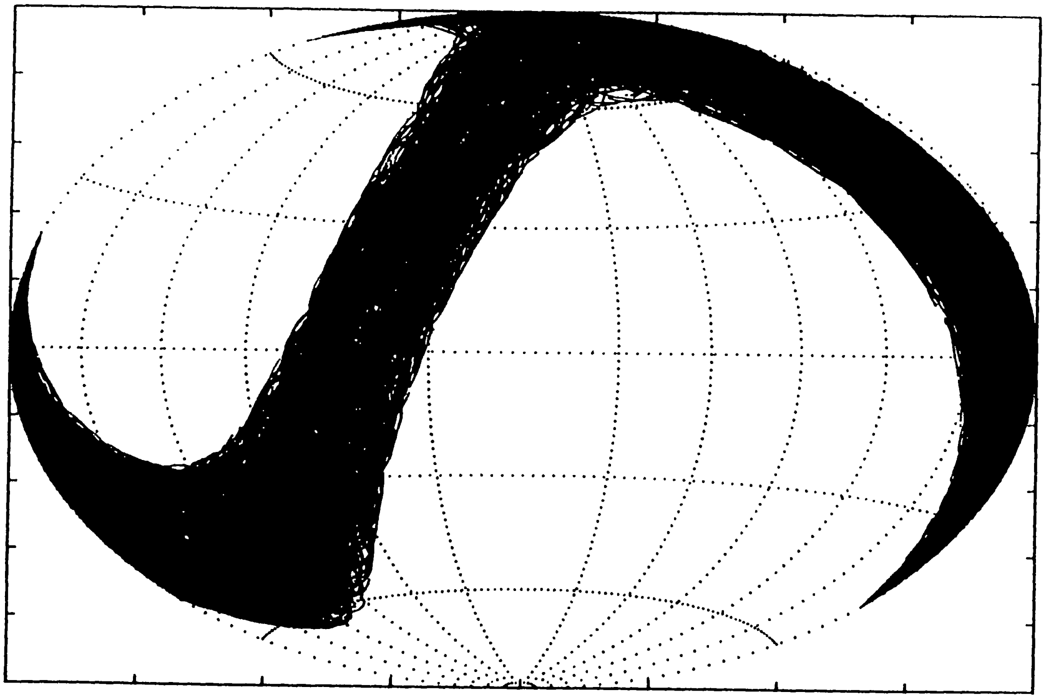

Figure 4: Galactic map of SERENDIP's sky coverage to date. SERENDIP has observed 89% of the sky visible to the Arecibo telescope (-3 to +38° declination).

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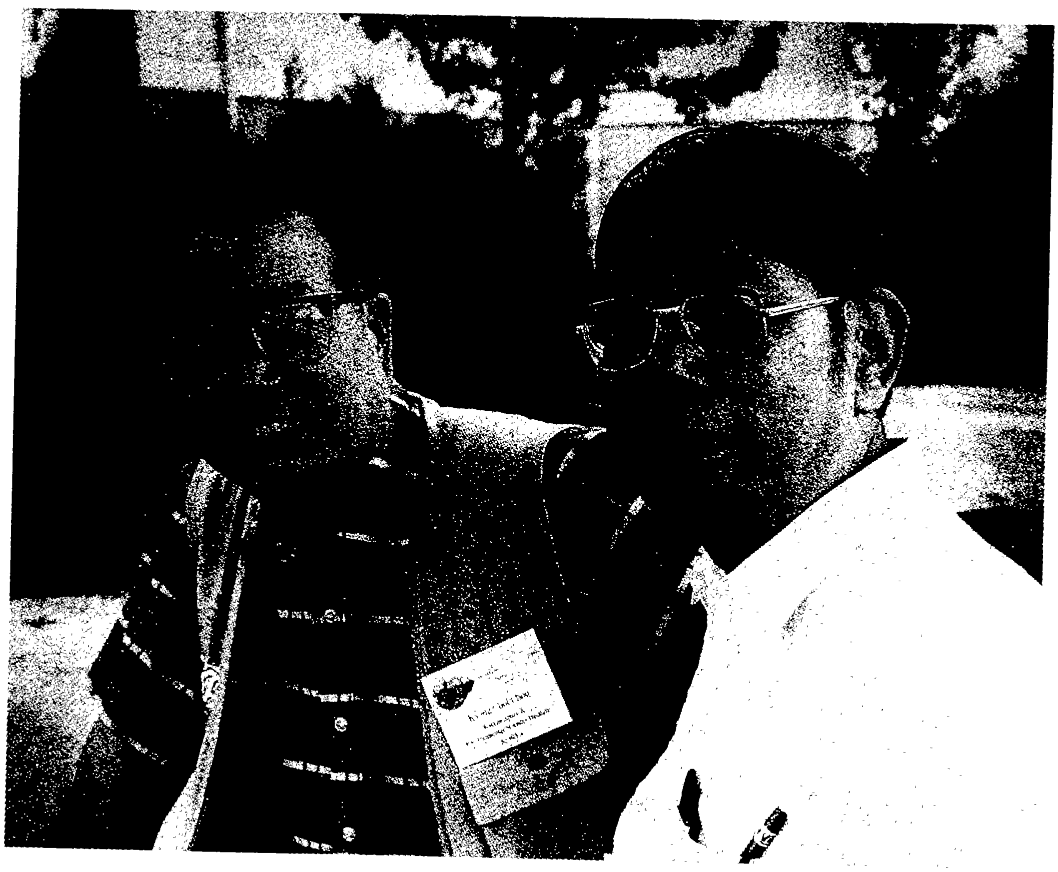
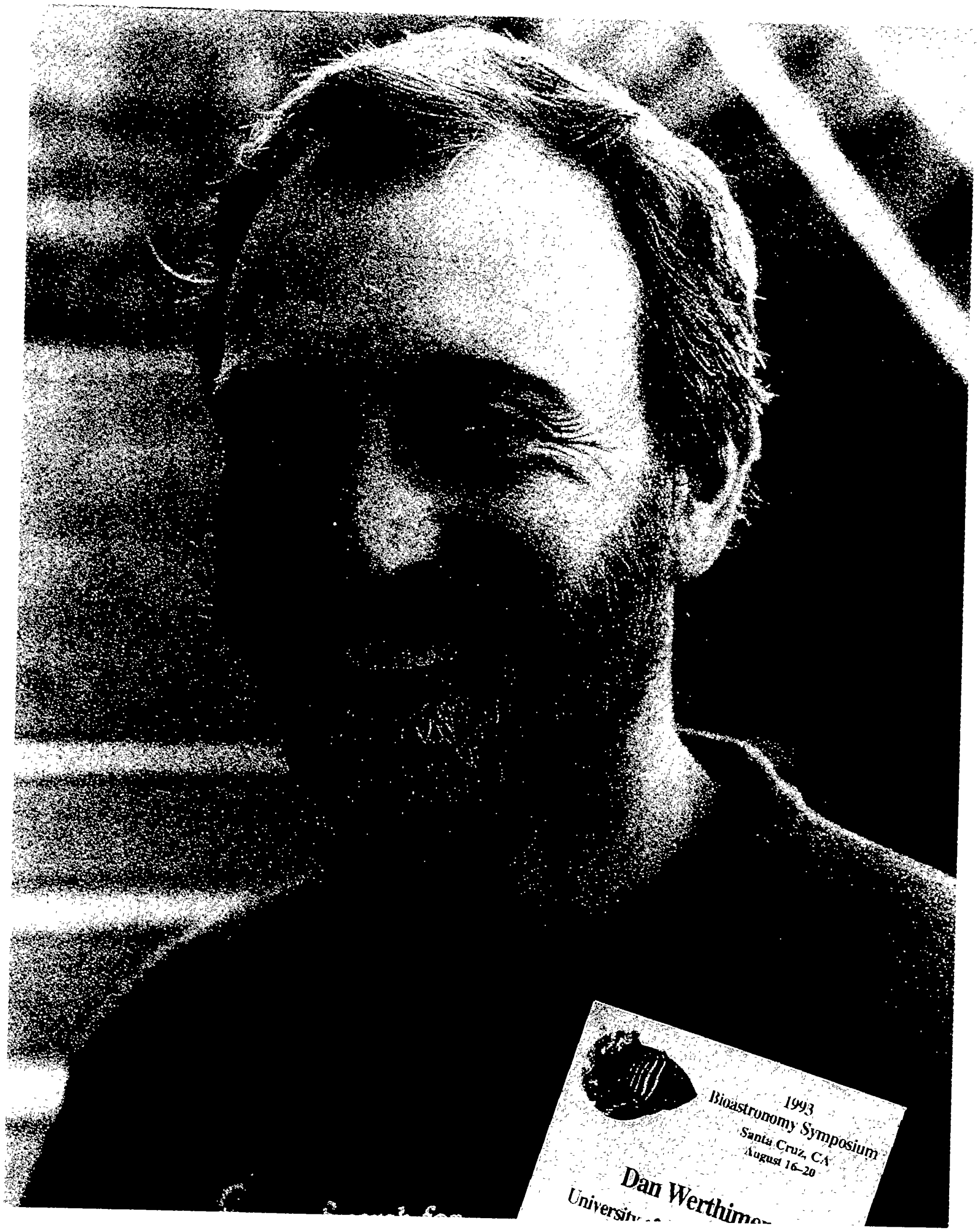


Kyong Chou and Hiromitsu Yokoo enjoy Santa Cruz's intermittent sun.



Dan Werthimer laughs in the face of signal overload.