Objectives and First Results of the NASA SETI Sky Survey Field Tests at Goldstone

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Field tests of SETI prototype hardware and software began in March 1985 at Goldstone. With emphasis on the Sky Survey component of the NASA SETI search strategy, the article describes the survey characteristics, the detection strategy, and preliminary results of system tests.

I. Introduction

The long-range plan (Ref. 1) for the NASA SETI program calls for a systematic search for microwave signals of extraterrestrial intelligent origin. The search will be conducted with existing radio telescopes, state-of-the-art low-noise receiving systems, and special purpose data acquisition and analysis systems. Two complementary search strategies have been adopted (Ref. 2): a Sky Survey of the entire celestial sphere in the 1–10-GHz frequency range and a high sensitivity Targeted Search in the 1–3-GHz range.

The program is currently in a research and development phase that is being jointly carried out by the NASA Ames Research Center (ARC), Moffett Field, CA, and JPL. The two centers are developing detailed plans to begin the full-scale search in the early 1990s.

The near-term plans are to develop prototype instrumentation, search algorithms and observing procedures, and to test the system concepts under observatory conditions. The initial field tests, using prototype hardware and software, began at DSS 13 in March 1985. An aerial view of the site is shown in Fig. 1. This article reports the objectives and preliminary results of the test activities that relate primarily to the Sky Survey component of the NASA search plan.

II. Field Test Instrumentation

The field test instrumentation consisted of a 26-m antenna, low noise receiving systems in the 2200–2290-MHz and 8400–8500-MHz bands, a 65K channel Fast Fourier Transform (FFT) spectrum analyzer, and a prototype spectrum analyzer system designed specifically for SETI. The prototype system consists of a 72K channel digital spectrum analyzer, a VAX 11/750 computer and an interactive graphics terminal. The prototype analyzer, known as the Multichannel Spectrum Analyzer (MCSA), was designed and built at Stanford University (Ref. 3). The FFT spectrum analyzer is a multi-user facility designed and built at JPL (Refs. 4 and 5) and operated by the Deep Space Network. It is housed in a movable van, which is currently parked near the DSS 13 control building for the SETI field tests.

The MCSA and the FFT analyzers were connected to a common receiver output, and both systems were used to detect signals of various strengths from the Voyager 2 and the Pioneer 10, 11, and 12 spacecraft. Modifications were made to the MCSA to implement and test baseline and threshold algorithms in the processors. The MSCA system was also used to test signal detection algorithms that will be used for the Targeted Search. The results of these tests will be reported elsewhere.

A portable spectral surveillance system was installed at DSS 13 for the field tests. This system was designed and built for SETI to enable the SETI team to survey the RFI environment over the frequency range 1–10 GHz. The system consists of a 1-m paraboloidal antenna, an RF amplifier module that can be sequentially tuned over the 1–10-GHz band, a Tektronic swept-frequency spectrum analyzer, a programmable Tektronic controller, and a floppy disk system. The system is designed to operate unattended for several days at a time. It is also portable so that it can be moved to other observatory sites that are candidates for SETI observations.

III. Sky Survey Approach

The emphasis for the Sky Survey is complete sky coverage and expanded frequency coverage relative to the Targeted Search (Refs. 6 and 7). This component of the search strategy will be capable of detecting a class of strong signals, whose location may be unpredictable. We estimate that more than a million solar-like stars lie within a thousand light years of the Earth, and that their density per unit steradian is approximately uniform. Since we do not know how strong a signal might be, it may be true that there is no preferred direction within this volume of stars. A survey of the entire sky insures that all potential life site directions are observed.

To complete a microwave survey of the sky over a wide range of frequencies in a reasonable amount of time, one must scan the antenna at a rate that is considerably faster than, e.g., the sidereal rate. However, rapid scans result in less sensitivity because a signal remains in the antenna beam for only a short time. We have adopted a reasonable survey time (approximately 5–7 years) and frequency coverage (1–10 GHz) and have designed our strategy to achieve maximum sensitivity and spatial uniformity. The characteristics of the Sky Survey are listed in Table 1.

To meet these objectives and requirements, the system design and the observing procedures are selected through an iterative process involving the scan strategy, the signal detection strategy, the limitations of the antenna drive system, and the signal processing algorithms that will recognize and ignore radio frequency interference (Ref. 8). Potential strategies and signal detection concepts are being tested as part of the field test activity.

A. Sky Pixelation

Recognizing that SETI will not be the sole user of the antenna, we decided to subdivide the celestial sphere into elements that can be observed within a few hours and be easily incorporated into a complete sky map with minimum overlap. Figure 2 is a schematic representation of the scan strategy that is currently being tested. The sky is divided into 10- by 60-deg pixels along lines of declination and right ascension. The third dimension in the figure represents the frequency bins of the spectrum analyzer and Sky Survey processor system. The pixels visible to the observatory are mapped by scanning the antenna beam in the boustrophedonic pattern depicted schematically on the frequency element in the foreground. Alternative scan patterns will be considered for parts of the sky where antenna drive rates become excessively high, e.g., near the celestial poles (for equatorially mounted antennas) and near the zenith (for azimuth–elevation systems).

The field test activity includes tests of the scan strategy to evaluate the effect of variations of system temperature with antenna motion, the survey time that is lost during changes in scan direction, and the advantage of comparing signals from adjacent scans. The adjacent scan comparison is an important element in the Sky Survey processor strategy described below.

B. Sky Survey Detection Strategy

In the operational system, the Sky Survey processor will identify and record potential SETI "events" in each of 10-million frequency bins derived from a wideband spectrum analyzer. For the field tests, software modifications in the 65,000-channel FFT analyzer will support quasi-real-time tests of the Sky Survey detection algorithms.

The detection strategy being tested is depicted in Fig. 3. The antenna beam is swept back and forth across the sky pixel. Consecutive scans are separated slightly less than the half power beamwidth (HPBW) as indicated by the two cross-hatched circles. The power of each of the complex points from the spectrum analyzer is accumulated, baselined, and passed through a digital convolutional filter that is programmed to match the antenna response as it sweeps across a point source. The data in each frequency bin are processed and stored in memory just long enough to enable the processor to compare data from adjacent scans. These processing steps are schematically shown by the two panels in the lower left corner of Fig. 3.

Signals in each frequency bin that surpass a preset threshold and that appear at the same location on the sky on at least two adjacent scans are identified as a "SETI event." Signals that pass threshold but fail the SETI event tests (e.g., repeatable, fixed on the sky and exhibiting "reasonable" Doppler frequency drifts) are either saved in the Radio Astronomy data file or designated as RFI and discarded (lower right hand panel in the figure).

Signals that pass the SETI event test are time tagged, the location on the sky is computed, and the relevant information is recorded in a disk file for further analysis. Confirmation observations of events will then be carried out after the pixel observation is completed. Events passing this confirmation will be re-observed at later times and, perhaps, by a different radio astronomy observatory.

IV. Sky Survey Field Tests

The principal objectives of the field test activity are to provide verification of hardware designs, to test and further develop the signal detection strategy described above, to develop automated search procedures, and to characterize the RFI environment at the site over the 1–10-GHz frequency range. In the process, a limited observing program will be conducted from time to time in the 2200–2290-MHz and 8400–8500-MHz frequency bands using the extant receiving systems at DSS 13. These observations are intended to provide end-to-end system tests of the survey hardware, software and search strategy. Results of these tests, which will undoubtedly include RFI, will be compared with theoretical performance characteristics based on Gaussian noise statistics. The observational experience with the Sky Survey system will also stimulate ideas on ways to use the SETI system and/or the data for Radio Astronomy experiments.

The system configuration currently in use for the Sky Survey field tests at DSS 13 is shown in Fig. 4.

A. Pioneers 11 and 12

Among the first of the SETI field tests at DSS 13 was the detection of narrow-band signals from some of NASA's spacecraft. Signals received by the 26-m antenna from Voyager and Pioneer spacecraft were processed by the prototype MCSA and by the DSN FFT analyzer. In Fig. 5 we show the output from the FFT analyzer at three spectral resolutions for Pioneer's 11 and 12.

The upper left panel shows the suppressed carrier and the upper and lower sidebands of the signal from Pioneer 11 (PN11). At its distance from Earth of more than 18 Astronomical Units (AU), the signal is clearly the weaker of the two spacecraft. The resolution is 305 Hz, which is the normal resolution of the FFT running at full speed.

The signal in the upper right panel is from the Pioneer 12 (PN12) spacecraft in orbit around the planet Venus. The resolution of the FFT for this test was 256 Hz. Note that the carrier does not appear at this resolution because it is attenuated by a 300-Hz high-pass filter in the analyzer. Being so much closer to Earth, the PN12 signal is more than 20 dB stronger than that of PN11. The signal levels in the spectra from both spacecraft were calibrated by injecting broadband noise from a thermally controlled test diode. (Note that a narrowband test signal, which also appears in the figure, was used for a different purpose.) The comparison demonstrates the dynamic range of the system.

The lower right panel shows the upper sideband of the PN12 signal at higher resolution. Once again, note that approximately ten resolution elements at the center are lost due to the 300-Hz high-pass filter. This test illustrates the operation of the FFT analyzer at a typical resolution for the Sky Survey.

With the software modifications that were implemented for SETI, the FFT spectrum analyzer is now capable of running at any resolution between 305 Hz and 1 Hz. The PN12 signal was observed at the 1-Hz resolution but is not shown here.

B. Baseline Tests

The design of the Sky Survey processor includes a baseline module that will remove frequency-dependent variations in the system gain by multiplying each frequency bin by the inverse of a baseline value. After each accumulation cycle of the processor, the baseline will be updated by applying an exponentially decaying filter to each of the frequency bins. The baseline algorithm is:

$$S_k(n) = P_k(n)/B_{k-1}(n) \qquad (1)$$

where

$S_k(n)$ = baseline adjusted signal in the nth frequency bin from the kth accumulation

$P_k(n)$ = accumulated signal in the nth frequency bin

$$B_k(n) = (1\text{-alpha})\, B_{k-1}(n) + \text{alpha}\, P_k(n) \qquad (2)$$

Alpha is the exponential factor with a time constant equal to the time required for the beam to sweep through approximately five HPBWs. A range of values for this time constant is being tested to determine the optimum value under field test conditions.

An illustration of this exponentially updated baseline technique is shown in Fig. 6. The effectiveness of the baseline updates can be seen as the accumulation time steps progress from the top spectrum (with no baseline update) to the bottom spectrum (where the baseline has been updated 11 times). For this example, a sinusoidal variation with amplitude 3 dB was imposed on the system gain while the gain in the first 100 frequency bins was increased by 1.5 dB above the average gain of the remaining channels. We note that the effects of these gain variations have been removed from the baseline adjusted spectra by the ninth accumulation time step.

C. Antenna Control Tests

The SETI requirement to drive the antenna at a relatively high angular rate (0.2 deg/s) calls for several tests of the antenna monitor and control subsystems. Antenna dynamics and servo control time constants must be understood in order to avoid the excitation of the normal modes of oscillation of the structure as the antenna is decelerated and accelerated into and out of the turnaround segments of each scan. Not only is it desirable to optimize the turnaround to avoid wasting time, it is extremely important to prevent excessive wear to the antenna drive systems. The accuracy of the antenna pointing system during rapid scanning must be determined.

Software has been written to enter sky mapping patterns in the standard right ascension and declination coordinates. The DSS 13 Station Controller converts these to time steps in azimuth–elevation coordinates. The monitor and control subsystem was also modified to deliver time-tagged antenna position data to a floppy disk recorder; the station was not equipped to monitor and record the position data while the antenna is driven at Sky Survey speeds.

Having overcome some unforeseen problems with the implementation of these tasks, we are about to begin the first of these antenna scanning tests.

D. RFI Survey

The impact of radio frequency interference on the Sky Survey is expected to be significant. One of the objectives of the field tests is to study RFI environment at the DSS 13 site to determine how to minimize the problem with the observational strategy and in the Sky Survey processor. We have begun to conduct a survey of RFI in the 1–10-GHz frequency range at the DSS 13 site. The objectives of the survey are to determine the signal strength and time history of RFI as a function of frequency. With this information we hope to identify ways to work around the problem, for example, by scheduling our SETI observations at troublesome frequencies on weekends, or at certain times of the day, or to avoid certain directions, etc.

The survey is being carried out with the SETI RFI Spectral Surveillance System (SETI RSSS) shown in Fig. 7. The one-meter parabolic antenna shown in the photo is currently located atop the DSN's FFT spectrum analyzer van. The system can be programmed to calibrate the system at any time and scan a specified number of frequency ranges between 1 and 10 GHz at specified azimuths and report signals that exceed a requested threshold. An example of the report from a typical frequency interval is shown in Fig. 8, where five signal components were detected above threshold (–143 dBm) approximately 240 kHz below the center frequency (1722.8 MHz).

The system is being operated to collect preliminary data that will be used to evaluate the SETI relational data base management software.

V. Conclusion

The SETI field test activities reported here are scheduled to continue for at least two years. The test results and observational experience will be used to finalize the design of the SETI Sky Survey processing system and to optimize the observational strategy and procedures in time to begin a full-scale Microwave Observing Program in 1990.

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Table 1. Characteristics of the Sky Survey for a 34-m parabolic antenna

Spatial coverage	All sky
Frequency coverage	1–10 GHz & higher spot bands
Survey duration	5–7 yr (8 h/day)
Dwell time on source	0.5–10 s
Frequency resolution	10–30 Hz
Sensitivity:	$\sim 10^{-23}$ W/m
Spatial uniformity	12% peak-to-peak
Variation with frequency	$\sim f^{1/2}$
Polarization	Simultaneous dual circular
Signal type	Continuous wave (CW)

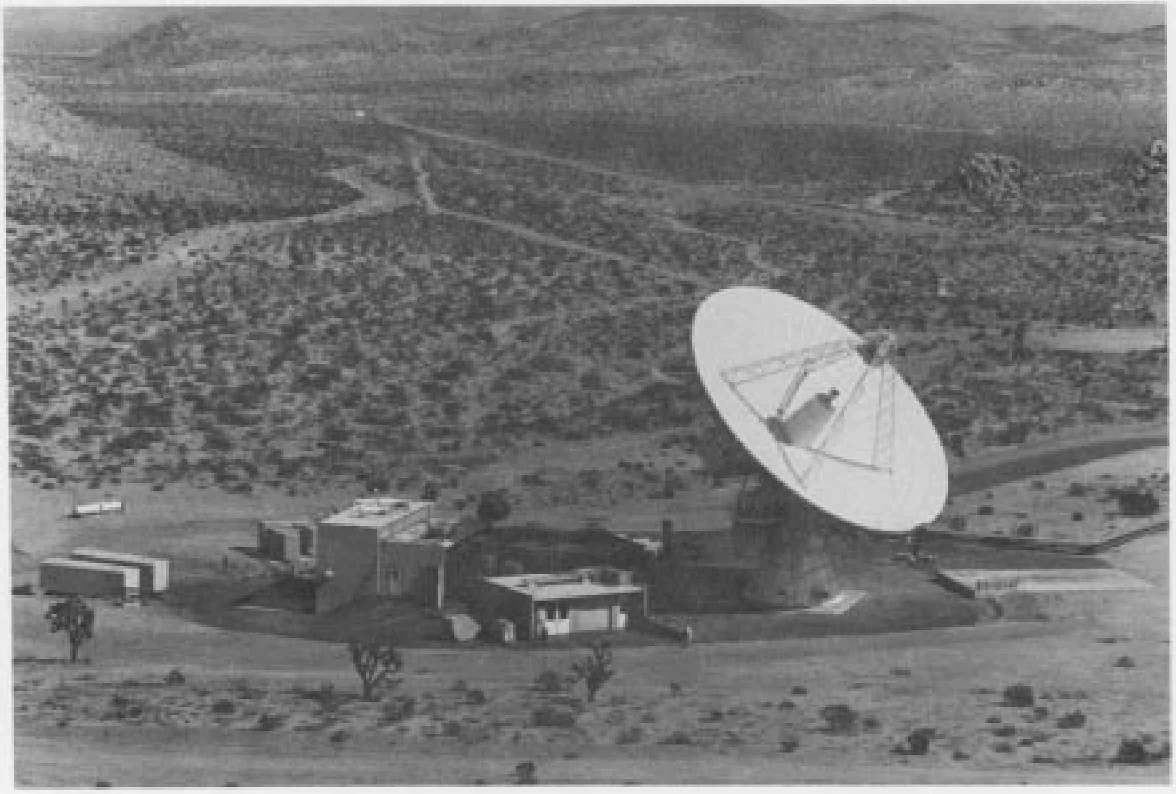

Fig. 1. SETI Sky Survey field tests at DSS 13, 26-m antenna

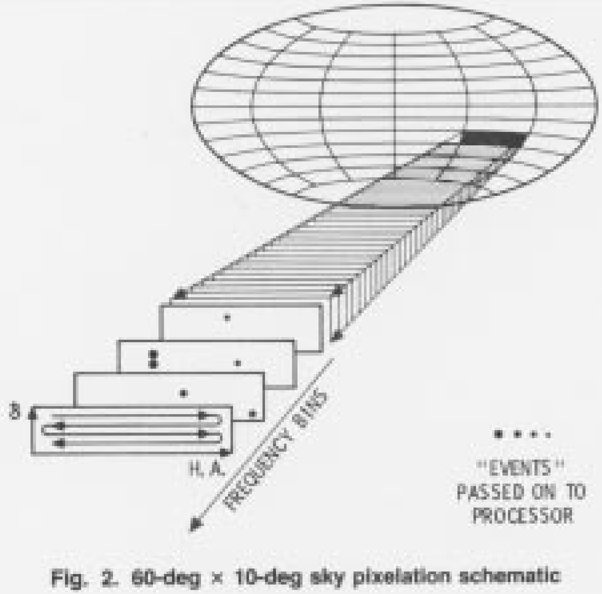

Fig. 2. 60-deg × 10-deg sky pixelation schematic

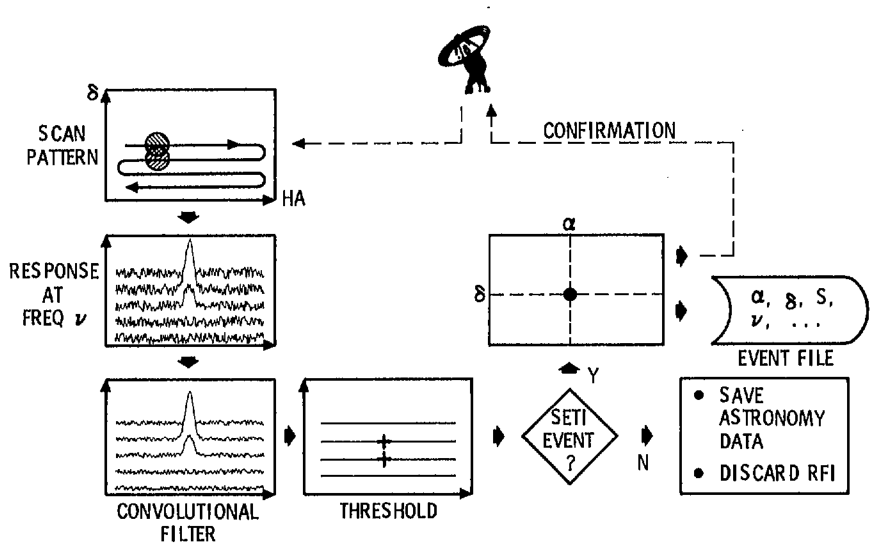

Fig. 3. Sky survey detection strategy

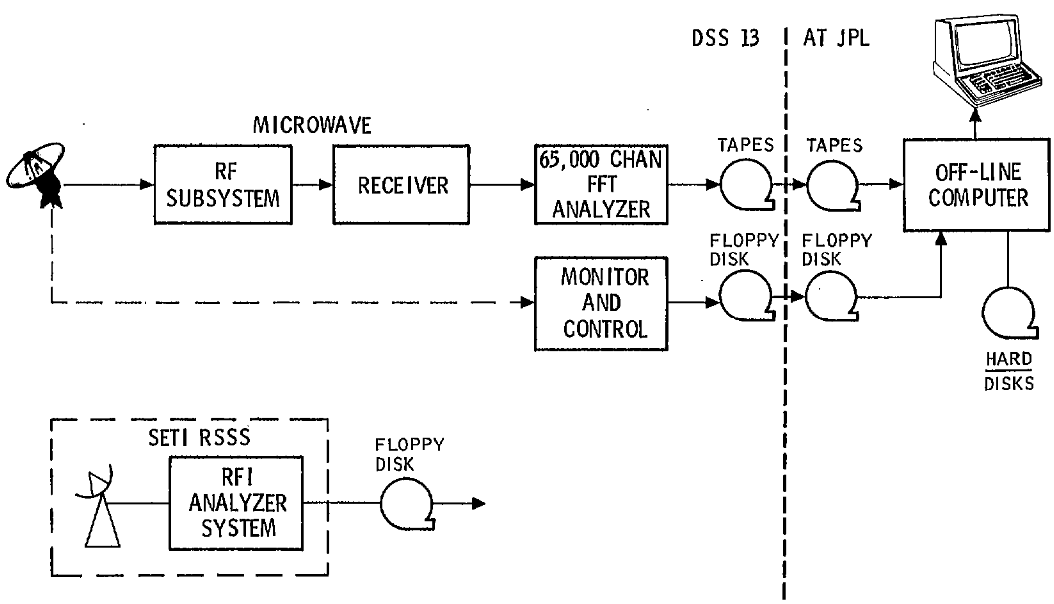

Fig. 4. System configuration for Sky Survey field tests (1985)

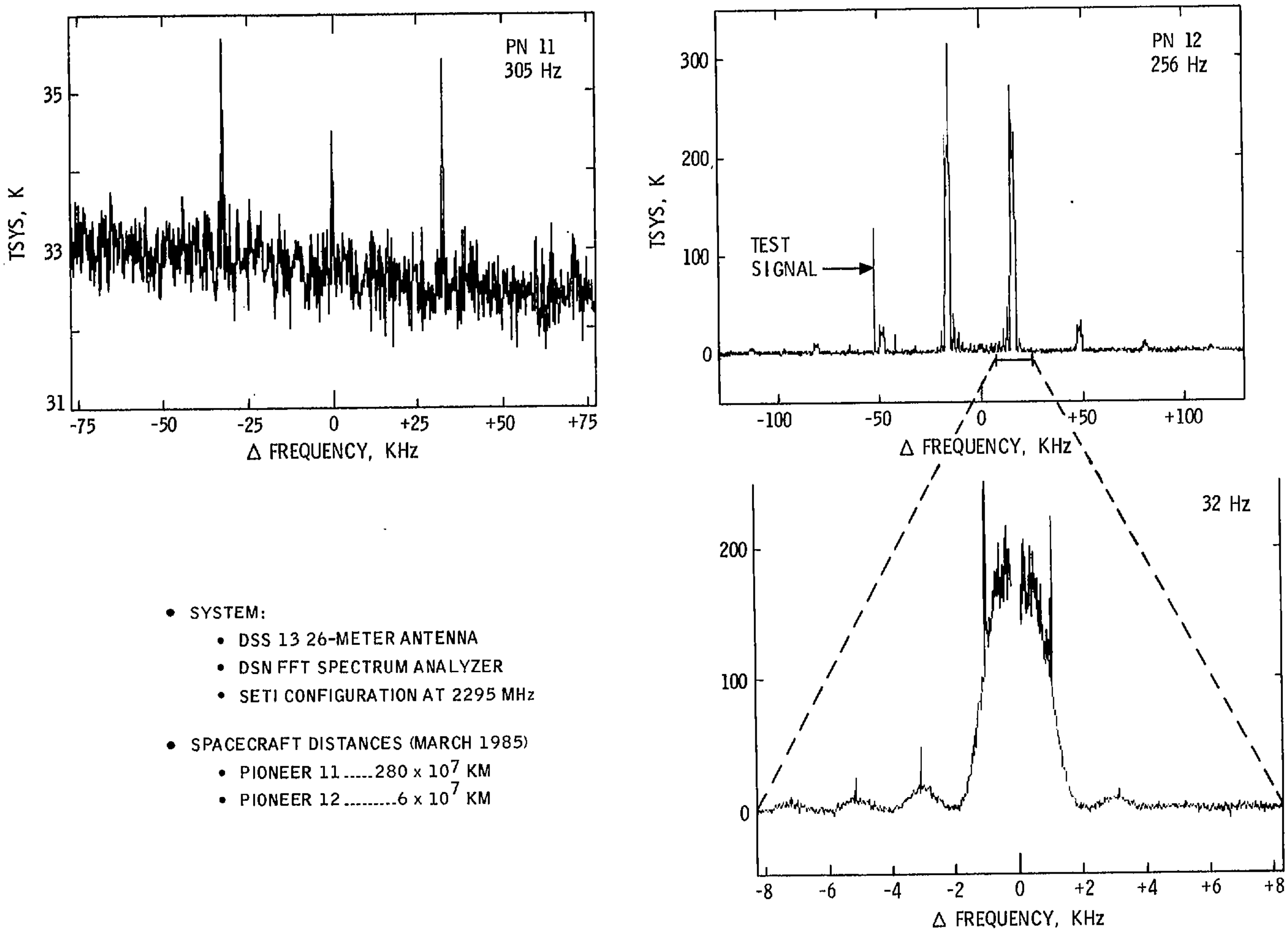

Fig. 5. DSS 13 verification tests using spacecraft signals

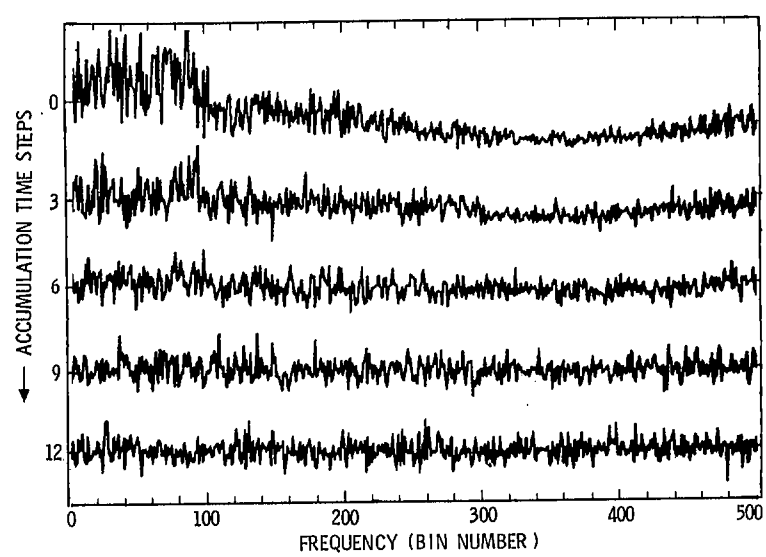

Fig. 6. Exponential baseline update

Fig. 7. SETI RFI spectral surveillance system

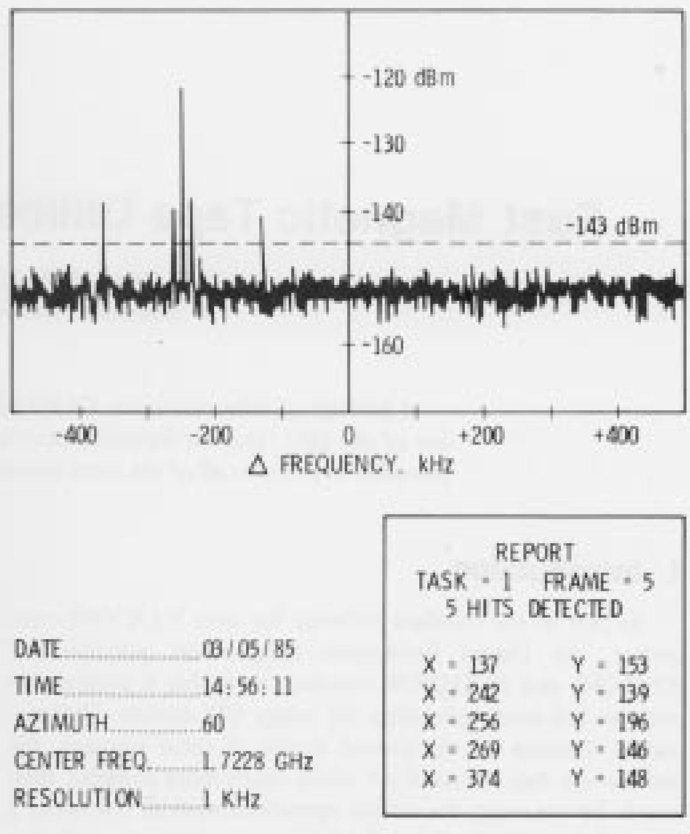

Fig. 8. SETI radio spectrum surveillance system report