AN ANALYSIS OF THE ELEMENTS OF AN ALL SKY SURVEY

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ABSTRACT. One component of the NASA search for microwave signals of extraterrestrial intelligent origin will be an all sky survey at a significantly low limiting flux over a broad frequency range. We are currently designing an overall strategy which will permit this survey to be: (1) carried out using existing antennas in less than 3 years of observation time, (2) uniform in sensitivity (within 0.5 db) over the celestial sphere for any given frequency, and (3) complete to 6×10^{-23} W/m^2 or better over the frequency range $1.2\text{GHz}<\nu<10\text{GHz}$ with a frequency resolution of 32 Hz.

1. THE ANTENNA SCAN STRATEGY

A survey of the entire sky to a uniform limiting flux requires that the main beam of the telescope be scanned at a rate which is independent of its position on the celestial sphere but varies inversely as the square of the system temperature. Our signal confirmation and RFI rejection strategy requires that the scans be of moderate length and that successive scans be adjacent to one another. It is therefore necessary to break up the celestial sphere into smaller areas which can be mapped over the course of one to four hours. Efficient utilization of the antenna requires that the turnaround time at the end of each scan be a small fraction of the time taken to complete the scan, and that the sky areas observed over a period of time must be easily pieced together with minimum overlap to cover the celestial sphere.

Figure 1 is a schematic representation of one scan strategy for an alt-azimuth antenna mount which satisfies these requirements. The sky areas visible to the observatory are mapped by scanning the beam along lines of constant declination near transit. The maximum rate at which the antenna may be driven places an upper bound to the declination range at which this strategy may be employed and still yield a uniformly sensitivity survey, since the required azimuth rate for this strategy varies inversely with the cosine of the declination. A different scan strategy must be employed at higher declinations.

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Antenna dynamics and servo control loops determine the duration of the turnaround period at the end of each scan. Care must be taken not to excite the normal modes of oscillation of the mechanical system. Preliminary tests at Goldstone using the 64m telescope indicate that the minimum turnaround time during high speed scans (rate ≈ 0.2 deg/sec) is approximately one minute. Thus if the turnaround time is required to be less than 20% of the search time, the scan length (width of a sky element) must satisfy the relation:

$$L > 240\,\omega \quad \text{degrees} \tag{1}$$

where ω is the rate in degrees/second at which the antenna beam is swept across the sky. The turnaround time will be utilized for calibration.

2. THE SENSITIVITY OF THE SKY SURVEY

If the number of independent samples included in the accumulation is large, the limiting sensitivity to a constant CW source achieved by accumulating for τ seconds as the antenna beam is swept through its position is:

$$\Phi(t,\tau) = \frac{4\alpha kT}{\pi\eta D^2} \sqrt{b/\tau} \frac{1}{\frac{1}{\tau}\int_t^{t+\tau} G(\psi)\, d\psi} \quad \text{watts/meter}^2 \tag{2}$$

where α is the SNR (signal to noise ratio) for detection, T is the system temperature (K), k is Boltzmann's constant (watt-sec/K), η is the aperture efficiency, D is the diameter of the circular equivalent aperture (meter), b is the spectral resolution (Hz). The effective gain during the integration is represented by the dimensionless function, $G(\psi)$, which is defined here to be unity when the source is centered in the beam. If the antenna beam tracks the source position rather than scans through it, the integral becomes τ and the limiting sensitivity decreases as $1/\sqrt{\tau}$.

The time required to move the antenna beam one HPBW is:

$$\xi = \frac{70c}{\nu D\omega} \quad \text{seconds} \tag{3}$$

where c is the speed of light (m/s), and ν is the frequency at which the survey is being carried out (Hz). The length of time that a source will be in the beam is approximately equal to ξ, but the effective gain will drastically change over that period. We will show in the next section that it is convenient to choose $\tau = \xi/n$, where $2<n<4$.

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If a sky survey is carried out on a 34m telescope with a 25 K system temperature and $\tau = \xi = 1$ second, the sensitivity achieved is $7\times10^{-24}\alpha$ W/m^{-2} to a source which is fortuitously centered in the beam at the midpoint of the accumulation. In the general case there will be more than one accumulation taken in time ξ, and the limiting sensitivity achieved in the sky survey is a function of how the independent accumulations are combined.

Finally, the time required to survey a fraction, g, of the sky at one frequency setting is:

$$T_1 = \frac{70g\pi^2\eta D}{c\varepsilon\langle\omega\rangle} \frac{(1 + \rho)}{\kappa} \quad \text{seconds} \qquad (4)$$

where ε is the beam efficiency, κ is the spacing between scans in HPBWs, and ρ is the ratio of the turnaround time to the average time required to complete a scan. If a survey is carried out on a 34m telescope at 1 GHz with an average scan speed of 0.2 deg/sec, it will require $3.02g(1 + \rho)/\kappa$ days to cover the fraction, g, of the sky. Equations (2) and (4) are more complete descriptions of the sky survey sensitivity and observing time than those first presented by Gulkis, Olsen, and Tarter (1980) in that they take into account the necessarily discreet character of the observations.

3. THE ACCUMULATION STRATEGY

The accumulation strategy must optimize the survey sensitivity while remaining within realistic bounds for data processing resources. An accumulation strategy which convolves each ($b\tau=1$) spectrum with the optimal weighting function derived from the antenna beam shape and scan rate yields uniform sensitivity within a scan and a minimum limiting flux, but the data processing requirements are extreme. For example, matched filter processing of the independent samples spanning γ HPBWs from an N-bin spectrum analyzer operating at b Hz resolution requires $\gamma Nb\xi$ words of memory to hold the data and a like number of store, multiply, add, and compare operations. Representative values for a sky survey might be $\gamma = 3$, $b = 32$, $N = 8\times10^6$, and $\xi = 1$. Thus this approach requires nearly 8×10^8 words of memory and processing power approaching 10^9 floating point operations per second.

The signal processing can be greatly reduced at small loss in sensitivity by abandoning the perfectly matched filter strategy, but care must be taken to ensure that the requirement for uniformity of sensitivity is not violated. Assume a survey in which the beam is swept across the sky at a rate of 1/3 HPBW/sec while the analyzer acquires ($b\tau=1$) spectra at a rate of 32 Hz, and consider the case in which a CW source is fortuitously centered in the beam at the midpoint of a group of independent data samples which span the movement of the beam across an arc of length X_0. How is the sensitivity of the survey affected by reducing the signal processing? We will use as reference the SNR which results from using the perfect matched filter algorithm

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to combine the 288 independent samples taken while the beam sweeps through X_o= 3 HPBW.

One manner in which the signal processing may be reduced is to restrict the number of independent samples which will be combined in the matched filter manner before applying a threshold. If the central 96 samples taken while the beam sweeps through X_o= 1 HPBW are used, the SNR loss is 5% since not much signal is lost by ignoring the contribution from the wings of the response function. If only the central 48 samples taken over X_o= 1/2 HPBW are used, the SNR loss increases to 11%. Even in the latter case the signal processing requirement is large, since 48 separate accumulators must be run for each spectral resolution element. The sensitivity of the survey to the source is uniform along the scan but degraded by 11% for a reduction by a factor of six in signal processing.

The signal processing is significantly reduced if the independent samples are accumulated to form ($b\tau$>1) spectra before combining them in a matched filter sense for thresholding. This reduction is accomplished at some loss in uniformity of the survey sensitivity in a process we call "scalloping". Figure 2 shows the scalloping of the SNR loss as a function of the accumulation time (expressed as a fraction of ξ, the time taken to move the beam through one HPBW) for X_o= 0.6 and 1 HPBW. The best SNR is achieved if the source is on the beam axis at the midpoint of the range of data which are to be combined, and there is almost no loss in SNR even if the accumulation time spans a beam movement equivalent to a full HPBW. The worst SNR results if the source is on the beam axis at a time which is offset from the midpoint by $\tau/2$. In this case, the SNR loss rapidly mounts as τ is increased. The points on the curves correspond to an integral number of accumulations during the time the beam sweeps through X_o. Thus the sensitivity of the survey to a source will vary between these two extremes since its position cannot be known in advance. To achieve less than 12% variation in sensitivity there must be at least two accumulations in the time required to scan through 1 HPBW. The signal processing requirement is reduced by a factor of 144 in this case.

A further reduction in memory and processing requirements may be accomplished by delaying the start of the matched filter analysis until the power detected in a single accumulation crosses a very low threshold. If the threshold is set so that the probability of false alarm due to noise alone is 10^{-3}, a thousandfold decrease in memory and processing may be gained. The scalloping becomes greater since the matched filter might be delayed by one full accumulation interval. This strategy would require four accumulation intervals during the time the beam sweeps through one HPBW to reduce the scalloping to less than 12%.

4. INTERSCAN SCALLOPING AND RFI REJECTION STRATEGY

We have shown that the accumulation strategy must be carefully designed to avoid sensitivity scalloping along a scan. Similar care must be taken to avoid sensitivity scalloping which may arise because

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the source is located between two scan tracks. Lokshin and Olsen (1984) have shown that an interscan separation of 1 HPBW is compatible with the requirement for uniformity if signals detected at low thresholds in neighboring beam areas are combined with equal weights and thresholded again.

An efficient RFI rejection automatically results from this correlation and combination of signals in neighboring beam areas in adjacent scans. The antenna cannot be halted during a scan to confirm a signal detection because the turnaround time is not negligible. The first reobservation to confirm that the signal is fixed on the celestial sphere and is not a momentary burst of RFI is automatically carried out within a period of one to five minutes on the return scan while the detection algorithm is removing the interscan scalloping.

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FIGURES

Figure 1. A schematic representation of a scan strategy for the all sky survey. The sky visible from the observatory is broken into pixels which are mapped by scanning the beam along lines of constant declination near transit. The maximum rate at which the antenna may be driven places an upper bound to the declination range at which this strategy may be employed and still yield a uniform sensitivity survey.

Figure 2. The effect of accumulation strategy upon the uniformity of sensitivity achieved in the all sky survey. The sensitivity to a CW source is a function of the accumulation time (expressed as a fraction of the time taken to move the beam through one HPBW) and the delay between the time that the source is on the beam axis and the midpoint of the data which are combined in a matched filter sense. The best SNR is achieved if the source is on the beam axis at the midpoint of the range of data which are to be combined, and there is almost no loss in SNR even if the accumulation time spans a beam movement equivalent to a full HPBW. The worst SNR results if the source is on the beam axis at a time which is offset from the midpoint by $\tau/2$. The points on the curves correspond to an integral number of accumulations during the time the beam sweeps through X_o.

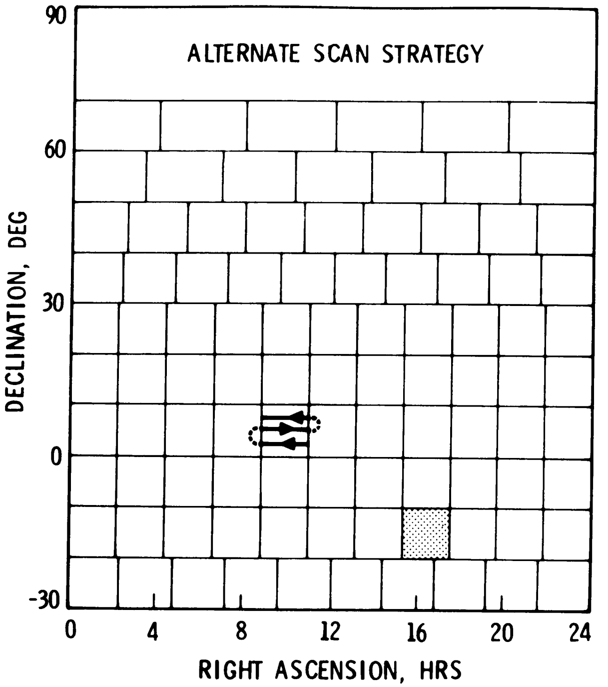

Figure 1

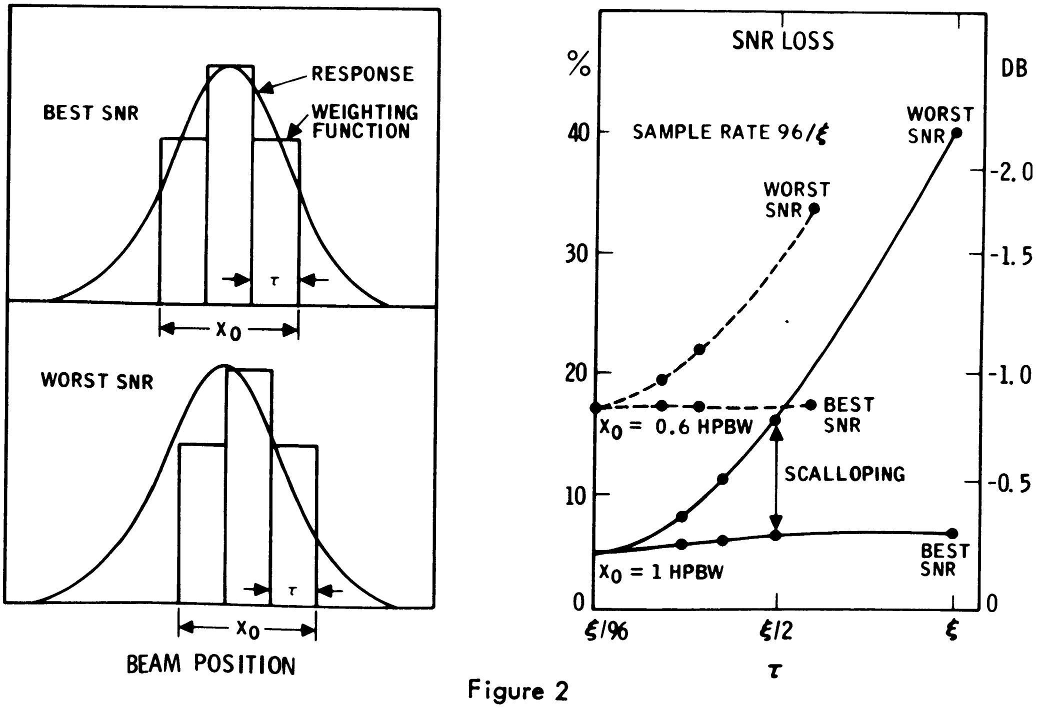

Figure 2

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