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"SIGNAL" SEARCH FOR INTELLIGENCE IN THE GALACTIC NUCLEUS WITH THE ARRAY OF THE LOWLANDS†

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Abstract—In August, 1981, the Westerbork Synthesis Radio Telescope was used for 4 h to search for narrow-band pulsing radio beacons in the direction of the Galactic Center. By using both the spatial discrimination and temporal stability available to an interferometric measurement, weak intermittent signals can be detected even in the face of the strong, naturally caused radiation from this region. A radio beacon within our bandwidth, centered on the 21 cm neutral hydrogen line, would be recognizable if it had a repetition period between 40 sec and 1/2 h. The rms sensitivity to point sources was ~50 mJy/cycle, and the detection limit was 500 mJy/cycle. The limit degrades for pulse widths <0.02ˢ.

No repetitive signals were found. For a swept, narrow-band radio beacon constrained to the Galactic Disk (beamwidth = 0.02 rad), our detection limit corresponds to a transmitter power of 10^{11} MW at the Galactic Center.

1. MOTIVATION

Virtually all SETI experiments to date have used single-dish radio telescopes, either to scan portions of the sky, or to observe nearby solar-type stars. However, single-dish instruments are compromised by lack of resolving power, susceptibility to drifts in receiver noise and interfering signals (RFI). For one particularly interesting region of the Galaxy, the Galactic Center (GC), such limitations are serious, since the strong natural radiation (both line and continuum) in this direction may swamp any artificial signals. One might then preferentially search for modulated transmissions. An unsuccessful search for extremely short radio bursts from the GC (>4 μsec) was conducted in the southern hemisphere by Cole and Ekers[1], but receiver instabilities ruled out the detection of weak signal variations on time scales longer than about 1 sec.

Use of an interferometer, on the other hand, besides discriminating against the spatially extended natural emission, has the enormous advantage of relative insensitivity to gain changes in the receivers, and fringe-average suppression of any signals with nonsidereal motion such as RFI from ground, air-mobile or satellite out-of-band transmissions.

To profit from these observational advantages, we have used the Westerbork Synthesis Radio Telescope (WSRT) to search for periodic signals in the Galactic Center. Authors in [2] have already suggested the GC as a likely site for advanced intelligence, primarily on the basis of the high density of raw materials and the increased probability of a serendipitous discovery of other nearby civilizations. It is conceivable that an extraterrestrial intelligence would install a radio beacon at the GC to initiate contact with other worlds. Such a device could sweep a directed beam across the sky, much as a lighthouse. While the repetition frequency is conjectural, periods of a minute or more are considered reasonable from the standpoint of achieving adequate received signal-to-noise in each "flash," and our own limited experience with construction of rotating platforms in space.

2. OBSERVATIONS

At a declination of −29°, the GC is visible for 4 h a day from Westerbork. Since our intention was not to produce full synthesis maps, which normally require a 12 h observation, but rather to maximize sensitivity to intermittent signals, the restricted hour-angle range only affected the total integration time. The twenty longest interferometer baselines were used, from 1332 to 2700 m, in increments of 72 m, thus discriminating against extended sources. In particular, the ~100 Jy central continuum feature[3] had a typical visibility of only 12 Jy with these baselines.

We chose the frequency of observation to be that of the 21 cm HI line at the Galactic Center of Rest (GCR), as proposed by Dixon and Cole[4]. Two advantages of a Galactic Center search are: i) uncertainties in the sun's circular velocity (~250 km/s) are inconsequential and ii) the local rest frequency for any transmitter on the line

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of sight to the GC will be close to the GCR frequency. Note that in this direction the GCR frequency is nearly identical to the HI line rest frequency.

The 4 h observation was made using a digital cross-correlator backend, with 63 frequency channels equally spaced over a 0.15625 MHz total bandwith (~33 km/s). Spectral solution after processing was 3 kHz. Two noise-independent polarizations were observed, and data were sampled every 20 sec for the longer baselines and every 40 sec for the shorter.

After calibration, the complex visibility data were written to tape and further analyzed as described below using the Groningen Image Processing System[5].

3. DATA ANALYSIS

The data analysis employed was designed to achieve the maximum possible signal-to-noise ratio by both spectral and spatial filtering. The processed output from the telescope consisted of a "data cube," comprising 512 time samples of the complex visibility function for each of the 20 observed baselines and for each of the 63 frequencies. The approximately 717 originally observed time samples ($= 4^h$ at the longer baselines) were reduced to 512 ($= 2^h\ 50^m$) in order to facilitate processing. Data from the second observed polarization were not reduced, but held in reserve for confirmation of suspected signals.

A frequency average of all data was made to establish a mean "continuum visibility," and this was subtracted from each of the frequency channels, thereby removing strong natural continuum signals. This procedure assumes that any artificial signals will have a bandwidth significantly narrower than the total observed bandwidth (0.156 MHz).

A raster of $32 \times 8 = 256$ points on the sky was searched for signal. The size of the raster was $4' \times 4'$, with a spacing of $7.5'' \times 30''$ arc ($\alpha \times \delta$), corresponding in the right ascension direction to the dimensions of the half-power synthesized beam. In declination the beam-width was 36′ arc, and the half-minute spacing was intended to accommodate the slight rotation of the beam as a function of hour angle, ensuring that the elemental search area ($7.5'' \times 30''$) was visible for every time sample. The raster was centered at $\alpha = 17^h\ 42^m\ 29^s$, $\delta = -28°\ 59'\ 19''$[3], and extends 12 pc in right ascension at the distance of the GC.

For every frequency, the 20 visibilities for each time step were Fourier transformed to produce the radio brightness at a given raster point. That is, at each raster point, the radio brightness (as seen by a fan beam) is computed as a function of time, at 20 sec intervals. Thus, for each of the selected directions in our $4' \times 4'$ search box, we produced 512 brightness values, spanning $2^h\ 50^m$ of time. (Note that because of our elongated beam, the search box really extends 36 arcmin NS, albeit with reduced sensitivity because of beam rotation.) While making the transform, we gave equal weight to every baseline (normally they would receive weights proportional to baseline length); this minimizes noise. Note also that the lack of short spacings (apodization) produced a narrow (7.5″ HPBW) fanbeam with high negative sidelobes (~80%). Since this is a detection experiment, beam shape is of little consequence.

Finally, the 512-element brightness vector at each raster point was Fourier transformed in the time domain to produce a power spectrum, constructed from the quadratic sum of the real and imaginary parts of the transform. The spectra were also 512 samples long, and were sensitive to signal variations having periods between 40 sec and one h. A sample spectrum is given in Fig. 1. The spectra were automatically scanned for values significantly greater than the expected system noise, and the latter were printed out for further consideration.

Note that the total search space was $32 \times 8 \times 512 \times 63 = 8\ 10^6$ points for each polarization. This required approximately 35 h computer time, and the reduction was run as a batch job.

4. RESULTS

In Fig. 2 there is plotted a histogram of the measured flux densities for all raster points and all periods, together with an empirically fitted Rayleigh distribution of the form

$$P(S) = P_0 \frac{S}{\sigma^2} e^{-S^2/2\sigma^2}, \tag{1}$$

where S is the flux density averaged over one period.

This is the distribution expected if the visibilities consist only of noise. The value of σ is found to be 62 mJy/cycle. We emphasize that this refers to the signal strength averaged over a complete repetition period and must be corrected for pulse width as discussed below. In Fig. 2 large values having infinite period (i.e. constant over $2^h\ 50^m$) have been omitted. Such narrow-band features are likely to be HI absorption lines. It was the nature of this experiment to search for time-varying features only.

We note that systematic noise in the telescope has caused a slight broadening of the histogram relative to the fitted distribution, but remark that no signal with amplitude >450 mJy was seen. We may thus establish a detection limit of 500 mJy/cycle.

5. PULSE WIDTH AND SENSITIVITY

While SIGNAL is sensitive to pulse patterns with repetition periods of 40^s to ~1/2 h, the level of sensitivity is dependent on the pulse width. This is because the WSRT computes the *average* correlation between antenna pairs over a (20 or 40^s) integration period, and multiplies this by the average system temperature to determine the antenna temperature of the source.

For a pulse width of t_p and an integration time of t, the average correlation is

$$c = \frac{t_p}{t} \frac{T_p}{T_{sys} + T_p}, \tag{2}$$

where T_p is the antenna temperature due to the source while the pulse is on, and T_{sys} is the WSRT system

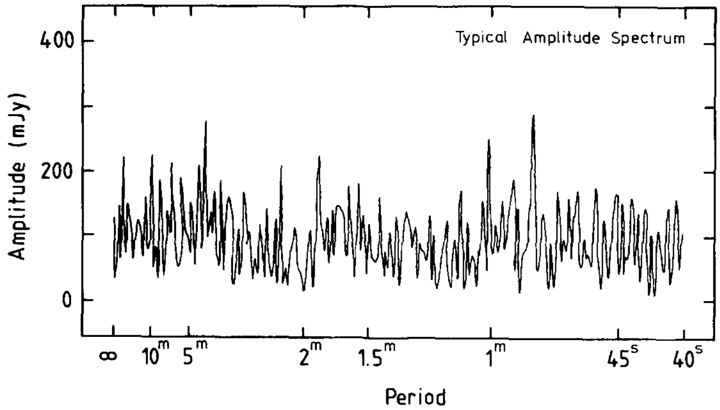

Fig. 1. Typical amplitude spectrum for a given search point; i.e. for a single position and receiver frequency. A repetitive signal would appear as regularly spaced peaks in the spectrum, corresponding to the fundamental repetition period and its harmonics. Note that the temporal resolution decreases with increasing period.

temperature ($T_{sys} = 50\ K$). The measured system temperature is raised by the source pulse to

$$T'_{sys} = T_{sys} + \frac{t_p}{t} T_p. \tag{3}$$

Thus, the derived antenna temperature for a pulse occurring within one integration period is

$$T_A = cT'_{sys} = \frac{\langle T_p \rangle (T_{sys} + \langle T_p \rangle)}{\left(T_{sys} + \frac{t}{t_p} \langle T_p \rangle \right)}, \tag{4}$$

where we express T_A in terms of the mean pulse antenna temperature $\langle T_p \rangle = (t_p/t)\, T_p$. For the WSRT, 10 Jy ~1 K T_A. Note that we have assumed a maximum of one pulse per integration period; a higher repetition rate cannot be resolved with our experiment.

For long pulses, $t_p \sim t$, and consequently $T_A \sim \langle T_p \rangle$, as it should. However, for single short, very bright flashes $t_p \ll t$, and $T_A \sim (t_p/t)\langle T_p \rangle$; in this case the measured signal is only a fraction of the true mean signal.

Our sensitivity in this experiment (Fig. 2) corresponds to a mean amplitude of $\Delta S = 0.5$ Jy. In Fig. 3 we show the degradation in detectable *mean* flux density as a function of pulse width. Clearly, for widths $\leq 0.02^s$, the detection limit becomes substantially more than 0.5 Jy, reaching ~10,000 Jy for millisecond pulses.

One may ask if such short widths are expected. To begin with, our total bandwidth was 156 kHz, so pulses shorter than 1 μsec would be so broad as to be undetectable. Further, intrinsically short pulses will be broadened by passage through ionized gas in the interstellar medium.

Following Manchester and Taylor[5], the expected temporal smearing (dispersion) over a bandwidth $\Delta\nu$ will

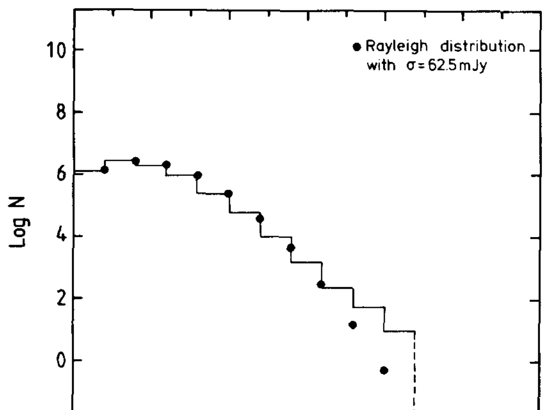

Fig. 2. Histogram distribution of observed amplitudes for all frequencies and positions. The dots correspond to a fitted Rayleigh distribution integrated over intervals of 40 mJy width. The relative excess of observed points for amplitudes >320 mJy is believed due to systematic effects in the instrument, and is not thought to be caused by received signals. A firm lower limit to such signals is 500 mJy.

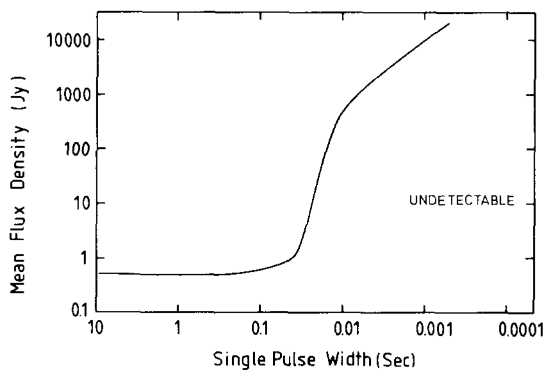

Fig. 3. Degradation of sensitivity with decreasing pulse width. The curve gives the minimum mean detectable flux density (averaged over a repetition period) as a function of the single pulse width. For pulses <0.02 sec duration, sensitivity deteriorates substantially. Scattering by ionized gas probably limits the minimum pulse width from the GC to >0.001 sec. This curve is based on a sample integration time of 20 sec. Note that if the signal consists of repeated short bursts (<20 sec) of pulses, one may still evaluate signal degradation by replacing the single pulse width with the sum of the individual pulse widths.

Table 1. Summary of observational results

Observing frequency:	0 km/s, Galactic Center of Rest (21 cm HI line)
Area Searched:	4′ × 4′ box, centered at = $17^h 42^m 29^s$ = −28° 59′ 19″ (4′ × 36′ at reduced sensitivity)
Bandwidth:	156 kHz
Frequency resolution:	3 kHz
Spatial resolution:	7.5 arcsec EW × 36′ arcmin NS
Number of time samples:	512
Sample integration time:	20 or 40 sec, depending on baseline
Repetition range searched:	40 sec–∼30 min
Minimum pulse width without degradation in sensitivity:	0.02 sec (see Fig. 3)
Sensitivity limit ΔS (mean flux density):	500 mJy
Corresponding power limit ΔP_o:	1.5 10^{-23} W/M^2

be

$$\Delta t \approx 8.3\ 10^{15}\ DM \frac{\Delta \nu}{\nu^3}. \qquad (5)$$

Taking a value for the dispersion measure DM = 300 cm^{-3} pc, and using our channel width $\Delta\nu$ = 3 kHz, we derive $\Delta t \sim 3\ \mu$sec.

More important than dispersion will be scattering by gas off the line of sight to the source. As shown in Ref. [6] (p. 139), the major effect of a scattering screen will be to broaden the pulse by a truncated exponential, having a width $\Delta t \sim \nu^{-4}$. Scaling their 318 MHz data given for the pulsar PSR 1859 + 03 to 1420 MHz yields $\Delta t \sim 0.5$ msec. This pulsar has a dispersion measure similar to that in the direction of the GC.

In conclusion, narrow-band signals originating from the GC should have pulse widths >0.5 msec. Figure 3 shows how our minimum detection sensitivity would be degraded for such short pulses.

6. CONCLUSIONS

From Fig. 2 it is clear that no obviously significant varying signal was found. In Table 1 a summary of this result is given. Note that the minimum detectable power flux for pulses of length >20^s is $\Delta P_0 = \Delta S \Delta \nu$ = 1.5 10^{-23} W M^{-2}.

Some appreciation of the meaning of these limits can be derived from an example. Consider a CW transmitter at the GC with a rotating antenna sweeping in longitude, and with a beam angle α in latitude. Assume that the transmitter has a power P, and spans a bandwidth $\Delta\nu \leq 3$ kHz, our spectral resolution. The received flux density averaged over a complete rotation is

$$\langle S \rangle = \frac{P}{2\ \pi\ \Delta\nu\ R^2\ \alpha}, \qquad (6)$$

where R = 10 kpc is the distance to the GC. If α = 0.02 rad (= 200 pc at the solar radius), ΔS = 500 mJy corresponds to a minimum detectable ΔP >10^{11} MW (EIRP = 2 10^{13} MW). For a rotation period of 5 min, a round beam will have a pulse width t_p = 1 sec. For shorter widths, the value of P must be raised in accordance with Fig. 3.

We note that for pulse widths >0.1 sec, the SIGNAL experiment has a flux density sensitivity approximately 200 times better than the Ohio State All Sky Survey[4], with 7 times finer spectral sensitivity.

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