Acta Astronautica Vol. 9, No. 6-7, pp. 415-419, 1982
Printed in Great Britain.

0094-5765/82/060415-05$03.00/0
Pergamon Press Ltd.

A SYMBIOTIC APPROACH TO SETI† OBSERVATIONS: USE OF MAPS FROM THE WESTERBORK SYNTHESIS RADIO TELESCOPE

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(*Received* 9 *December* 1981)

Abstract—High spatial resolution continuum radio maps produced by the Westerbork Synthesis Radio Telescope (WSRT) of The Netherlands at frequencies near the 21 cm HI line have been examined for anomalous sources of emission coincident with the locations of nearby bright stars. From a total of 542 stellar positions investigated, no candidates for radio stars or ETI signals were discovered to formal limits on the minimum detectable signal ranging from 7.7×10^{-22} W/m^2 to 6.4×10^{-24} W/m^2. This preliminary study has verified that data collected by radio astronomers at large synthesis arrays can profitably be analysed for SETI signals (in a non-interfering manner) provided only that the data are available in the form of a more or less standard two dimensional map format.

1. INTRODUCTION

Aperture synthesis arrays consisting of many individual telescopes routinely produce maps of the radio sky, which offer good spatial resolution (typically 1-3 arcsec) over interestingly large fields of views (typically 1-2 degrees). In those cases where the digital data of the maps are readily accessible, it is possible to search down to the noise level for radio emission at the positions of cataloged nearby stars. Given the distribution of noise and surface density of stars down to a limiting magnitude for the stellar sample, positional coincidences satisfying precise criteria are meaningful even at the 1.5 σ noise level. Such coincidences become candidates for signal identification and can, in some cases, be re-examined using independent maps of the same field observed at other epochs or at other sites. Although the program described here is very non-real-time approach to signal detection and identification, it is relatively immune to many sources of false alarm producing signals which plague single dish SETI observations, and which necessitate real-time signal analysis techniques. Most natural astrophysical sources that are spatially extended and any man-made interfering signals (RFI) are automatically filtered out in a multiplying interferometer. The advantage is thus clear; the synthesis array provides a nearly perfect matched filter for detecting signals which are point sources moving through the sky at the sidereal rate—for example a SETI beacon at a nearby star.

There are several other advantages in the symbiotic use of observations obtained for astronomical purposes. Such a procedure implies an unbiased approach for SETI applications: all the stars within the field are examined without selection criteria other than that responsible for their inclusion in a particular catalog (usually apparent visual magnitude). No extra expenditure in terms of observing time is involved: the data have already been collected and calibrated by the primary observer. The SETI specific results can be obtained for a very minor computational investment.

Two disadvantages must, however, be recognized. By their very nature aperture synthesis observations are completed only after several hours (typically 8-12 hours), which may be a long time compared to the duration and repetition rate of a potentially periodic SETI signal. However, a variable source with sufficient strength ($\sim$ 10-20 σ) will show up in the synthesized map with a characteristic pattern, which differs markedly from that of a non-variable source. To date only previously known sources such as X-ray variables or pulsars (interstellar scintillation) have shown such behavior. Another disadvantage is that most of the available aperture synthesis data are the result of continuum observations with large bandwidths (of order 4-10 MHz). The spectral dilution is a problem for narrowband SETI signals, which may have intrinsic widths of only 1 Hz. This problem is less severe in the case of aperture synthesis line observations using narrower channel bandwidths (typically 5 kHz) which data are now becoming available. However the computational costs of making a SETI search increases linearly with the number of such narrow spectral channels used.

This paper presents the results of analysis of many galactic fields of continuum data taken at frequencies near the 21 cm wavelength of HI with the WSRT of The Netherlands. The analysis was performed on the Leiden University computer system and on the GIPSY

†Search for ExtraTerrestrial Intelligence.

image processing and software system of the Kapteyn Astronomical Laboratory in Groningen. Two separate data reduction procedures were developed to allow "blind" searches of numerous fields at Groningen and more individualized treatment at Leiden. The data fields examined included: (a) galactic fields observed by one of the authors (FPI), as part of his own astronomical research, (b) a selection of fields from the WSRT background survey[1], and (c) a selection of fields stored in the Groningen data base.

2. THE WSRT AND RESULTANT MAPS

Prior to 1979, the WSRT consisted of 12 25 m parabolic antennas arrayed along an East-West line at north latitude 52°50′. Of these antennas, 10 are fixed with separations of 144 m and 2 are movable along a 300 m track to provide a maximum baseline of 1602 m. The movable antennas can be correlated with all 10 fixed antennas to yield 20 simultaneous interferometer baselines[2, 3]. The field of view of the array is limited by the primary beam response pattern of a single 25 m antenna; at 1415 MHz this beam has a 36 arc min half power diameter. The standard maps made with this instrument are usually $1.4° \times 1.4°$ fields and at the maximum spacing the array produces a synthesized antenna pattern with a half power beam which is 24 arc sec (right ascension) $\times$ 24 cosec δ arc sec (declination). The minimum detectable signal for a single 12 hr observation with this array is set by the r.m.s. noise per synthesized beam area and is typically 0.1 mJy $= 4 \times 10^{-24}$ W/m^2 over a 4 MHz bandwidth. Recently two additional 25 m antennas have been added to the array. Their location at a distance of 3 km from the fixed antennas results in a synthesized antenna pattern which is a factor of 2 smaller than the value cited above, but the limiting sensitivity of the instrument has remained approximately the same. The current configuration of 14 antennas is illustrated in Fig. 1.

The WSRT is equipped with receivers at 6 and 50 cm as well as 21 cm. Although some investigators might argue that either of these other frequencies is as likely for a SETI beacon as the "classical" HI frequency, the program reported here did not access any of the available 6 or 50 cm data fields. The primary reason being one of computational economy. The processing overhead described below is only slightly dependent on the number of stars examined within a given field of view. Since the higher frequency data fields are about 3.5 times as small, the number of candidate stars examined drops drastically while the processing time does not. On the other hand, the larger fields at lower frequencies contain many stars but are extremely confused by numerous weak radio sources. At such future time as these symbiotic searches may become incorporated into the map making process itself, the processing required will reflect the actual number of stars examined and the higher frequency fields will then perhaps prove feasible. The lower frequency fields are likely to remain unrewarding due to confusion.

3. SELECTION OF DATA FIELDS AND STARS

The authors pursued this project at two separate institutions in Holland which routinely access WSRT maps in digital format stored on magnetic tape; the Huygens Laboratory at Leiden University and the Kapteyn Laboratory at Groningen University. In almost all cases, a mapped field existed on magnetic tape because an interesting astronomical object at its center had been observed. For a single 12 hr observation, the response of the WSRT array to a point source produces a series of concentric elliptical grating rings spaced at multiples of 10 arc min in right ascension. The stronger the source, the stronger the grating rings and the larger the fractional area of the field thus obscured. From the point of view of SETI, the known astronomical source or sources and their associated grating rings represent unwanted noise, see Fig. 2. These grating rings can be and often are removed by the observer as in Fig. 3. However this process involves careful subtraction of numerous point sources from the raw data or "cleaning" the field by removing Gaussian response patterns from the map itself. This is a tedious and processer intensive procedure which cannot be accomplished as a "blind" or background program and therefore falls outside the possibilities for a symbiotic SETI search except in those cases where the primary observer had already performed these tasks. Thus the first criterion for choosing a map field was that there be no *strong* source(s) within the field or that the field had already been cleaned of these sources by the primary observer. In practice this meant that no fields containing sources strong enough to be in the 3C catalog of radio sources could be considered, except those observed by one of the authors (FPI) and those which constituted the specially prepared set of 96 fields

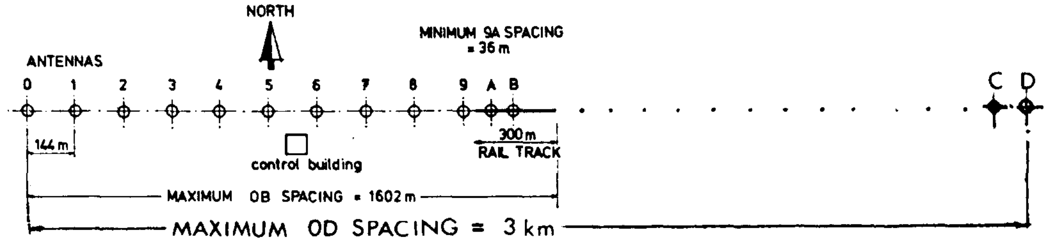

Fig. 1. Antenna configuration of the WSRT

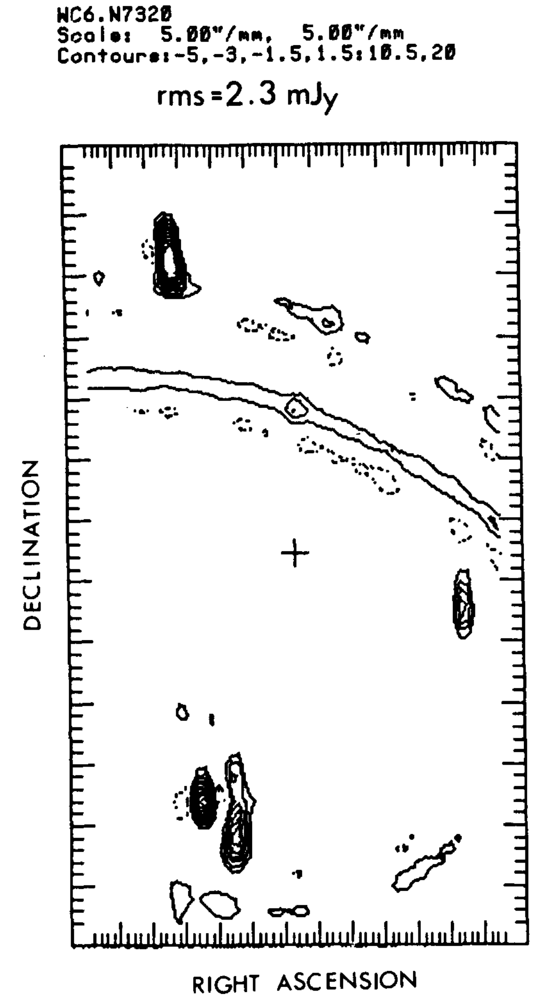

Fig. 2. Portion of field obscured by grating ring response to strong source.

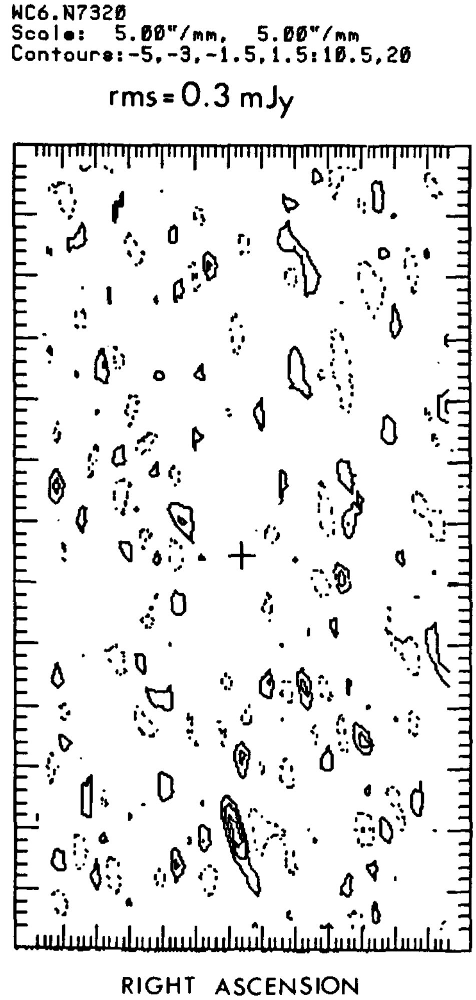

Fig. 3. Same portion of field after source subtraction.

near the north pole used for the Westerbork background survey. The second criterion for choosing a field was at least 8 hr and preferably one or more times 12 hr of observational coverage. This maximized sensitivity and spread or minimized the grating ring responses. Next the field must not be too confused by multiple radio astronomical sources of modest intensity. This could be judged only after the field had been selected and previewed or processed. Thus not all fields originally selected were eventually analysed. Lastly the data fields stored on tape had to be sucessfully readable by the processing system. This was no small consideration as some tapes had been stored in less than ideal environments for many years without being used. This requirement plus the steady increase in instrumental sensitivity limited the fields considered to those fields observed later than 1977 plus the background survey fields. In total there were 34 fields analysed at Groningen and 15 fields (out of possible 35) were analysed at Leiden.

The stars for this program were selected from the 3rd Katalog der Astronomischen Gesellschaft (AGK3) available on machine readable tape at Leiden University. This catalog of bright stars distributed over the northern hemisphere is intended for astrometric reference work and therefore the positions of the stars are very accurately determined with rms errors being ~ 0.15 arc sec. The AGK3 contains about 180,000 stars and is not strictly a magnitude limited sample as the aim was to define a reference system with, on average, 10 stars per square degree. While $m_V = 9$ may be considered a completeness limit, stars as faint as $m_V = 12$ do appear in the catalog. For the purposes of SETI or more general searches for radio stars, the limit on statistically significant coincidence will be set by the pointing accuracy of the array (typically a small fraction of the synthesized beam) rather than by the smaller errors in stellar positions. For any future programs, a catalog of the 2200 stars closest to the Sun (RGO Catalogue of Stars Within 25 Parsecs of the Sun) or a more extensive sample of spectral types with a lower magnitude limit (such as the SAO Catalog containing 258,977 stars brighter than $m_V = 14$) might provide a more meaningful choice of directions to examine in each field. Consistent with the symbiotic, non-interfering approach adopted for this search, we made use of only the stellar data available to the processing systems being used to analyse the maps. The AGK3 catalog was scanned to pick out stars within 1.5° of the chosen field centers. A file of card images was created for use at the Leiden computing facility and actually punched for those fields to be analysed at Groningen. The input lists of stars covered larger areas than were actually analysed in order to allow for unsuspected offsets in the field centers of the chosen maps and for stellar coordinate precession.

4. DATA PROCESSING AND RESULTS

The computational processing at Leiden University was accomplished via batch submissions to the IBM 370. Existing software packages were utilised to transform a file of stellar positions (epoch 1950) obtained from the AGK3 catalog to the epoch of the observation, and to superimpose a plot of these stellar positions onto a selected-contour map of the entire field and to generate oversized plots of the resultant overlay at a scale of 5 arc sec/mm using a CalComp plotter. Plots of fields which were not overly confused were then studied and measured to uncover any meaningful coincidences between stellar positions and nearby contour lines. For all fields, the initial definition of coincidence required only that the candidate feature appear to be an isolated event falling within a quarter power synthesized beam centered on the stellar position and further that the feature not be an obvious part of a grating reing or an extended radio source. All 15 of the Leiden fields analysed to date are either part of the WSRT background survey or from one of the author's (FPI) own research projects, thus they have all been cleaned of strong sources. For these fields, individual computations of the true rms background noise per synthesized beam area were warranted because of the increased sensitivity available due to the extensive processing previously performed by the primary observer. In some few cases the 0.1 mJy levels for a 12 hr observation was realized.

At Groningen University a "blind" approach was followed using the GIPSY image processing system built around a PDP 11/70. In many ways this project underutilized the real-time interactive capabilities of the system in order to mimic the Leiden batch processing and investigate the feasibility of the search technique as a possible non-interfering background process at major map making facilities. Existing software modules were used to build a batch-like self-prompting task which took the stellar positions punched at Leiden as input and output multiple small area contour plots at 5 arc sec/mm scale (one for the immediate vicinity of each star) using a Gould printer/plotter.

The major differences between the Groningen and Leiden procedures were the decision to save time in the interactive Groningen environment by plotting only those portions of the field surrounding the individual stars and the opportunity to save further processing effort by taking a quick look at the field before contour plotting was begun. This eliminated the fields that were too badly confused by responses to multiple moderate sources. In addition, the rms noise level for the Groningen fields was calculated in a standard way for all fields. The entire area of the map within 0.6° of the field center was used for the statistical calculations, thereby including grating rings, central sources and any other anomalies present. The resultant r.m.s. noise level was artificially elevated and did not approach the true sky noise level except in six cases as explained below. This approach best represents the situation to be encountered in any future background processing scheme.

Because of the attenuation across the field of view caused by the primary beam response, we considered only those stars within 0.6° of the true field center, corresponding to the 10 dB point. This produced an average of 10 stellar candidates per field (minimum number = 3, maximum number = 44). For a reduced portion of the map (1.2° square) the r.m.s. fluctuations in the data were calculated and selected contours were plotted for -5, -3, -1.5, 1.5, 2.5, ... 10.5, 20 σ levels referred to this calculated r.m.s. Since the maps used were for the most part uncleaned, the grating ring response to the central astronomical source or sources strongly biases the calculated r.m.s. to a higher value. Indeed in quiet regions of the map the local r.m.s. of the noise background may be many times lower than this calculated value. Confining the search to multiples of the biased r.m.s. represents a loss in sensitivity to signals originating from a star in one of these quiet neighborhoods. This is one of the disadvantages of the "blind" symbiotic approach, but the technique does permit *some* non-zero level of sensitivity to signals contained in data otherwise not used for SETI. To estimate the actual loss in sensitivity relative to that theoretically possible, we have examined repetitive maps produced from the same observational data. For 6 of the 34 fields analysed at Groningen, more than one map was available of the same field. These maps differed only in the number of point sources that the observer had specified to be subtracted from the raw data before the maps were produced (see Figs. 2 and 3). In all such cases the most successful map (as judged by the global r.m.s. value) was analysed to achieve the best possible sensitivity limit. But in addition the noisier map from the unperturbed data was also analysed; the point sources removed by the astronomical observer might have been exactly the ETI signal being sought. In these cases the mean difference in the calculated r.m.s. values, and therefore in the achievable sensitivity, is a factor of 5.1. This agrees roughly with another estimator of the calculated 1.5 σ level significance. For the fields analysed at Groningen, the output contour plots covered an area 40×40 Westerbork grid units centered on the precessed stellar position. From a total of 336 contour plots surrounding that many stars, some 8 of them or 2% failed to show a single contour at the 1.5 σ level or higher. This rate of non-occurrence corresponds to the rate expected if the calculated r.m.s. overestimated the true average of r.m.s. fluctuations of the random noise component in the background and instrumentation by a factor of 3.3. This ratio corresponds to the best estimate of the potential sensitivity loss.

5. CONCLUSIONS

In all the 34 fields and 336 stars examined at Groningen, no case showed evidence for the coincidence between stellar positions and noise peaks or holes $\geq 1.5 \times$ calculated r.m.s. for the field. If beacons were being transmitted by ETI civilizations near the star positions studied during the time that the observations were being made, then we must conclude that they were (a) at another frequency (b) possessed a very low duty cycle (c) were sufficiently distant and/or sufficiently weak as to have fallen below the minimum detectable level for the specific field studied or (d) they were aimed in another direction. Unfortunately such can be the only conclusions from a negative search. With respect to radio stars, we can at least remove the frequency caveat above, and state that none of the stars investigated provides a source of continuum radiation in excess of ~ 0.19 to 19 mJy at 1415 MHz. This is not terribly unexpected given the preponderance of early type stars arising from the catalog choice. For the 15 fields and 206 stars examined at Leiden, exactly the same set of conclusions can be drawn at the 6.4×10^{-24} W/m^2 flux level corresponding to the lowest limit in the Groningen data. But at a slightly lower formal limiting flux available for the Leiden data, 9 coincidences were recorded having a 40% level of statistical confidence at the 1.5 σ limit. One or more of these coincidences may be real, but the statistical approach cannot say which one. Additional fields containing these same stars as well as the remaining 20 fields from the original Leiden set will be analysed during the coming year. A list of stars examined during this search is available from the authors upon request.

6. RECOMMENDATIONS FOR FURTHER STUDIES

What about future attempts at symbiotic interferometric SETI? We feel that this study (not withstanding its current negative results) has demonstrated that a simple SETI software package could be tailored to function transparently on astronomically motivated synthesis maps *at the time that they are being constructed.* We emphasise this latter point because working with the maps while they are still in the processing system will (a) minimize the processing overhead which is dominated by I/O time when trying to access a tape archive (b) allow use of the correct data bits without the chance of I/O errors which increase with the age of the externally stored data (c) provide the best opportunity to channel the SETI specific results to a single responsible individual or group for study and documentation (d) provide a single access point to the relevant data fields rather than attempting to retrieve them at a later date from widely distributed sources (e) provide detailed information about the manipulation imposed upon the raw data during map construction (f) facilitate the process of obtaining consent to make such peripheral use of the data.

Additional considerations with respect to the applicability of this search technique deserve mention. It can only succeed at a facility where an interested individual or group of some permanence can be identified to visually inspect and document the output. Because of the anticipated use of raw maps emerging from a standard pipeline construction process, complete with contaminating grating rings, it is probable that any automated coincidence detector will have a very high false alarm rate. A human must be willing to become part of the loop and visually inspect the output. In such a search, the most extensive stellar catalogs, not necessarily those with the greatest positional accuracy, should be used. This may have implications for a particular facility's rapidly acessible data storage capacity. Even the higher frequencies currently being employed at WSRT and the VLA (Very Large Array in Socorro, New Mexico, U.S.A.) with their correspondingly smaller fields of view may be cost and time effectively searched (or not depending on the existence of a star within the field) if some sort of standard map becomes the norm and the SETI software is used at the time of its construction.

Acknowledgements—This research was sponsored in part by NASA Cooperative Agreement No. NCC 2-36. JCT gratefully acknowledges the warm hospitality of the Kapteyn Laboratory in Groningen and the tireless efforts of R. Scancisi to make clear the puzzles inherent in GIPSY. Stellar positions were obtained from the Huygens Laboratory in Leiden through the kind heart and efficient software of R. Windhorst. A. Tucher provided expert assistance in reviewing and archiving the output results.

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