A VERY LONG BASELINE INTERFEROMETRY SKY SURVEY

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INTRODUCTION

The development of new high-accuracy celestial reference frames composed of compact extragalactic radio sources will permit astrometric and geodetic studies of previously unobtainable accuracy to be performed (Shapiro and Knight, 1970; Counselman, 1975). These studies require the use of the observational technique of very long baseline interferometry (VLBI). Previous investigators have utilized only a relatively small set of detected compact sources in initial experimental development of the technique. In this paper, we discuss a systematic VLBI sky survey which has been undertaken to find a suitable set of compact celestial radio sources from which a more complete VLBI reference frame can be constructed. The results of this survey are presently being used to form a VLBI reference frame of about 100 to 200 sources by determining precise relative positions (Purcell et al., 1979).

SELECTION OF CANDIDATE SOURCES

The survey was conducted by searching known celestial radio sources for compact components by means of VLBI observations. Our baseline lengths were about 7×10^7 RF wavelengths ($\lambda = 13.1$ cm), so the spatial wavelengths being sampled by the interferometer were generally on the order of a few milliarcseconds. Hence, the radio sources detected by this survey have a measurable portion of their total flux density contained in components that are no more than a few milliarcseconds in angular extent. Into this category of radio sources fall certain quasars, BL Lacertae type objects, and galactic cores.

In order to keep from searching all known celestial radio sources for VLBI components, we have used existing information on radio sources as clues to source size. The following criteria proved useful in determining which sources might have structure confined to the milliarcsecond level:

(1) Spectrum – Power does not fall off with increasing frequency as rapidly as more typical radio sources in the range 1 to 10 GHz. An even stronger indicator is if the spectrum is flat, sloped upward, or peaked in this range. Such behavior is typical of the synchrotron self-absorption characteristic of compact sources. Of all the indicators of milliarcsecond

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structure, spectral properties have proved the most useful. In the absence of any other information about a source, we selected sources whose spectral index between 2.7 and 5.0 GHz was $\gtrsim -0.6$ ($S \equiv S_0 f^{\alpha}$).

(2) Variability – Identified as radio or optical variable.

(3) Optical Identification – Identified as extragalactic.

(4) Size Limits – A short baseline interferometer can determine if a source has components smaller than its resolution limit (resolution does not exceed ~1 arcsecond).

(5) Interplanetary Scintillation – Radio sources that show scintillations when viewed through the solar corona possess components with angular sizes $\lesssim 0.1$ arcsecond.

(6) Detection in High Frequency Surveys – A larger percentage of sources detected in surveys between 1 and 10 GHz are VLBI sources than is the case at lower frequencies.

In general, we chose as candidates only those sources whose total flux densities were $\gtrsim 0.7$ Jansky at our observing frequency (2.3 GHz).

To date, about 1000 candidate sources have been observed, with 665 of these being detected with VLBI.

DATA COLLECTION AND REDUCTION

The observations were all performed with pairs of antennas within NASA's Deep Space Network (DSN) which were separated by intercontinental distances. In practice, this meant observing on the Goldstone-Australia or Goldstone-Spain baselines. All the observations were performed at 2290 MHz. The data were recorded on the Mark II VLBI recording system, which preserved a 1.8 MHz data bandwidth by digitally sampling at a 4-Mbs rate (Clark, 1973).

Matching tapes from the two antennas were cross-correlated on a special hardware/software computer at the National Radio Astronomy Observatory in Charlottesville, Virginia. Computer manipulation of the output of this correlator yielded the correlation constant, ρ, for each observation, or the fraction of bits on the two tapes that were correlated. Correlation constants were then converted into correlated flux densities, S_c (i.e., VLBI source strengths) by means of the expression:

$$S_c = 2.6\rho \sqrt{T_1 T_2 \left(\frac{dS}{dT}\right)_1 \left(\frac{dS}{dT}\right)_2}$$

where

S_c = correlated flux density in Jansky

T_i = the measured system temperature at antenna i in K

$(dS/dT)_i$ = the inverse sensitivity of antenna i in Jansky/K (i.e., how strong does a source have to be in total flux density (Jansky) to raise the system temperature 1K).

Most sources were observed for at least 3 minutes, but, for data processing, the observations were broken into 1-minute segments. The 5σ detection limit for this search for VLBI sources was about 0.1 Jansky. The random uncertainty in detected source strength was about 0.02 Jansky. However, in practice, systematic errors at the 5 or 10 percent level dominate the random contribution for most sources.

If a priori source positions are in error, the tapes must be correlated over a range of relative tape delay and delay rate offsets in order to detect a VLBI source. Appropriate searches in these parameters were performed so that the sky was completely searched within 0.5 arcminutes of all nominal source positions. Almost all a priori source position errors should be covered by this degree of position searching. In addition, once detections were achieved, the measured delay and delay rate offsets allowed positional errors to be measured to about one arcsecond.

RESULTS

Figures 1a, 1b, and 1c display the general sky distribution of detected VLBI sources as a function of VLBI source strength. These maps are equal area representations, so that local spatial densities in one area may be compared to local densities in another. Catalogs of source strengths and positions will be published elsewhere.

It should be noted that the strengths of the sources are a function of time, baseline length, and baseline orientation. Although the plots may not always show the true strength of a particular source at a certain epoch and on a certain baseline, they do indicate the general sky densities of sources as a function of strength.

Figure 1a shows the global distribution of all 665 detected sources. The lower limit of correlated flux strength is about 0.1 Jansky. Several things are evident from this plot:

(1) In general, the distribution is dense and rather uniform.

(2) Pairs of DSN antennas cannot commonly view the sky below $\approx -45°$ declination.

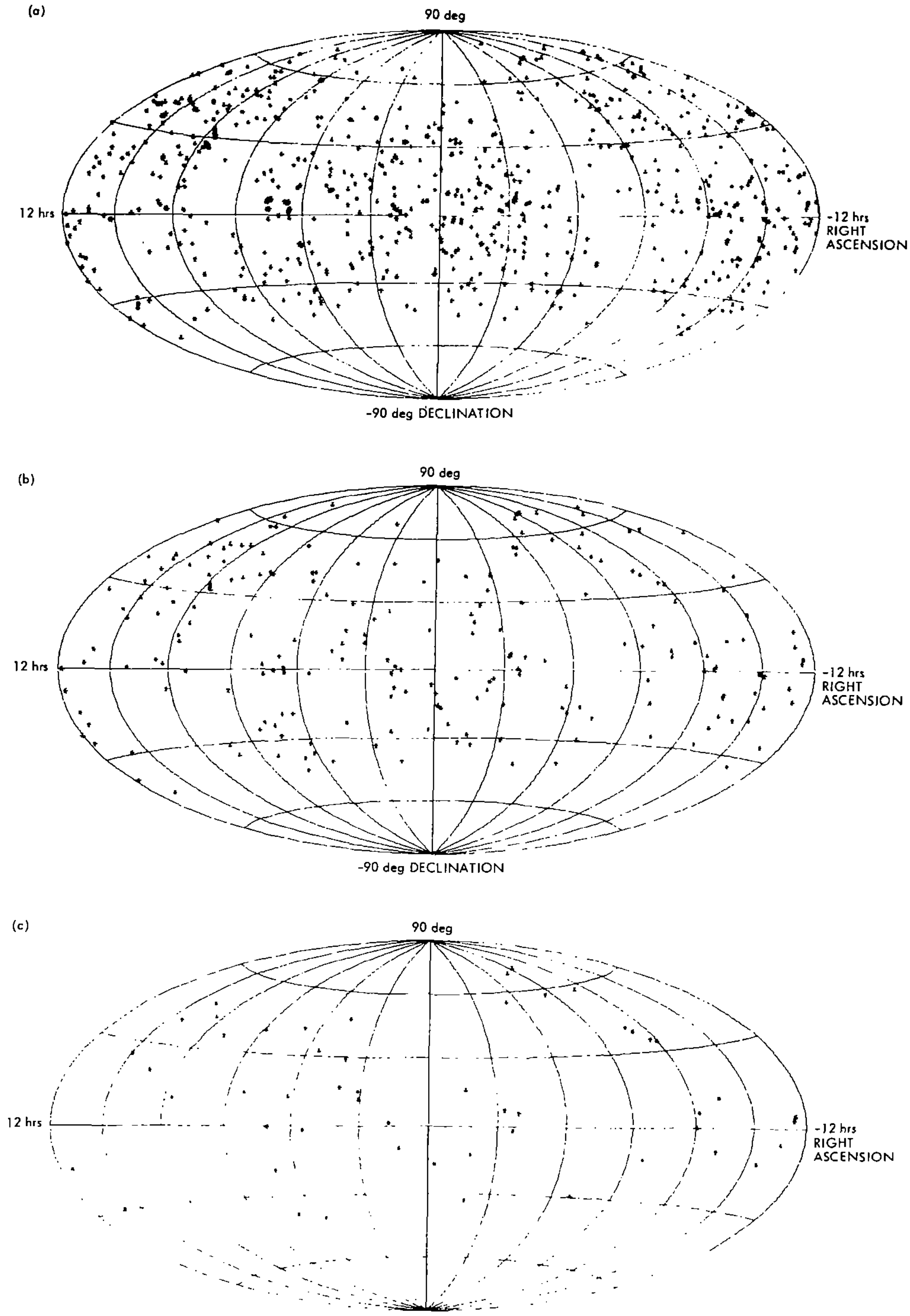

Figure 1. Sky distribution of VLBI sources: (a) 665 sources $\geq$0.1 Jansky, (b) 210 sources $\geq$0.5 Jansky, (c) 52 sources $\geq$1.0 Jansky.

(3) The north polar area is more sparsely populated. This is directly due to a lack of sufficient high frequency surveys in this region to easily identify candidate sources to observe.

(4) The areas near the plane of the galaxy (not shown) are more sparsely populated. This is particularly evident between ±30° declination at right ascensions of about −5 and +7 hours. This is due to the fact that high frequency radio surveys often skip the galactic regions and that interstellar charged particles near the galactic plane can cause intrinsically small sources to be scattered to large angular sizes.

We should point out that this is not nearly a complete map of the VLBI sky at the level of 0.1 Jansky. Since one of our criteria for choosing candidate sources was, in general, to keep only those sources with total flux densities greater than 0.7 Jansky, we have missed a large number of very compact sources with lower total flux densities.

Figure 1b shows the distribution of 210 sources with correlated flux densities greater than 0.5 Jansky. This is also a rather dense and even distribution, and is a more complete representation of the VLBI sky than was the 0.1 Jansky map.

The DSN Block 1 VLBI System is being developed to calibrate radio metric navigation data from deep space probes by measuring earth rotational position and clock epoch and rate offsets (Fanselow et al., 1978). The sensitivity of this system to VLBI source strength is 0.5 Jansky. In order to conserve antenna time, this system is intended to produce the appropriate calibrations with only 1 or 2 hours of observing on each of two intercontinental baselines. During that short time span, a single pair of DSN antennas will see only a small segment of sky in common. In order to properly estimate the desired parameters, there must be a good distribution of sources within this small common area of sky. This must be true at any time of day. Hence, this system requires a source catalog of about 100 sources. The number of sources we have found with strengths greater than 0.5 Jansky is nicely matched to the number of required sources.

Figure 1c displays the distribution of 52 sources with correlated flux densities greater than 1.0 Jansky. This is also quite a complete representation of the VLBI sky, but the distribution is no longer very dense. Note that less than 10 percent of the total number of detected VLBI sources have correlated flux strengths greater than 1.0 Jansky.

The falloff in number of sources with increasing source strength is shown more clearly in the histogram of figure 2. The number of detected sources at source strengths less than 0.5 Jansky is smaller than the true sky distribution, due to our candidate selection criteria and our approximate sensitivity limit of 0.1 Jansky. The actual number of existing VLBI sources with correlated flux densities greater than 0.1 Jansky is probably several thousand. At the high end of the source strength scale, we see that only six sources are stronger than 2.0 Jansky and none are stronger than 3.5 Jansky.

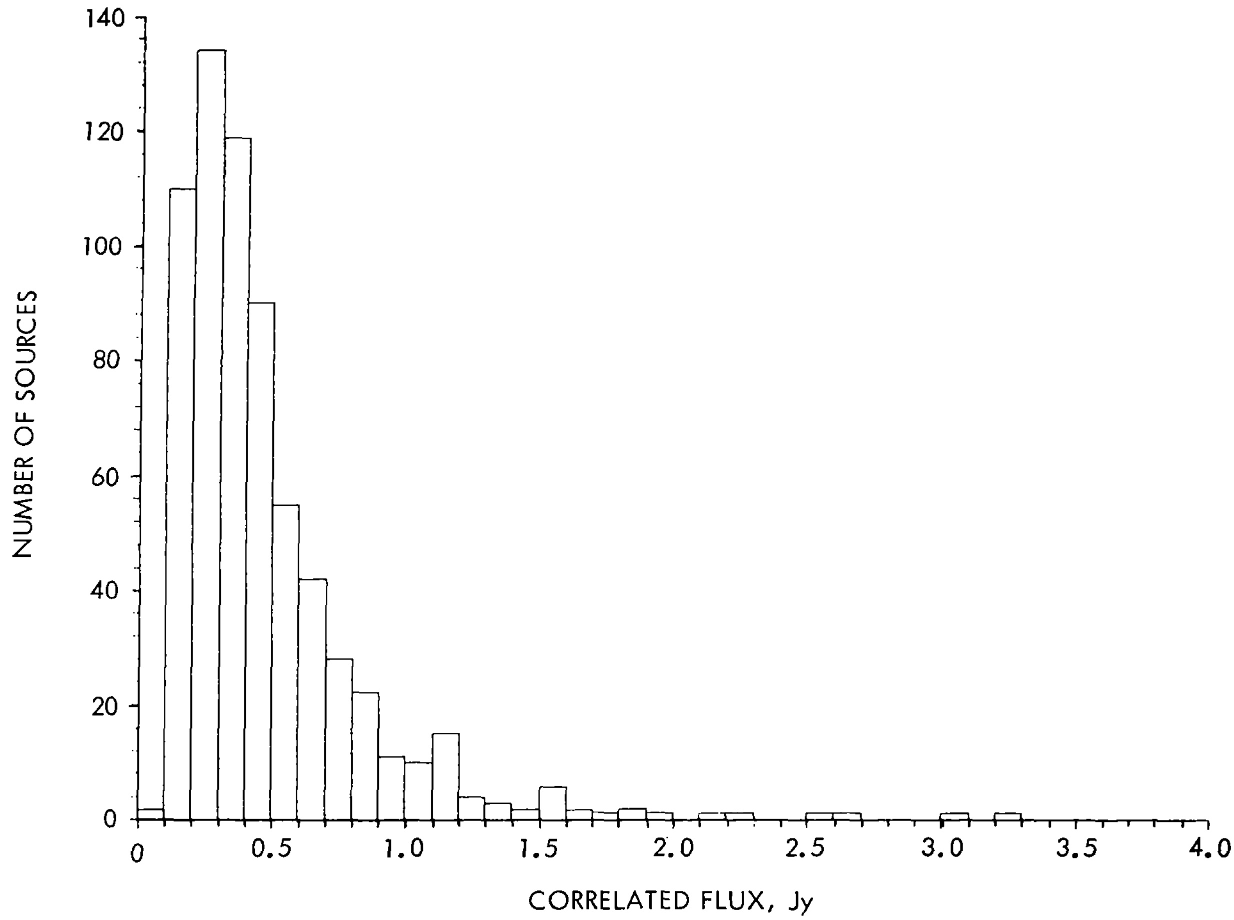

Figure 2. Histogram of number of sources vs correlated flux.

Geodetic VLBI investigations will often involve baselines shorter in length than the intercontinental baselines of this survey. A similar 13 cm VLBI survey has been completed on the same portion of sky for baselines of about 200 km length. The results of this survey show that if a given number of sources are required to form a VLBI reference frame, the sensitivity of a 200 km baseline 13 cm VLBI system need only be about half that of a similar intercontinental system. This difference is due to the fact that the shorter baseline system is sensitive to sources of larger maximum angular size. Actually, because of the shorter periods of source mutual visibility on the longer baselines, the number of sources necessary to form a reference frame for an intercontinental VLBI system would probably be larger than that for a 200 km system. Hence, intercontinental systems might have to be several times as sensitive as 200 km systems.

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