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Final Report

of a

Mission Feasibility Study

of a

Very Long Baseline Interferometer

Utilizing the Space Shuttle

NSG 5150 February 1978

Final Report
to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

for a

Mission Feasibility Study of a VERY LONG BASELINE INTERFEROMETER UTILIZING THE SPACE SHUTTLE

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SUMMARY

This report summarizes the results of a study of the effectiveness and feasibility of a Very Long Baseline Interferometry (VLBI) terminal in space, with particular emphasis on the near term advantages that may be expected to accrue from the advent of the Shuttle and the Space Transportation System. The study was supported by NASA Grant NSG-5150 from the Goddard Space Flight Center.

Following an introductory overview of VLBI as it exists and is used today, and the scientific advances that have been achieved with this technique in the past decade, the report briefly reviews developments now in progress that will improve ground station VLBI in the next few years, and the limitations that still will exist.

The main body of the report describes the advantages and the scientific return on investment that may be expected from a VLBI terminal in space, and outlines the practical problems that have to be faced, ranging from system design through hardware implementation, to data recovery and analysis.

1.0 VLBI TODAY

1.1 Introduction

Very Long Baseline Interferometry (VLBI) uses the excellent frequency stability of atomic time standards to synchronize observations made simultaneously at two or more remote radio telescopes. Because the data are recorded with a common time reference, the isolated radio telescopes can be paired as elements of a Michelson interferometer with a baseline limited only by physical considerations such as the size of the earth.

A VLBI pair observing a radio source, as in Figure 1-1, presents a projected baseline, D', normal to the direction of observation, and the output is obtained, *post facto*, by using a computer to evaluate the time average, $\overline{e_1(t)\ e_2(t+\tau)} = R_{12}(\tau)$, of the two received signals. In addition to the uncorrelated noise signals, there is a sinusoidally varying output whose amplitude and phase are proportional to the Fourier transform of the brightness distribution of the radio source. The difference in arrival time, τ_d, must be compensated for by inserting an equivalent time delay in the data reduction process.

The rotation of the earth alters the projected baseline and so gives a family of baselines which effectively synthesize a large aperture antenna. In principle, a complete map of a radio source may be obtained by this technique of aperture synthesis. All spacings and orientations of the interferometer baseline are generated by using a number of antennas which are moved in space by the rotation of the earth. This rotation allows the effective aperture size to increase linearly with the number of antenna spacings so that a

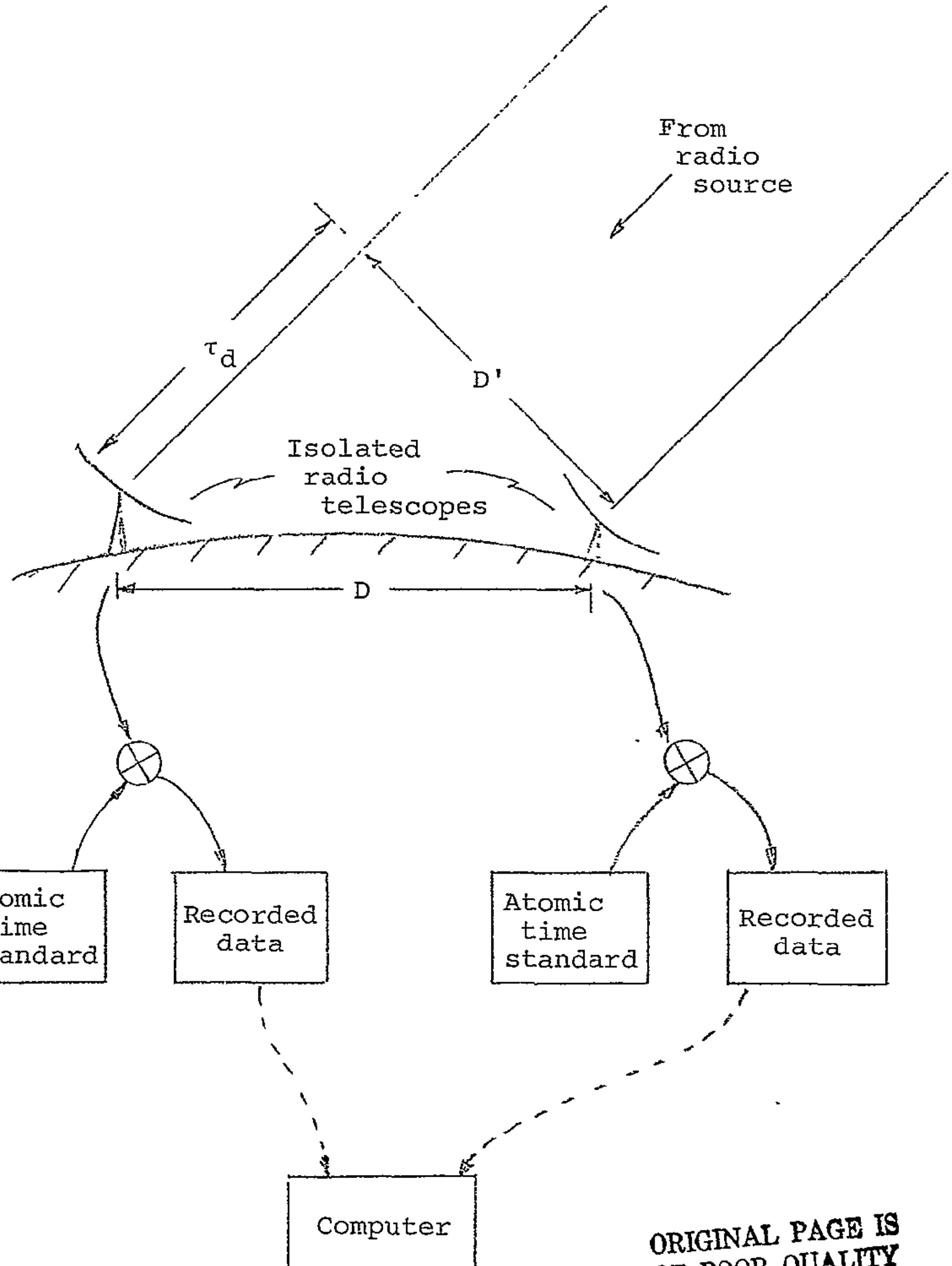

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Figure 1-1 Very Long Baseline Interferometry Schematic very large aperture can be realized with a relatively small number of elements.

Unfortunately, the existing network of earth-based radio telescopes provides only limited coverage of the Fourier transform plane. For radio telescopes located on an East-West baseline, a circular aperture is synthesized if the radio source is near the celestial pole, but the ellipse degenerates to a straight line at the celestial equator and then only one-dimensional angular resolution is achieved.

A further problem arises, for earth-based antennas, because antennas at different longitudes have differing coverage of the sky at any given time. In the limit of a pair of antennas separated by an earth diameter, a source at the celestial equator appears for only an instant, as it simultaneously sets in the west for one antenna and rises in the east for the other. For various reasons, such as low-angle refraction correction and physical horizon limitation, baselines less than an earth diameter may still be relatively unproductive, particularly for sources of low declination.

Despite these limitations, the VLBI technique has been used to construct radio brightness maps of quasars and interstellar masers with angular resolutions better than 0.0003 arc-seconds. Many interesting discoveries have been made, and some fundamental scientific results are discussed in Section 1.2 below. Then, in Section 1.3, we describe the salient features of the hardware presently used at some radio telescopes that participate in VLBI observations.

1.2 Current Scientific Results

The principal objects of study by VLBI methods have been quasars, galactic nuclei, and interstellar masers, although pulsars and one star (Algol) have also been observed successfully.

The most striking results, perhaps, have been observed in quasars - the luminous, highly red-shifted quasi-stellar objects that may (if the cosmological interpretation of their redshift is correct) be the most luminous objects in the universe, serving as potential "standard candles" for probing the large-scale structure of space. Unfortunately, the state of our understanding of these objects is so meager that astronomers have not reached a consensus about their general physical nature. If their scale size is correctly deduced from their time variations, dimensions of only a few light-years, or even light-months, seems indicated. For example, at the distance that one would infer from the redshift, one parsec structural details of the quasar 3C273 would then be of the order of 2×10^{-4} arc-seconds, a resolution that is achieved through VLBI when the longest earth baselines are used at wavelengths of the order of one centimeter. More distant quasars would require longer baselines still for comparable resolution. The most distant quasars have redshifts of the order of 3.5 (OJ287, for example), corresponding to a "distance" an order of magnitude greater than that of 3C273, and would hence require baselines greater than an earth diameter for one parsec resolution.

Nevertheless, the available data have revealed several striking results. The quasar 3C345 appears to be a double source, with the components increasing in separation by milli-arc-seconds/ year as shown in Figure 1-2. At the cosmological distance inferred from its redshift, the velocity appears to be about six times the velocity of light. The true interpretation is still a matter of intense debate. The simplest explanation may be that the model is too simple, and the result is an artifact caused by imperfect coverage of the fourier transform plane by the available radio telescopes. The possibility cannot be completely rejected, although the source does fit a double source model reasonably well. The velocities may be phase velocities, not group velocities, a question that can only be addressed through linked observations and theoretical studies. The laws of physics may be different in quasars, admitting velocities greater than c, but such an explanation would require far more conclusive data than presently in hand. The cosmological distance inferred from the large redshift can also be challenged. Since the physical nature of quasars is not understood, this is also an admissable explanation, but just as for the acceptance of super-relativistic velocities, one would accept such an explanation only with much stronger observational and theoretical evidence than presently exists.

Other sources have provided evidence for velocities greater than c, including 3C273 and 3C279. In both cases, the structures are more complex, as is shown in Figure 3-1 for 3C273. Changes certainly do occur, and can easily be interpreted as super-luminal velocities, but the incomplete modelling procedures leave some room for skepticism. One of the more disappointing qualities of

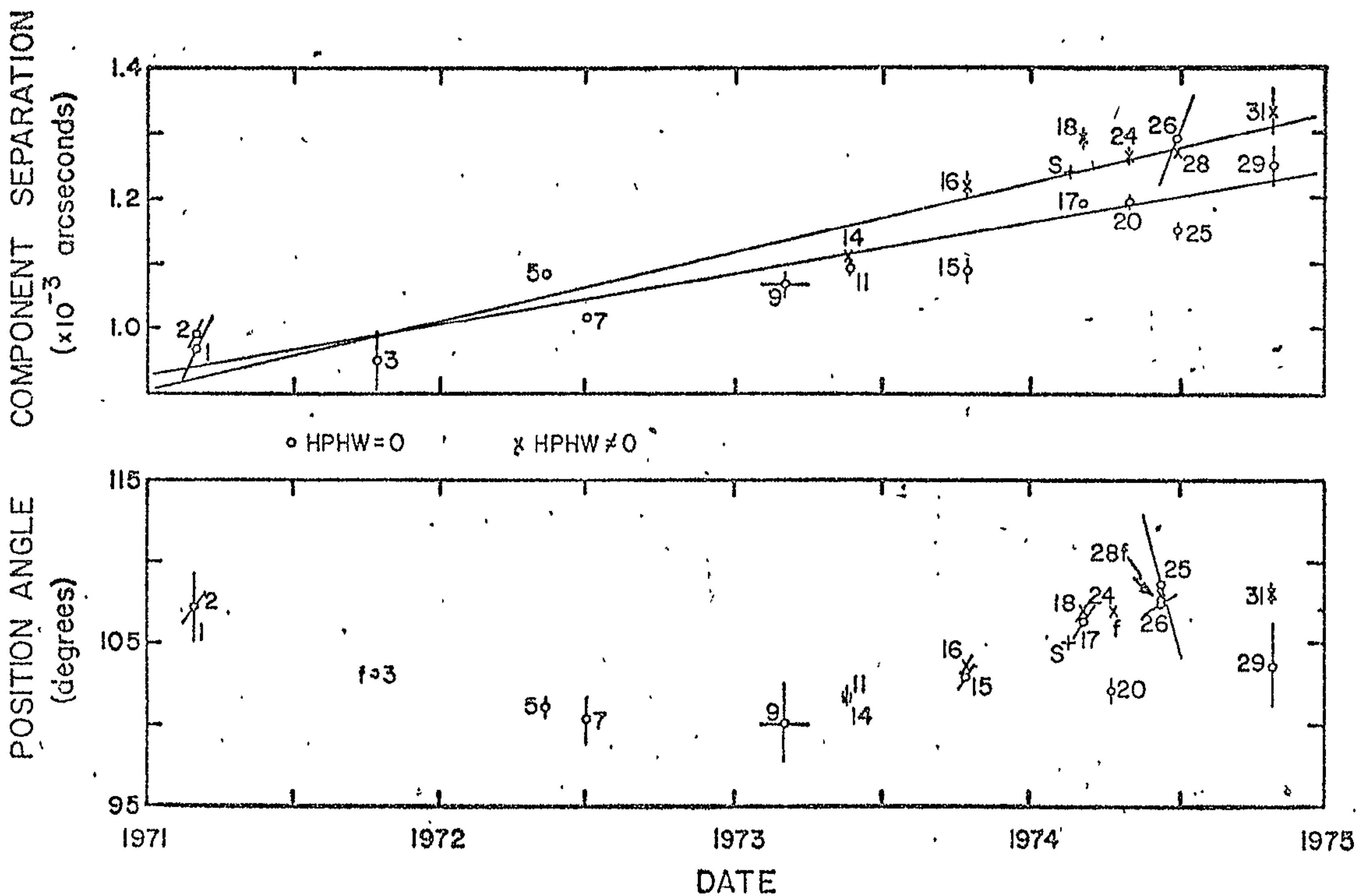
COMPONENT SEPARATION
(x10^-3 arcseconds)
1.4
1.2
1.0
o HPHW=0
x HPHW≠0
POSITION ANGLE
(degrees)
115
105
95
1971
1972
1973
1974
1975
DATE

Figure 1-2

these otherwise spectacularly interesting quasars (3C273 has the greatest apparent brightness, and 3C279 is presently the most luminous known quasar) is that both are near the celestial equator and hence are difficult to map completely with presently available earth baselines.

The energy sources for quasars, if they are at cosmological distances, must generate up to 1000 galactic luminosities. One class of models postulates the existence of a massive black hole, located at the nucleus of a galaxy, that generates the required energy by "swallowing" stars whose orbits bring them too close. Massive spinning objects have also been proposed - the equivalent of pulsars on a galactic scale - in which the energy comes from the mechanical energy of rotation. An abnormal rate of supernova occurrence close to a galactic nucleus has also been proposed. In all cases the scale of the phenomenon is a few parsecs or less, and high angular resolving power is the key.

Even if an energy source is given, the energy must be converted to radiation. The extraordinary radio brightness implies an efficient mechanism, probably by generating relativistic particles that then radiate synchrotron radiation in magnetic fields. If the electrons radiate incoherently, this implies an upper limit to the surface brightness of approximately 10^{12} °K, because of compton scattering of the relativistic electrons by the synchrotron-generated photons in their vicinity. The evidence for such a limit is not complete, however, since the parameters of the brighter sources are such that an earth-diameter baseline just resolves (or just fails to resolve) a source with that surface brightness. Most quasars are partly resolved at baselines that are an appreciable fraction of an earth diameter, but in many cases a substantial fringe visibility remains, implying still finer angular detail. The quasar AO0235+185, (actually a BL Lac class of object, discussed below) showed time variations in its brightness that imply a surface brightness of 10^{14} °K, far in excess of the compton scattering limit.

In summary, one might say that quasars present one of the greatest challenges in contemporary astronomy, with fundamental assumptions of physics and cosmology called to question. If the conventional assumptions prove to be correct, then they are singularly useful for probes to the greatest distances, and their angular structure provides a way of determining fundamental properties of the metric. On the other hand, fundamental assumptions in physics and astronomy have sometimes proved faulty in the past and may well prove to be so in the future. Either way, the lead has to be taken by new observing techniques.

BL Lac objects are presumed to be a sub-class of quasar that, since they exhibit no emission lines, are more difficult to classify. In some cases there are absorption lines of high red-shift in their spectra, and in one case (AO0235+185) simultaneous detection of the absorption lines of redshifted Lyman α in the visible, and at the redshifted 21-cm hydrogen hyperfine line in the radio spectrum showed that the constants of nature appear to vary very little with time. Like quasars, they exhibit angular structure that is incompletely resolved with the longest VLBI baselines. Although they share some of the characteristics of quasars, a clear demonstration is still lacking; like quasars, neither the energy source nor the energy conversion processes are understood, and the reasons for their differing appearance from quasars have yet to be given.

Galaxies with active nuclei also exhibit phenomena on a small scale that are linked to energetic processes. Radio galaxies such as Cygnus A have highly compact sources at their nucleus that are almost certainly linked to the prodigiously energetic events that generate their large radio halos, which are usually double in appearance. VLBI measurements of the nucleus of Cygnus A show that the source is less than three parsecs in size. The radio galaxy NGC1275 has a complicated nuclear structure that changes with time. At least four components can be identified by VLBI measurements, although their interrelationships are not yet clear. One of the principal unsolved problems is whether these galaxies with active nuclei represent the same phenomenon as that occurring in quasars. Are they both phenomena of galactic nuclei, and do they differ in size, or are they merely in different stages of evolution? If the history of astronomy provides a guide, it suggests that only through the study of many examples will the answers be demonstrated.

The Seyfert galaxies are another, perhaps related, class of object. These have activity that is predominantly confined to the nucleus, but the energy scale is lower still. Further down the scale of energy, "normal" galaxies also possess active nuclei, as demonstrated by VLBI methods. At the center of our own galaxy, there is a compact source of radio noise that is less than 30 astronomical units in size. Again, current speculation suggests that this is a condensed object, perhaps a black hole. Since spiral galaxies such as M31, M51, and M81 also possess compact nuclei that differ in their luminosity but are clearly identifiable, one suspects that the nucleus of a galaxy is in general much more than just a concentration of stars.

Interstellar masers represent a completely different class of astronomical object that has been revealed through VLBI studies. The OH masers, radiating at the four 18-cm lambda-doubling line frequencies, (and in higher rotational states also) and the H_2O masers, which arise from the rotational transition 6_{16} - 5_{23} at 1.35 cm, are the most spectacular examples, but the masering phenomenon has been demonstrated for methyl alcohol and silicon oxide (in its first excited vibrational state) as well.

The OH and H_2O masers appear typically as a compact cluster of bright spots, 10^{16} - 10^{17} cm in overall size. Each spot exhibits high brightness temperature (up to 10^{14} - 10^{15} °K) which demonstrates the need for a non-thermal mechanism, and the apparent size of each spot is only of the order of an astronomical unit. The total energy emitted in the radio lines is unexpectedly large (10^{27} - 10^{33} ergs, typically) and the need for a pump mechanism whose energy output must be as large or larger than the radiated maser energy suggests that one is dealing with stars in an extremely early stage of their formation. The stellar formation process occurs in dense regions, where obscuration by dust hampers optical observations, but radio waves escape unimpeded. One current puzzle has been raised by the H_2O maser complex associated with W3OH, for which a VLBI map is shown in Figure 1-3. No infrared energy has yet been detected at a level that could explain one of several pump mechanisms. One suspects that the stellar formation process is in such an early stage that even the infrared radiation (at 10μ) has not yet escaped. If this turns out to be a correct explanation, the infrared maser sources mark the site of solar system formation at an early stage indeed.

Like quasars, the maser sources vary with time, sometimes in only a few days. The individual spots are not fully resolved at the longest baselines, and while some mapping has been performed, more complete fourier coverage is essential.

One interesting (and complementary) feature of the maser sources is that they are intense and of narrow bandwidth. They are, as a result, excellent diagnostic sources, providing calibration information on time delays, baseline parameters, etc., that make quasar observations far easier.

VLBI observations have also been made of the binary star Algol, and of several pulsars, whose large proper motions (caused by their high space velocities) are measurable with only a short time between observing epochs. Further observation of stellar sources constitutes an interesting subject of speculation. X-ray sources in some cases have associated radio sources, and some

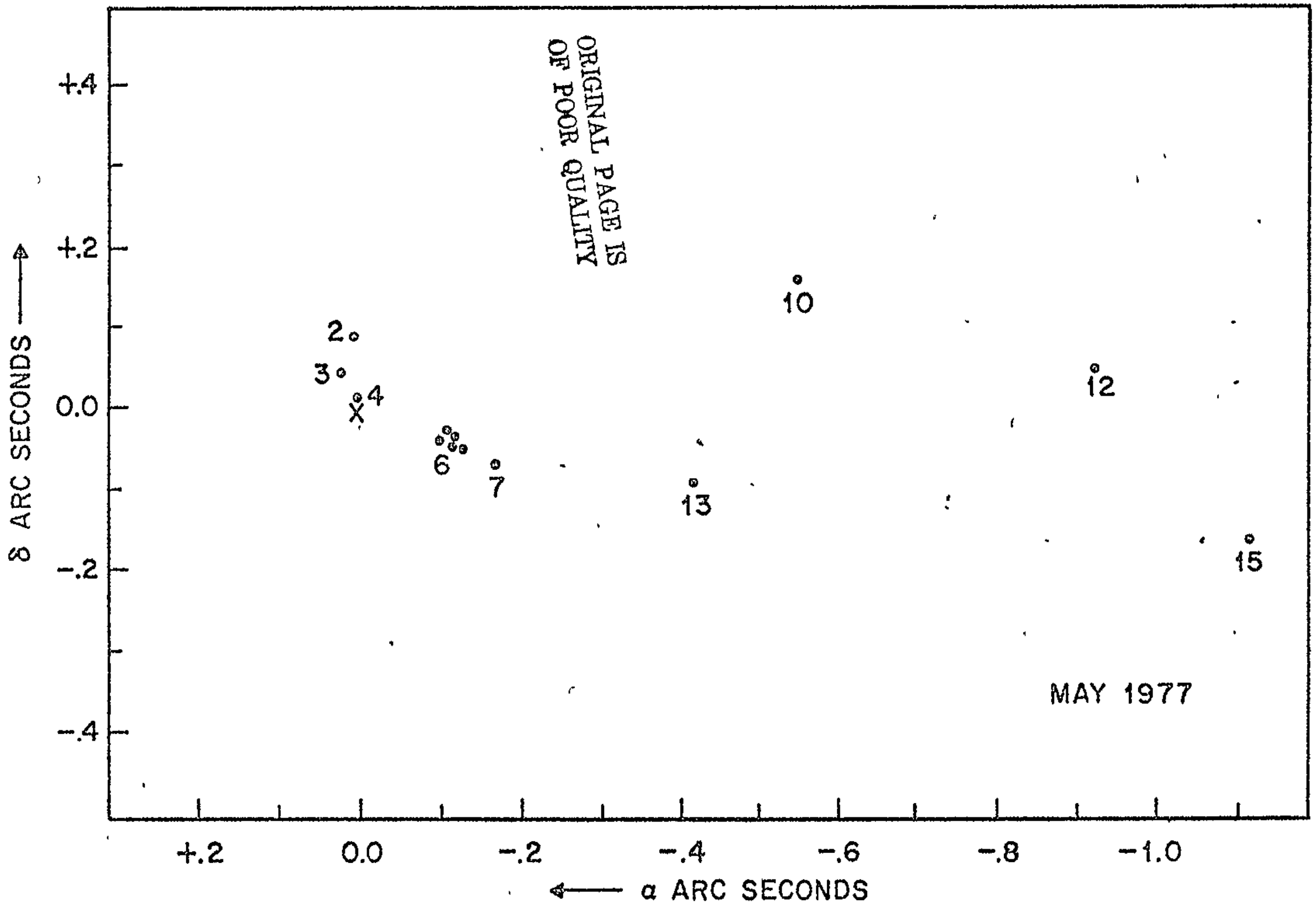

FIGURE 1-3: MULTIPLE FRINGE MAP OF W3(OH) TAKEN IN MAY 1977

stars should have observable coronas. Most of these will probably be faint, and will probably await a time when very large collecting areas and long integration times are available to VLBI methods.

1.3 Present VLBI Hardware

The purpose of the radio telescopes used for VLBI observations is to record the very weak, noise-like signals received from distant sources so that the signals observed at two isolated points can be cross-correlated to derive the desired radio brightness maps. The flux intensity of interest is, typically, a few Jansky ($1\ Jy = 10^{-26}\ W\ m^{-2}\ Hz^{-1}$). The wavelengths of interest are measured in centimeters; the radio signal frequencies ranging from about 1 to 30 GHz.

Because the signals cannot be recorded directly, a selected portion of the frequency spectrum is heterodyned down to baseband, and a sampled version of the baseband signal is recorded. Current practice is to use one-bit quantization: the baseband signal is sampled at a four megabit rate and the polarity of the signal is recorded in each 250 ns sampling interval. This has the effect of restricting the instananeous observed bandwidth to 2-MHz. Larger effective observation bandwidths are achieved by sequentially sampling different 2 MHz wide segments of the received signal.

The phase of the received signal is preserved by the heterodyning procedure; and it is critically important to the ultimate use of the recorded data that the phase stability of the local oscillators at each station be adequate to maintain phase integrity throughout whatever interval is required for eventual integration of the cross-correlation product. For this reason, all local oscillator frequencies are derived from an atomic frequency standard at each station. This frequency standard also is used as the master source for the sampling and switching rates and so serves to keep the stations synchronized.

A typical VLBI radio telescope therefore takes the form shown in Figure 1-4. A large area, steerable, dish antenna, typically 30 to 40 meters in diameter, provides input to a heterodyning receiver chain which includes a low noise front end amplifier, typically a maser or a paramp, an IF amplifier with a wide bandwidth, typically 50 to 500 MHz, a video amplifier, typically with a bandwidth of 5 to 10 MHz, and a sampling data recorder. All local oscillator frequencies are provided by a frequency synthesizer that is phase locked to an atomic frequency standard, typically a hydrogen maser or a rubidium clock. Output from the frequency synthesizer also controls a time standard which determines the frequency switching rate and the baseband signal sampling rate. The end output is a magnetic tape recording of the data which is taken later to a computer for cross-correlation with data tapes derived from other stations.

Until recently, the most common prime frequency standard was an HP 5065A rubidium clock, but this is rapidly being supplanted by hydrogen masers which provide more than an order of magnitude improvement in phase stability in the important range of averaging times around 100 seconds.

Current practice is to use the *(sic)* Mk II recording system. This makes use of an Ampex VR660 tape recorder, or, more recently, an IVC 825 tape recorder. These are rotating head machines that provide a 2 MHz signal bandwidth by recording diagonal stripes on a one-inch wide tape.

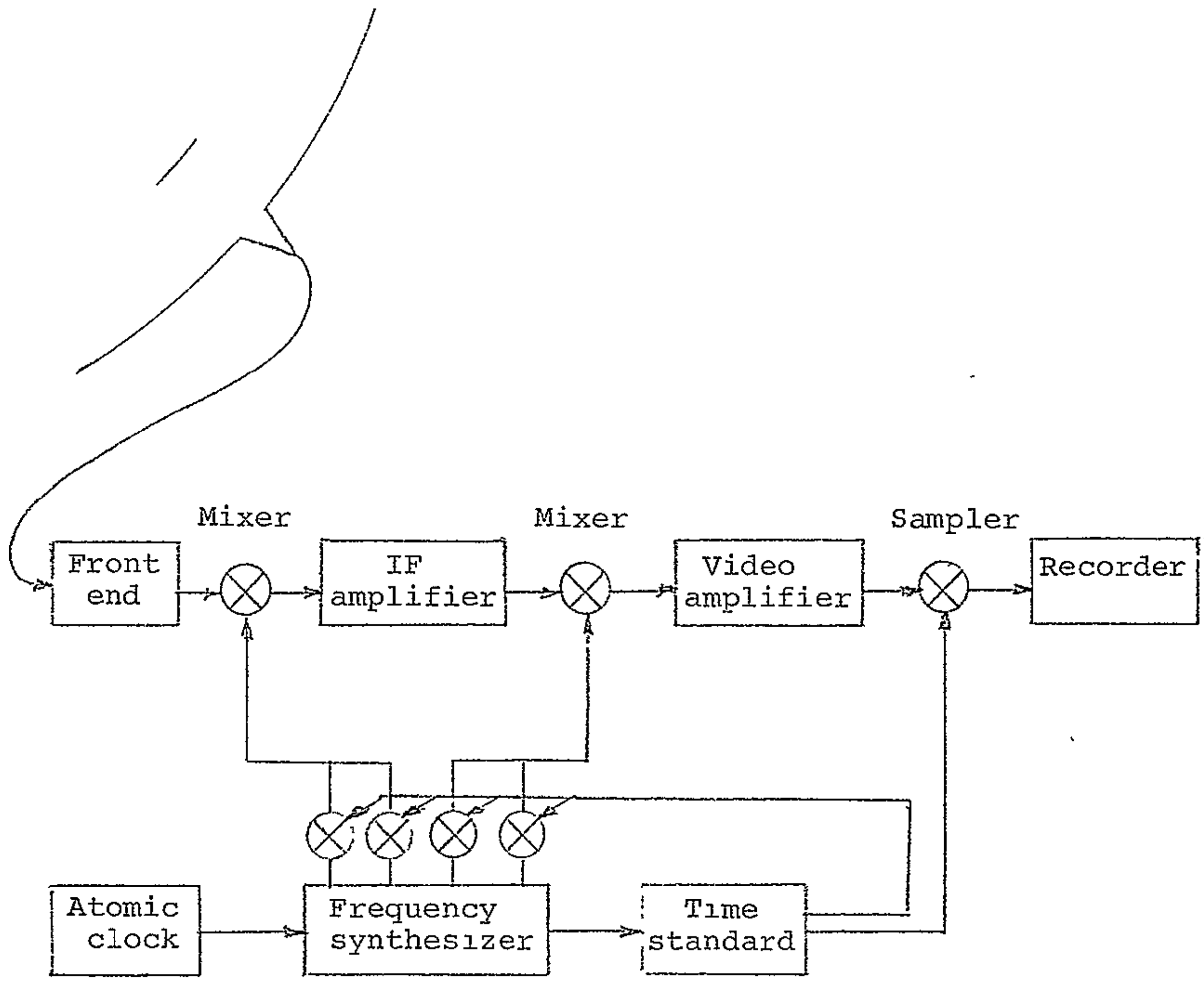

Figure 1-4 Typical Radio Telescope Hardware Used For VLBI

The other instrumentation: the amplifiers, mixers, and calibration arrangements, are implemented in diverse ways at different radio telescopes. This is partly due to budgetary constraints, and partly due to the fact that the telescopes were designed originally for purposes other than VLBI observations.

Worldwide, there are about 20 large radio telescopes that now are used, part time, in cooperative VLBI observing programs. As a specific example, four arbitrarily selected installations within the continental United States will be listed here. The four stations, in East to West sequence, are Northeast Radio Observatory Corporation's Haystack Observatory, Mass., (Haystack), National Radio Astronomy Observatory's 140 foot dish, W. Va. (NRAO), California Institute of Technology's Owens Valley Radio Observatory, Cal. (OVRO), and University of California's Hat Creek Radio Observatory, Cal. (Hat Creek).

Figure 1-5 shows the locations, antenna diameters, frequency standards, and available recording facilities of these four illustrative radio telescopes; other pertinent parameters of the hardware used for VLBI observations at these sites are listed in Table 1 (a) through (h). It is worth noting that these stations are able to work together satisfactorily despite some rather wide disparities in equipment, bandwidths, and system noise temperatures.

Station	Hat Creek	OVRO	NRAO	Haystack
Antenna diameter (m)	25.0	39.6	37.0	36.6
Frequency standard	Rubidium HP5065A	H maser H-10	H maser VLB	H maser VLG-10-P2
Recording facility	Mk II C IVC825A	Mk II VR660 IVC825	Mk II VR660 IVC	Mk II VR660 Mk I

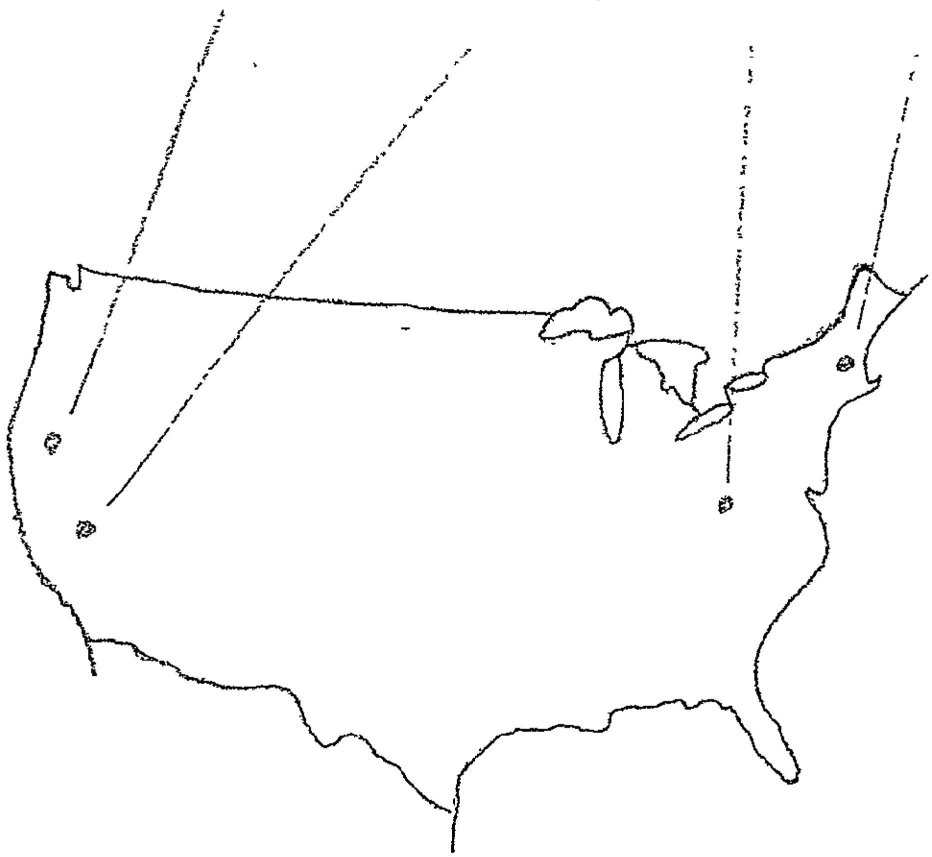

Figure 1-5: Location Of Four Illustrative Radio Telescopes Used For VLBI

Station	Antenna efficiency (%)	Polarization	Frequency range (GHz)	Front end type	System temperature (°K)	Bandwidth (MHz)
(a) Nominal wavelength = 1.3 cm						
Haystack	22	Orth Linear, RCP, LCP	21.5 - 25.0	Maser	100 - 300	25
NRAO	25	Orth Linear	22.2 - 24.0	Cooled mixer	500 - 600	500
OVRO	30	Linear	21.0 - 24.0	Paramp	400	100
Hat Creek	25	Orth Linear	21.5 - 25.5	Maser	100 - 140	25
(b) Nominal wavelength = 2 cm						
Haystack	30	Linear, Circular	14.6 - 14.8	Paramp	400	50
NRAO	40	Orth Linear, Dual Circular	14.4 - 14.9	Cooled paramp	100 - 150	500
(c) Nominal wavelength = 2.8 cm						
Haystack	36	Linear, Circular	10.0 - 11.0	Cooled paramp	70	1000
NRAO	45	Dual Linear, Orth Circular	10.3 - 11.0	Cooled paramp	70	300
OVRO	50	Dual Linear, Circular	10.0 - 11.0	Cooled paramp	60	300
(d) Nominal wavelength = 3.8 cm						
Haystack	40	Linear, RCP	7.5 - 8.5	Cooled paramp	75	150
NRAO	50	Linear, Circular	7.7 - 8.0	Cooled paramp	85	120
OVRO	50	Linear, Circular	7.5 - 8.5	Paramp	300	100

Table 1 System Parameters Of Four Radio Telescopes Used For VLBI (continued)

(e) Nominal wavelength = 6 cm

NRAO	50	Linear	4.5 - 5.3	Cooled paramp	50 - 70	250
OVRO	50	Linear, Circular	4.8 - 5.2	Paramp	120	50
Hat Creek	41	Linear	4.5 - 5.1	Cooled paramp	60	60

(f) Nominal wavelength = 13 cm

Haystack	50	RCP	2.2 - 2.3	Paramp	50	50
NRAO	50	Linear	2.0 - 2.5	Paramp	200 - 450	30 - 100
OVRO	50	Linear, Circular	2.26 - 2.34	Paramp	100	50

(g) Nominal wavelength = 18 cm

Haystack	50	Linear, RCP, LCP	1.60 - 1.75	Paramp	200	10
NRAO	50	Orth Linear	1.61 - 1.72	Cooled paramp	50	30
OVRO	60	Linear	1.60 - 1.75	Paramp	75	50
Hat Creek	50	Orth Linear, Orth Circular	1.50 - 1.76	Paramp	130	20

(h) Nominal wavelength = 21 cm

NRAO	50	Orth Linear	1.38 - 1.44	Cooled paramp	60	25
Hat Creek	50	Orth Linear, Orth Circular	1.33 - 1.43	Paramp	75	20

Table 1 (continued)
System Parameters Of Four
Radio Telescopes Used For VLBI

The signal-to-noise ratio obtained by cross-correlation of the data derived from a VLBI terminal pair is

$$\frac{S}{N} = \frac{2}{\pi} \frac{\sqrt{(Ta_1 \ Ta_2)} \ \sqrt{(B \ \tau)}}{\sqrt{(Ts_1 \ Ts_2)}}$$

where: the factor $2/\pi$ is caused by the one-bit quantizing used in the Mk II recording system;

T_{a1} and T_{a2} (°K) are the antenna temperatures induced by the observed radio source;

B (Hz) is the correlation bandwidth;

τ (secs) is the integration interval used in the cross-correlation process;

T_{s1} and T_{s2} (°K) are the individual system noise temperatures referred to the respective antenna terminals.

The antenna temperatures induced by the observed source are related to the source intensity by

$$\sqrt{(Ta_1 \ Ta_2)} = \frac{F \quad \sqrt{(A_1 \ A_2)} \quad 10^{-26}}{k \quad 2}$$

where: F (Jy) is the radio source intensity;

A_1 and A_2 (m^2) are the effective apertures of the individual antennas, including antenna efficiency factors;

k (J/°K) is Boltzmanns constant = $1.38 \ 10^{-23}$

the factor 2 is caused by the fact that a randomly polarized signal is received by a polarized antenna.

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Combining the foregoing, the 1 σ noise threshold, that is the source intensity required to yield a signal-to-noise ratio of unity, is

$$F = 4.3 \; 10^{3} \; \frac{\sqrt{(Ts_1 \;\; Ts_2)}}{\sqrt{(A_1 \;\; A_2)} \quad \sqrt{(B \;\; \tau)}} \quad \text{Jy}$$

Assuming a continuum source so that the bandwidth is limited only by the 2 MHz capability of the Mk II recording system, and assuming a typical 50 second integration interval, the source flux intensity required for unity signal-to-noise ratio is listed in Table 2 (a) through (h) for the various possible pairings of the four illustrative radio telescopes. These results are typical of the noise thresholds presently encountered in VLBI observations.

The source intensity required for a signal-to-noise ratio of unity, or system noise threshold, is a convenient figure of merit that may be used to adjudge the relative efficacy of various VLBI terminal pairs. For useful results, of course, the signal-to-noise ratio is required to be greater than unity: the limiting value is somewhat subjective, but usually is taken as 5 with adjustments depending on the purpose of the experiment and the conservatism of the workers. Virtual certainty is guaranteed with an SNR of 10.

Scheduling of radio telescopes for cooperative VLBI observations has, in the past, been accomplished mostly on an ad hoc basis, but an informal Network Users Group formed in 1974 has been actively promoting a more organized approach. The situation now is that, with reasonable advance notice, observing time on the major radio telescopes can be obtained for important experiments without too much difficulty.

(a) Nominal wavelength = 1.3 cm

	Hat Creek	OVRO	NRAO
Haystack	0.40	0.42	0.57
NRAO	0.61	0.64	
OVRO	0.44		

(b) Nominal wavelength = 2 cm

	Hat Creek	OVRO	NRAO
Haystack			0.26
NRAO			
OVRO			

(c) Nominal wavelength = 2.8 cm

	Hat Creek	OVRO	NRAO
Haystack		0.07	0.07
NRAO		0.05	
OVRO			

(d) Nominal wavelength = 3.8 cm

	Hat Creek	OVRO	NRAO
Haystack		0.13	0.07
NRAO		0.12	
OVRO			

(e) Nominal wavelength = 6 cm

	Hat Creek	OVRO	NRAO
Haystack			
NRAO	0.08	0.06	
OVRO	0.10		

(f) Nominal wavelength = 13 cm

	Hat Creek	OVRO	NRAO
Haystack		0.05	0.10
NRAO		0.13	
OVRO			

(g) Nominal wavelength = 18 cm

	Hat Creek	OVRO	NRAO
Haystack	0.19	0.08	0.08
NRAO	0.10	0.04	
OVRO	0.10		

(h) Nominal wavelength = 21 cm

	Hat Creek	OVRO	NRAO
Haystack			
NRAO	0.08		
OVRO			

(a) through (h): Bandwidth = 2 MHz; Integration Interval = 50 s

Table 2 Source Intensity (Jy) Required For Unity Signal-to-noise Ratio For Pairs Of Four Illustrative Radio Telescopes

Correlation of the recorded data tapes, in principle, is straightforward, but, in practice, is a tedious and time consuming "bootstrap" procedure. Based on an initial estimate of the source position, each data stream has to be played back at a continuously varying rate to compensate for the different Doppler frequency shifts experienced at the observing locations, and one data stream then has to be compared with many time-shifted versions of each of the other data streams to determine the best fit, that is to define the maxima of the cross-correlation functions. Several iterations usually are required to achieve a satisfactory result.

This lengthy data processing procedure has, in the past, been a severe bottleneck for multi-station VLBI observations. As recently as 1975, all Mk II observations had to be processed on one machine at NRAO, Charlottesville, VA. Data from a one baseline, two station, experiment could be processed in a time not much longer than the duration of the observation program, but the processing time is proportional to (n)(n-1)/2, where n is the number of stations involved, so a five day, five station, experiment occupied the NRAO processor for 24 hours per day, 7 days per week, for more than two months. The resultant job queue has been as long as six months.

The situation has now been ameliorated by expanding the NRAO processor to accomodate three stations simultaneously, and by a Caltech/JPL Mk II processor installed at Pasadena, CA. The software systems that allow conversion of raw correlations from the processor into useful maps have been extensively developed. While the data processing queues for large experiments are still not negligible, the time delays are not now serious.

2.0 VLBI TOMORROW

The first VLBI measurements were made about ten years ago and since that time there has been a steady improvement in the instrumentation, techniques, and analysis procedures used. Presumably, individually small and undramatic changes will continue to be made as existing radio telescopes are upgraded with better frequency standards, lower noise amplifiers, better calibration methods, and the like. There are fundamental limitations to earth-based systems however, that lead to strong arguments for a new generation of space-earth and (eventually) to space-space VLBI systems.

A report published by the Network Users Group in December 1975 contains a specific list of recommendations for equipment acquisitions and improvements. When this list is fully implemented, the VLBI user will have more convenient access to an extended network similar in broad outline to that available today, but refined to provide better spatial resolution, lower system noise temperatures, more compatible station capabilities, and less frustrating data processing facilities.

One of the more noteworthy advances underway at this time is the development of a Mk III recording and processing system: units are being fabricated at Haystack Observatory that will simultaneously record data derived from up to 28 separate frequency segments, each with a bandwidth of 4 MHz. These data will be recorded, in a manner that is backwards compatible with the current Mk II system, by recording separate tracks across the width of a high speed magnetic tape. Hardware implemented, computer controlled, correlators are being constructed concurrently with the development of this recording technique so as to make possible true 100 MHz VLBI bandwidth; for continuum sources this will improve system sensitivity by a factor of 7.

The fairly recent and continuing improvement in frequency standards promises another significant advance which is now being pursued actively: the measurement of true phase. The coherence time of the standards now available is sufficient to permit switching from test sources to reference sources in the sky so as to establish a direct measure of relative station phase. Most measurements to data have used only amplitude information: the retention of phase information would make the analysis procedure and the construction of radio brightness contour maps much less ambiguous and model dependent. Phase information also would make VLBI observations dramatically more useful for astrometric purposes, such as the definition of inertial frames an order of magnitude more precise than is possible today, and for the measurement of geodetic effects such as the measurement of earth tides.

Despite the improvements, and consequent scientific advances of ground-based VLBI observations that can now be predicted to occur in the next few years, there will remain some fundamental limitations of earth-based systems. Notably, coverage of the celestial sphere will continue to be limited because of geographical limitations on the placement of radio telescopes and the inherent non-transparency of the earth. Experience has shown that higher angular resolution is always needed, but earth-based systems can never achieve baselines greater than a major fraction of an earth diameter. It is for these reasons that we advocate development of a VLBI terminal in space: the subject of the main body of this report.

3.0 VLBI IN SPACE

3.1 The Orbiting Terminal

3.1.1 Scientific Benefits

Several classes of astronomical objects have been shown to have interesting properties when studied by VLBI methods, including quasars, interstellar masers, active nuclei of galaxies, and pulsars. Extensive studies of quasars and maser sources, in particular, have shown great complexity of structure and dramatic time variations.

Quasars are one of the most puzzling of astronomical objects. They exhibit a wide range of red shifts and, if the cosmologically inferred distance is the true distance, they are the most luminous objects in the universe. The physics of these objects is still not understood. Whether they are nuclei of galaxies, or unique objects of a completely new type, is not yet settled, nor is the mechanism by which they produce their energy. It appears that physical laws may be tested in a fundamental way by the study of quasars, where extreme physical conditions are found.

An interesting example of the fundamental character of VLBI quasar studies is provided by recent observations that the apparent internal velocities in quasars frequently exceed the speed of light. For example, the quasar 3C345, one of the most reliably modelled cases, appears to be a double source with separation increasing at more than six times the speed of light over the last several years. If this inferred motion is correct, the basic laws of physics would be challenged.

Although startling, this result is by no means proven, and there are many alternate hypotheses that might explain the observations. One possibility is that the assumptions that are used to determine quasar distances are incorrect, an explanation that would itself require fundamental revisions of cosmology. A more mundane possibility is that the models are incorrect due to the observational ambiguities inherent in data derived from the existing VLBI baselines.

Current VLBI technique relies on the rotation of the earth to change the projected baseline so that an elliptical locus of points is covered in the Fourier transform plane. At best, the coverage of the celestial sky, and the coverage of the transform plane, is incomplete. Some of the most active and interesting sources are at low declinations where they are not accessible to detailed study by the existing VLBI network, which is located primarily in the temperature zone of the Northern hemisphere. Even at high declinations, the mutual visibility of a given source is relatively limited in hour angle so, apart from the fact that many observations are undesirably curtailed, the projected baselines sweep out only very short paths in the transform plane. And, in any case, it is now clear that the incompleteness of the maps caused by the small number of available baselines gives rise to many ambiguities of interpretation when the source is a complex structure, as many of the most interesting sources appear to be.

The resolution of these difficulties, and the resolution of the present scientific enigmas, requires more detailed and complete mapping of many astronomincal objects. A VLBI terminal in space would be substantial, and cost effective, step forward in the mapping program.

As an example, Figure 3-1 shows models of the quasar 3C273 in three epochs; these maps were derived from the use of radio telescopes in the U.S. A typical set of projected baselines for these maps shows in Figure 3-2 as the set of small partial ellipses: the large curves, covering most of the figure, are the baselines that would be generated in a total of six hours using one ground station and a VLBI terminal in near-earth orbit. The Fourier transform plane is clearly covered more completely and is equivalent to a much larger aperture. The improved two-dimensional coverage, because of the larger range of North-South baselines, is evident. Further, because holes in the Fourier transform coverage generate spurious responses, the more complete coverage ensures a cleaner effective antenna beam with lower sidelobes, and this, in turn, permit observation over larger dynamic ranges of brightness, and thus permits study of weaker features that are lost when the incomplete ground-based network alone is used.

A computer program was developed to demonstrate the effective antenna beam resulting from a space-earth VLBI multiple orbit observation, using only one ground station. Several examples of a synthesized beam generated by only eight orbits are given in Figure 3-3, a through 1. The rms sidelobe levels are below 0.5%. A few close-in sidelobes have high values in some cases, but increased sampling with more ground stations has the effect of reducing these also. By VLBI standards, the beam patterns are extraordinarily clean.

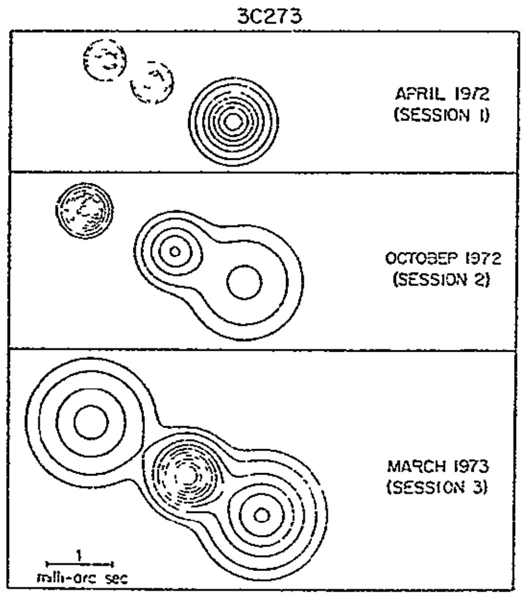

Fig. 3-1
Models for 3C273 derived from VLBI measurements at three epochs.
(Ref. 6)

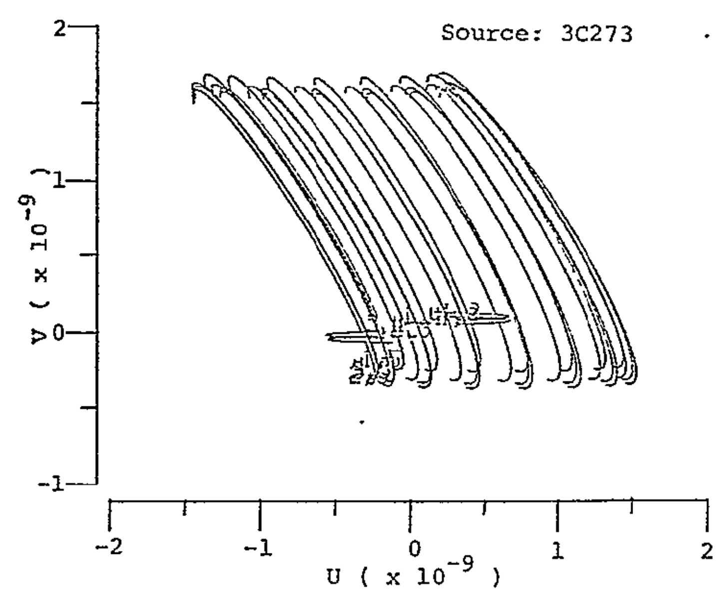

Fig. 3-2
Fourier coverage for 3C273 by a ground array (small elliptical segments) compared to the space generated coverage (long elliptical segments).

Figure 3-3:

Antenna beam patterns for λ = 3.8 cm generated by only eight orbits of a VLBI terminal in near earth orbit (altitude 400 km, inclination 23°) and the Goldstone ground terminal. Four different celestial sources at various declinations are shown each with three different longitudes (Ω = +90°; 0°; -90°) of the ascending node of the shuttle orbit. Contours are drawn at 10% intervals of the peak power. Beam patterns were obtained by combining beam-mapping programs of the NRAO and satellite orbital programs of Professor I. Shapiro of MIT.

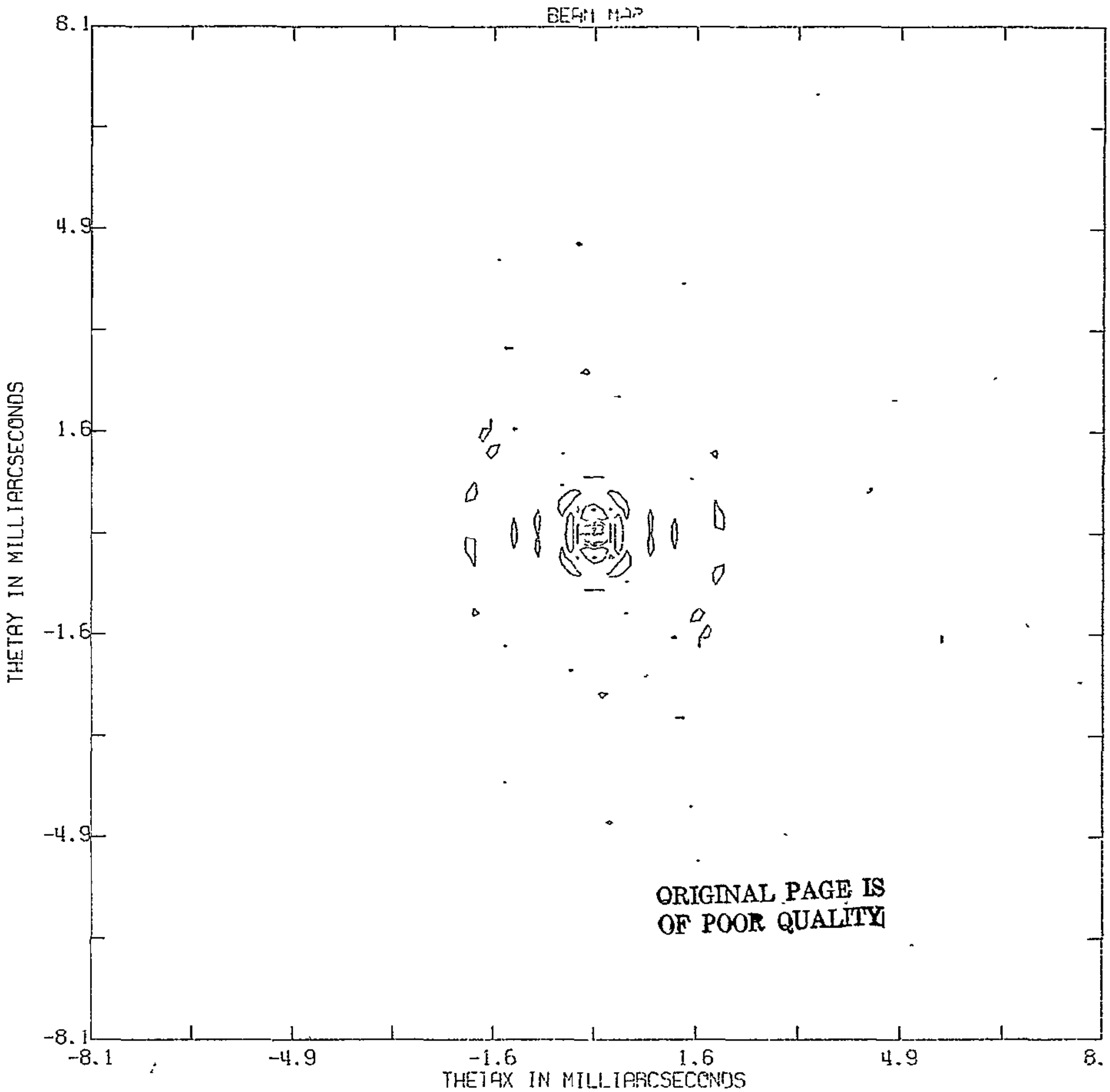

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Figure 3-3a: W3; Ω = +90°

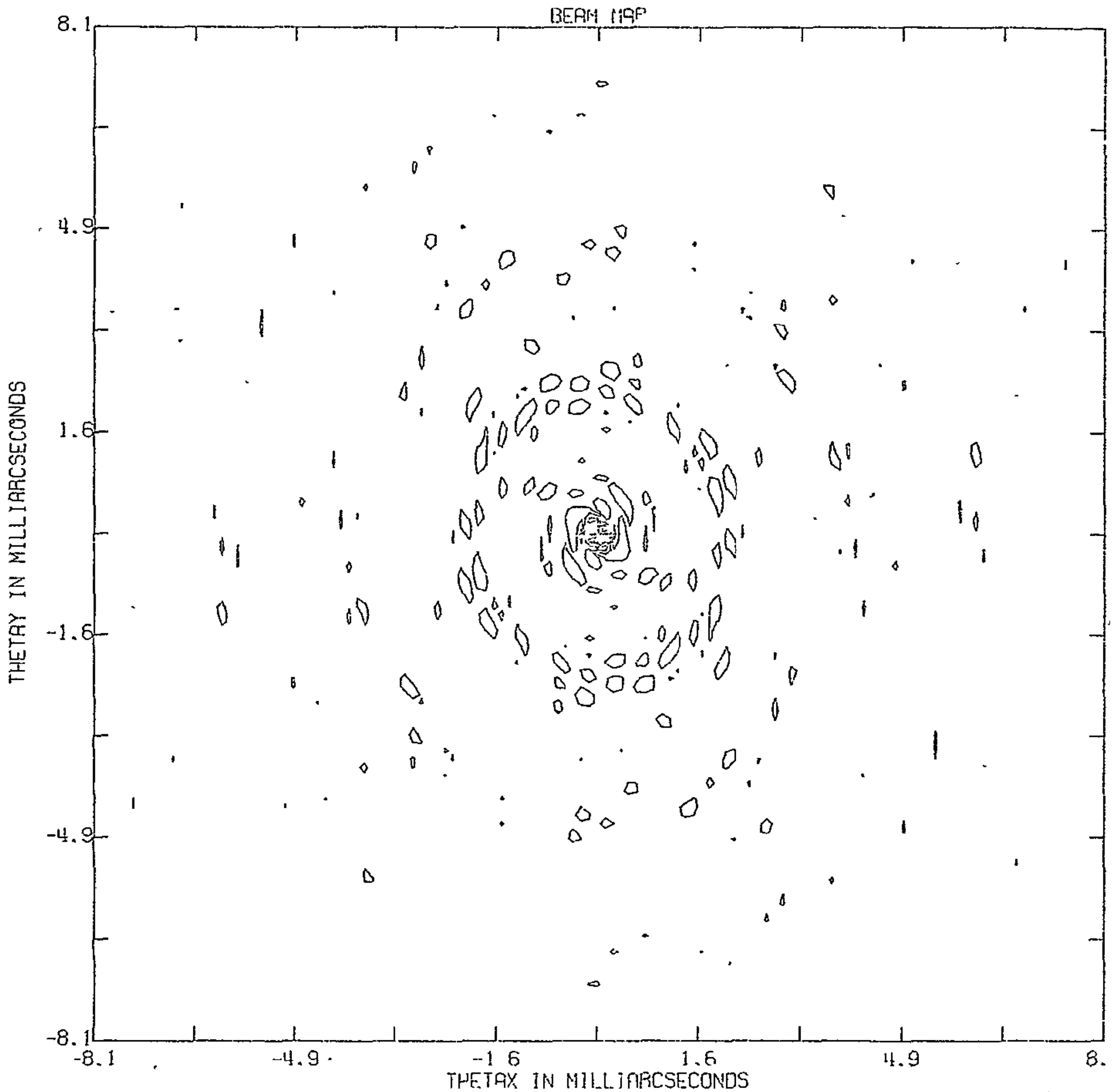

Figure 3-3b: W3; $\Omega = 0°$

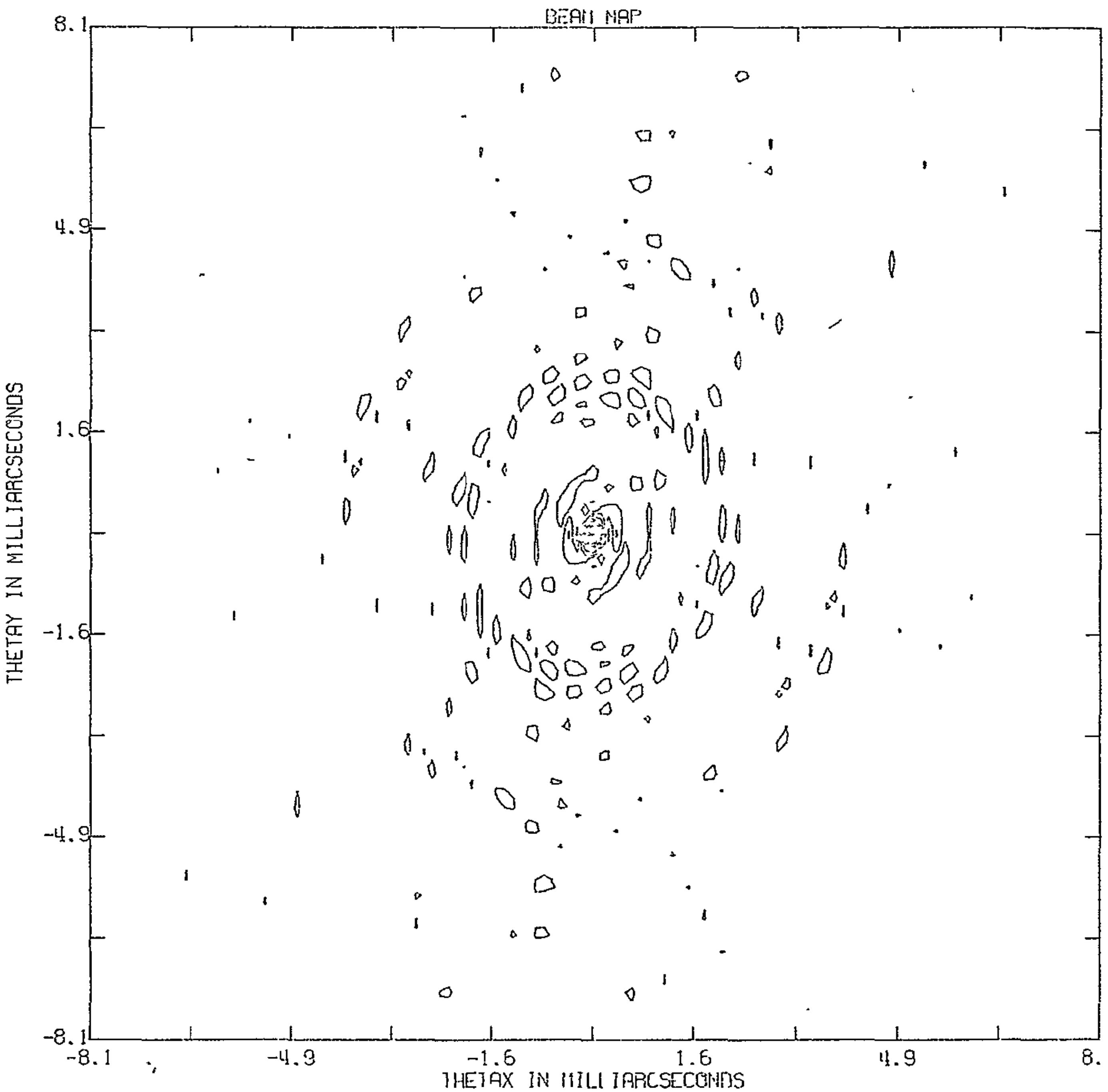

Figure 3-3c: W3; $\Omega = -90°$

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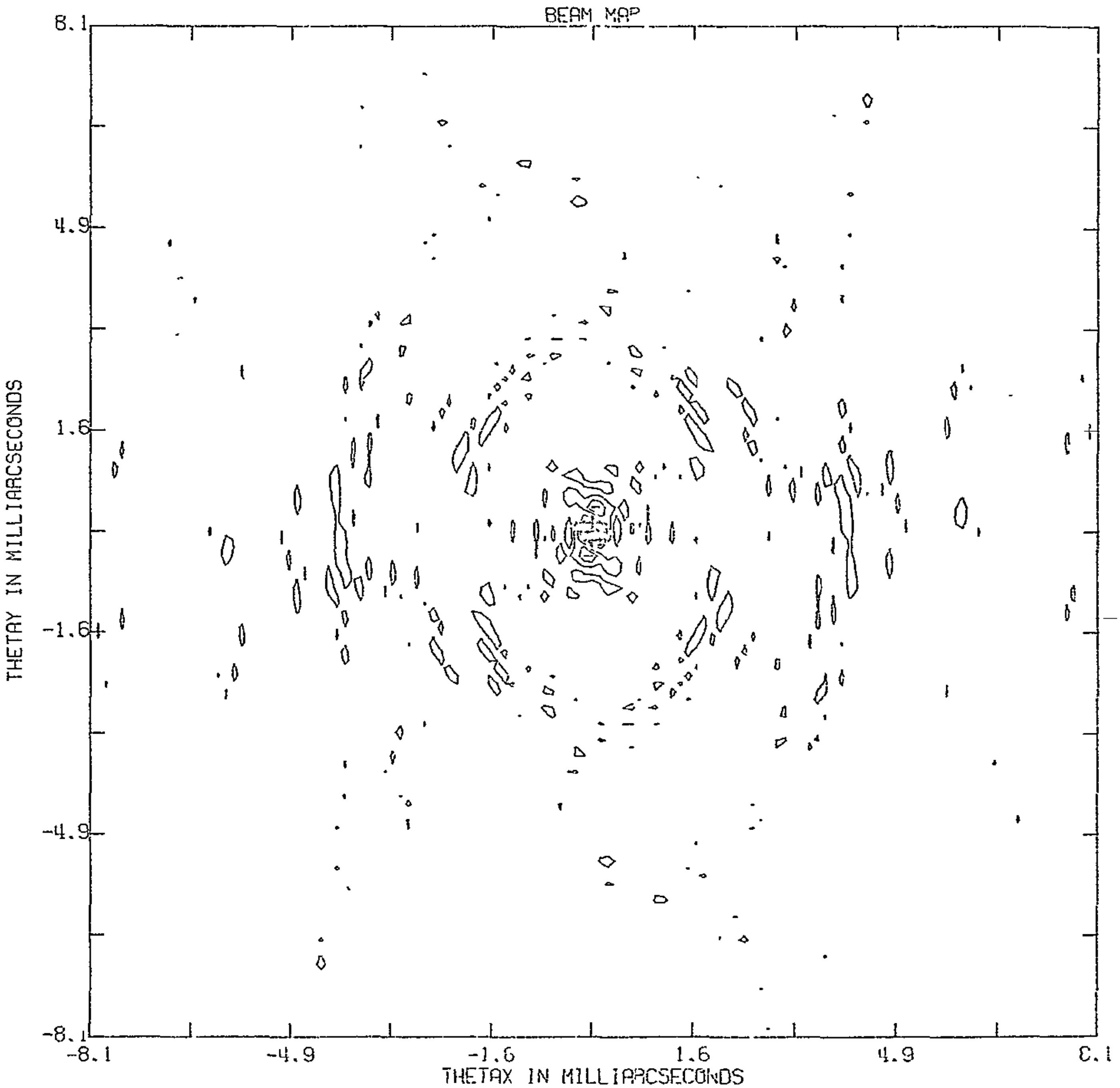


Figure 3-3d: 3C84; $\Omega = +90°$

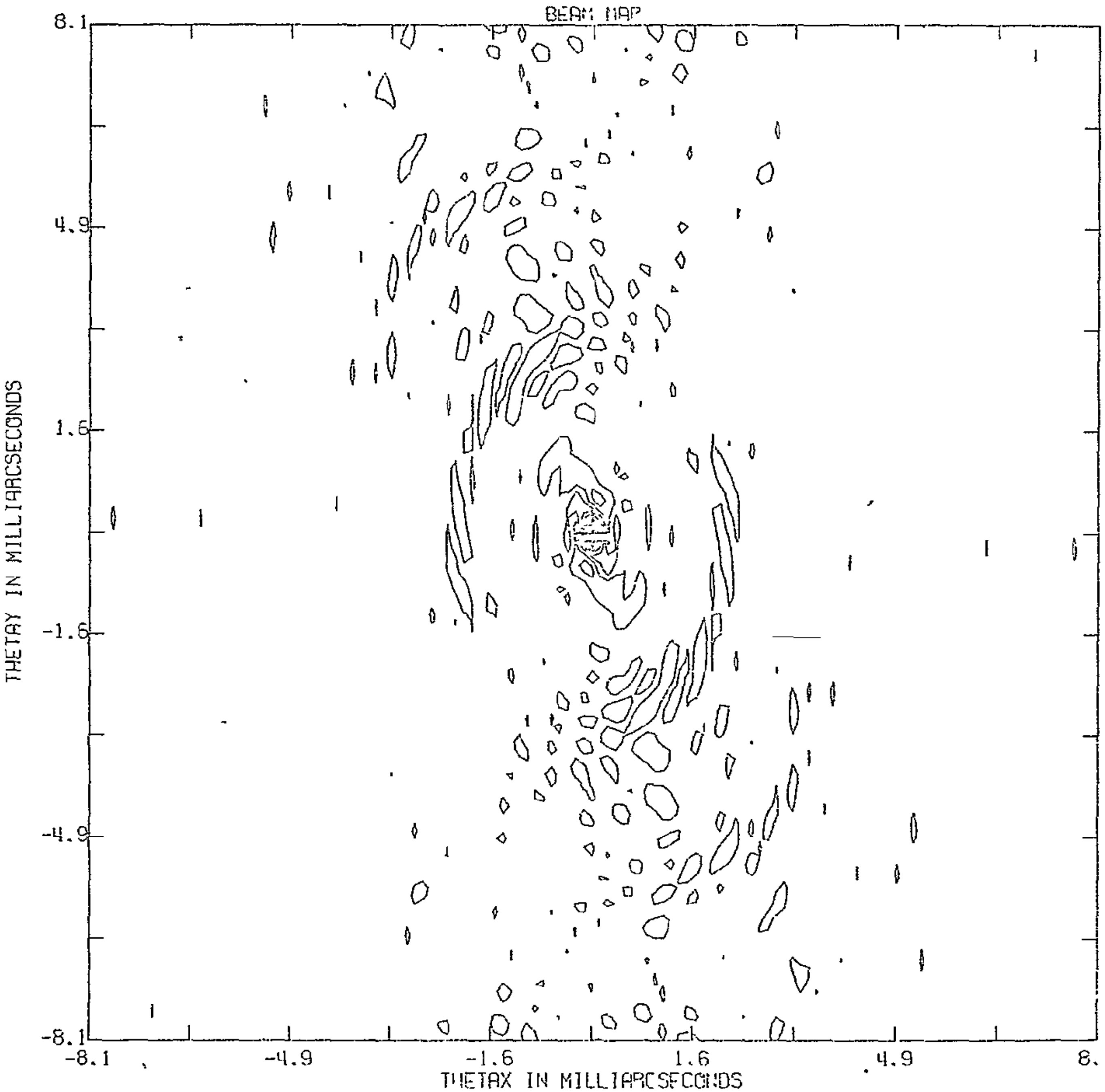


Figure 3-3e: 3C84; $\Omega = 0°$

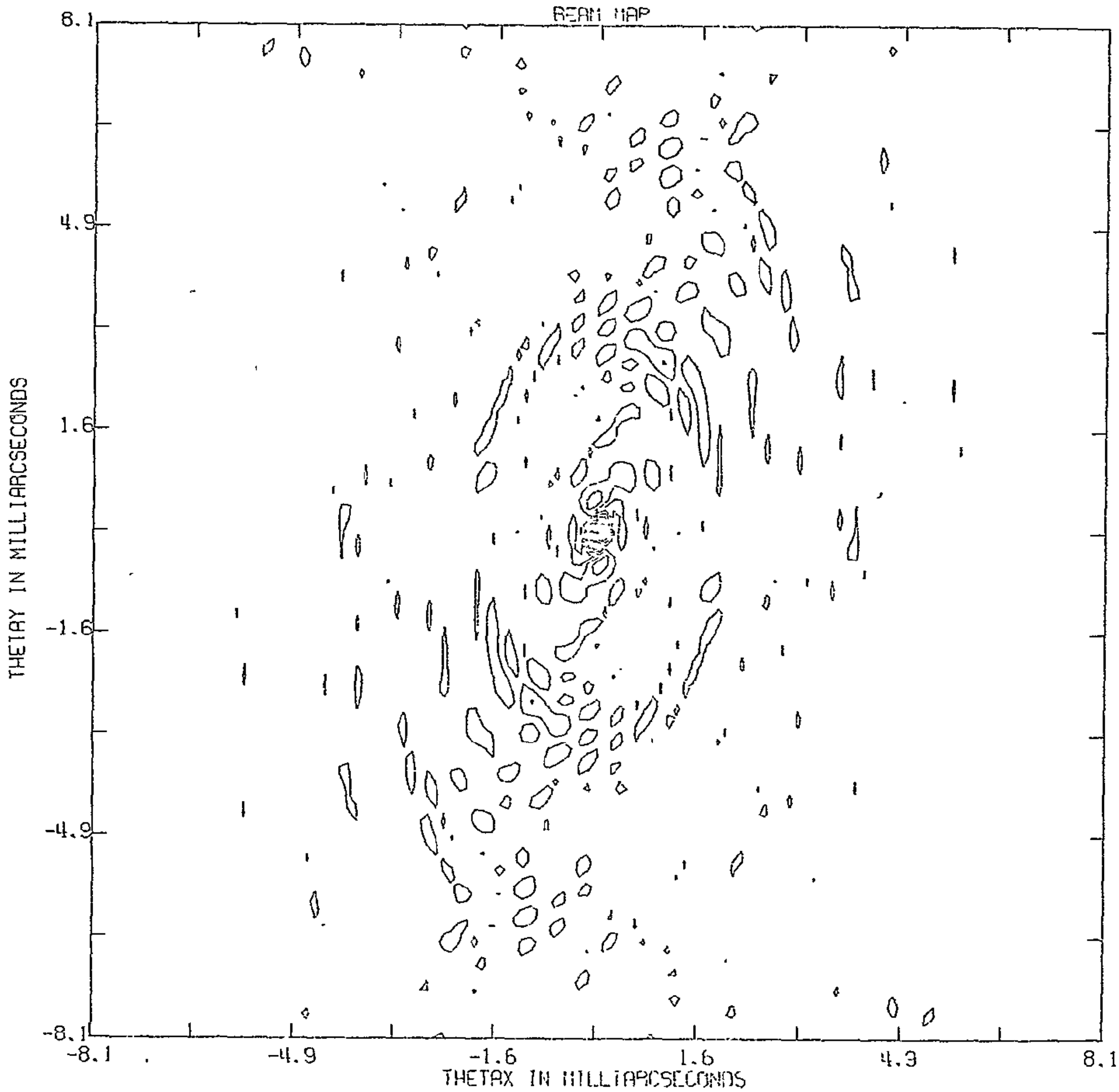


Figure 3-3f: 3C84; Ω = -90°

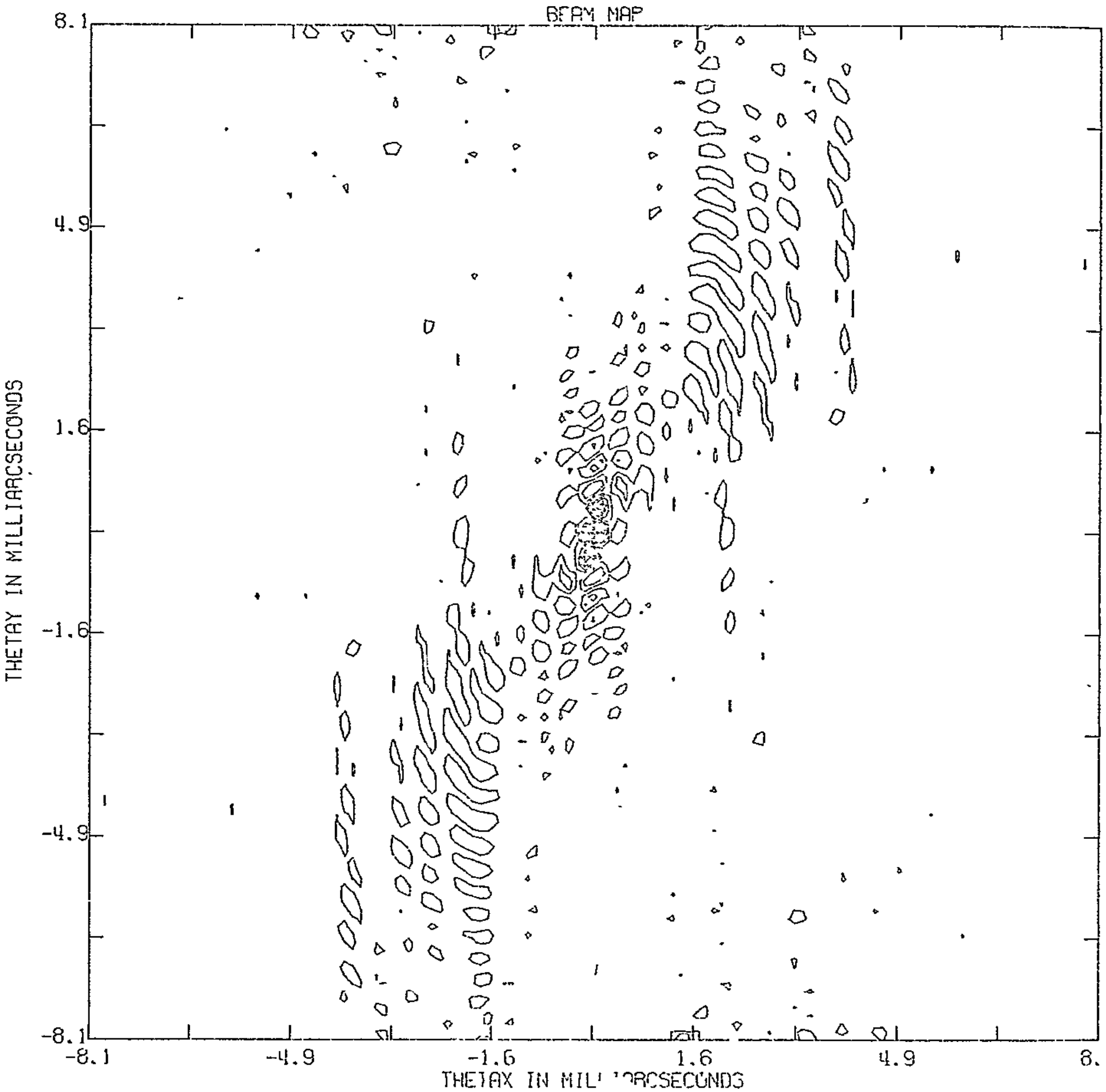


Figure 3-3g: W49; $\Omega = +90°$.

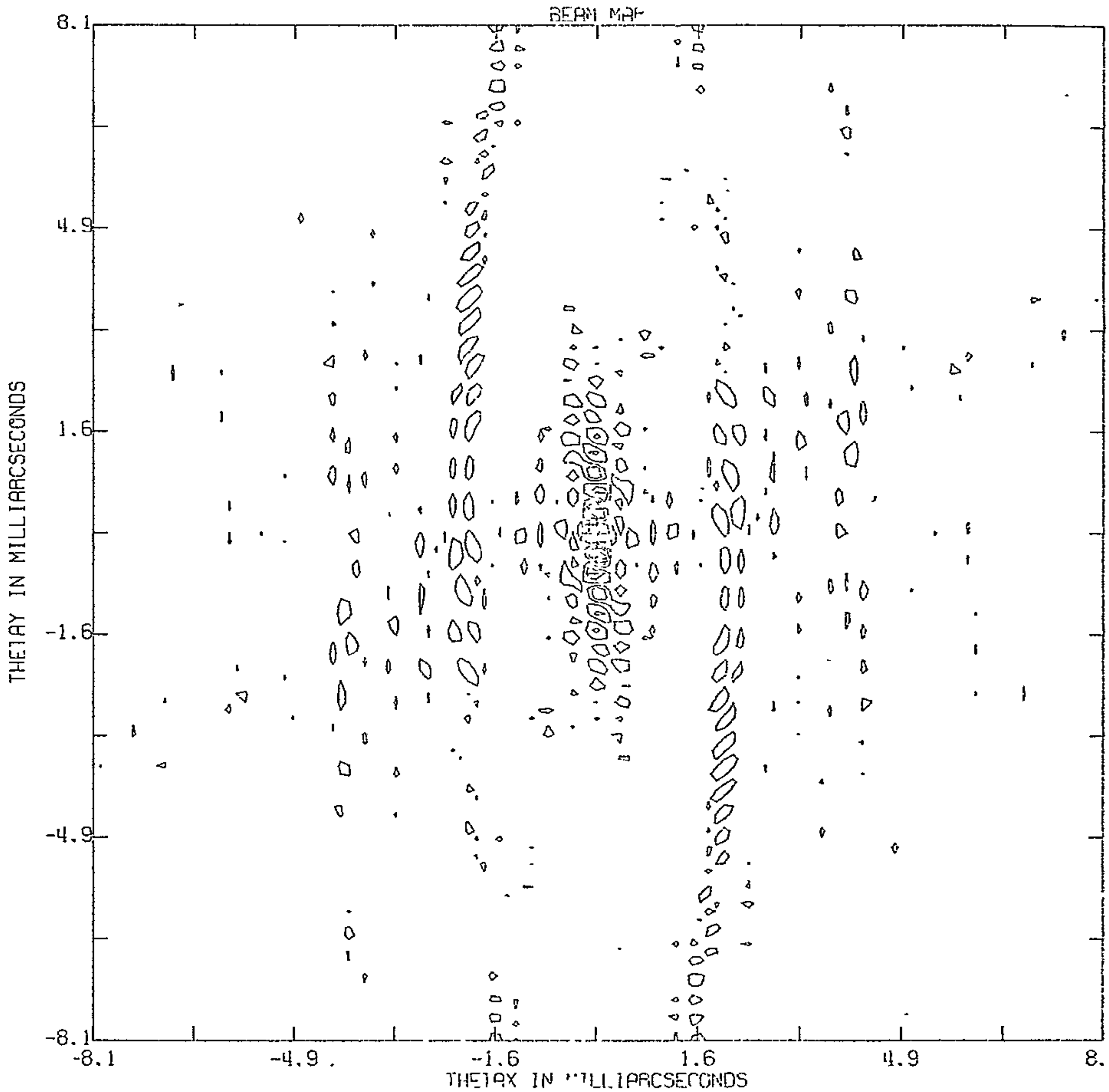


Figure 3-3h: W49; Ω = 0°

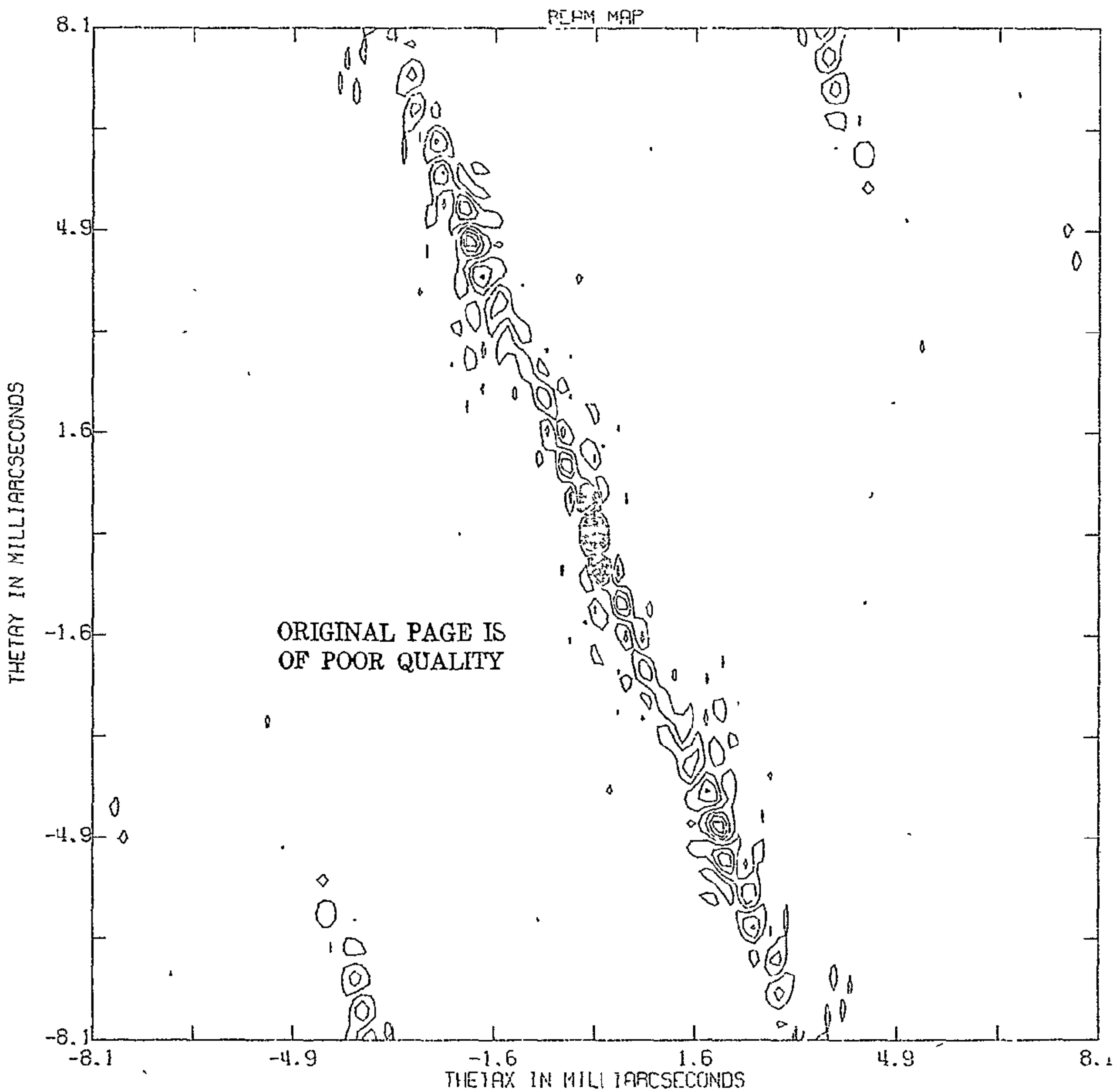


Figure 3-3i: W49; $\Omega = -90°$

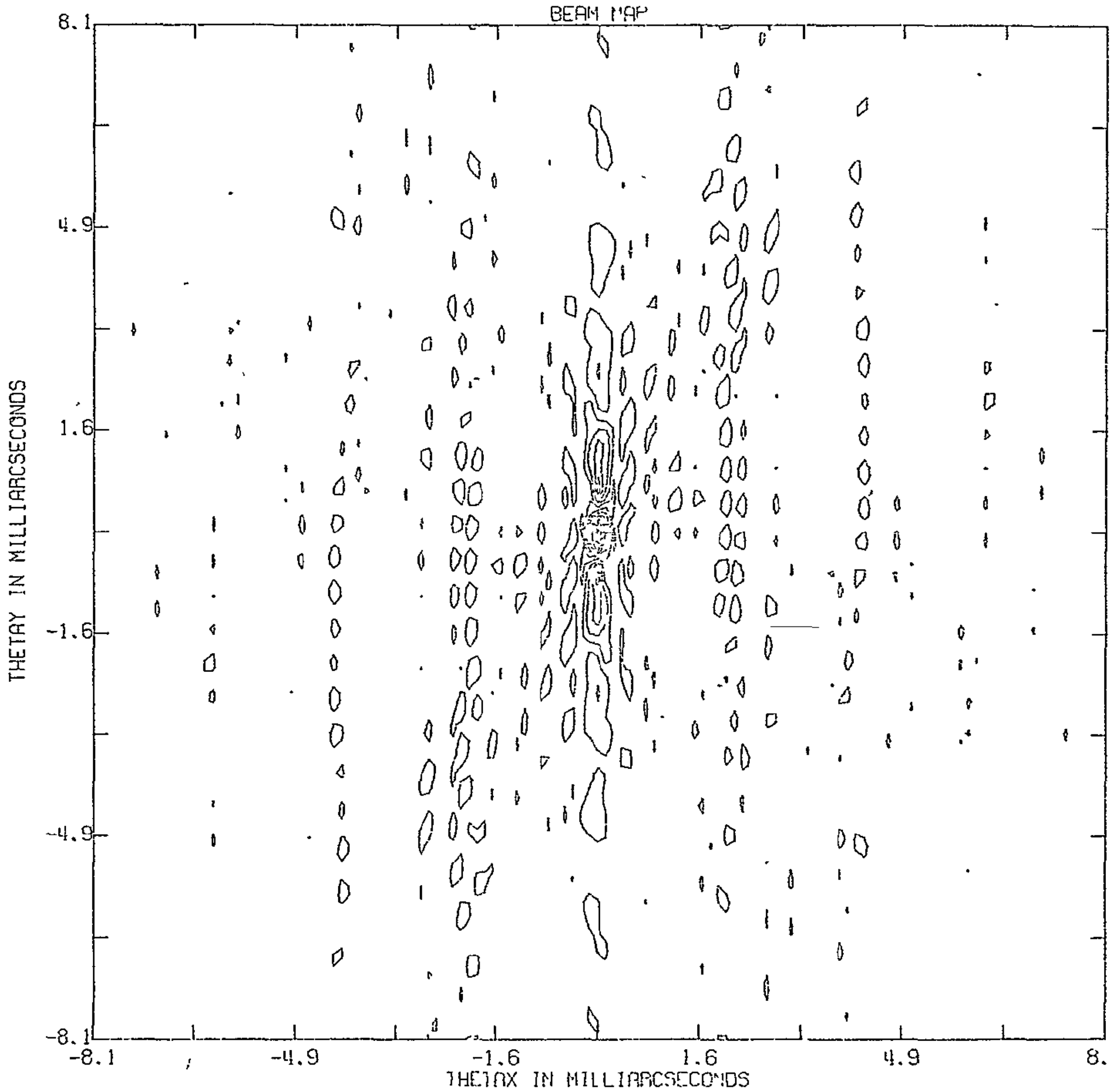


Figure 3-3j: 3C273; Ω = +90°

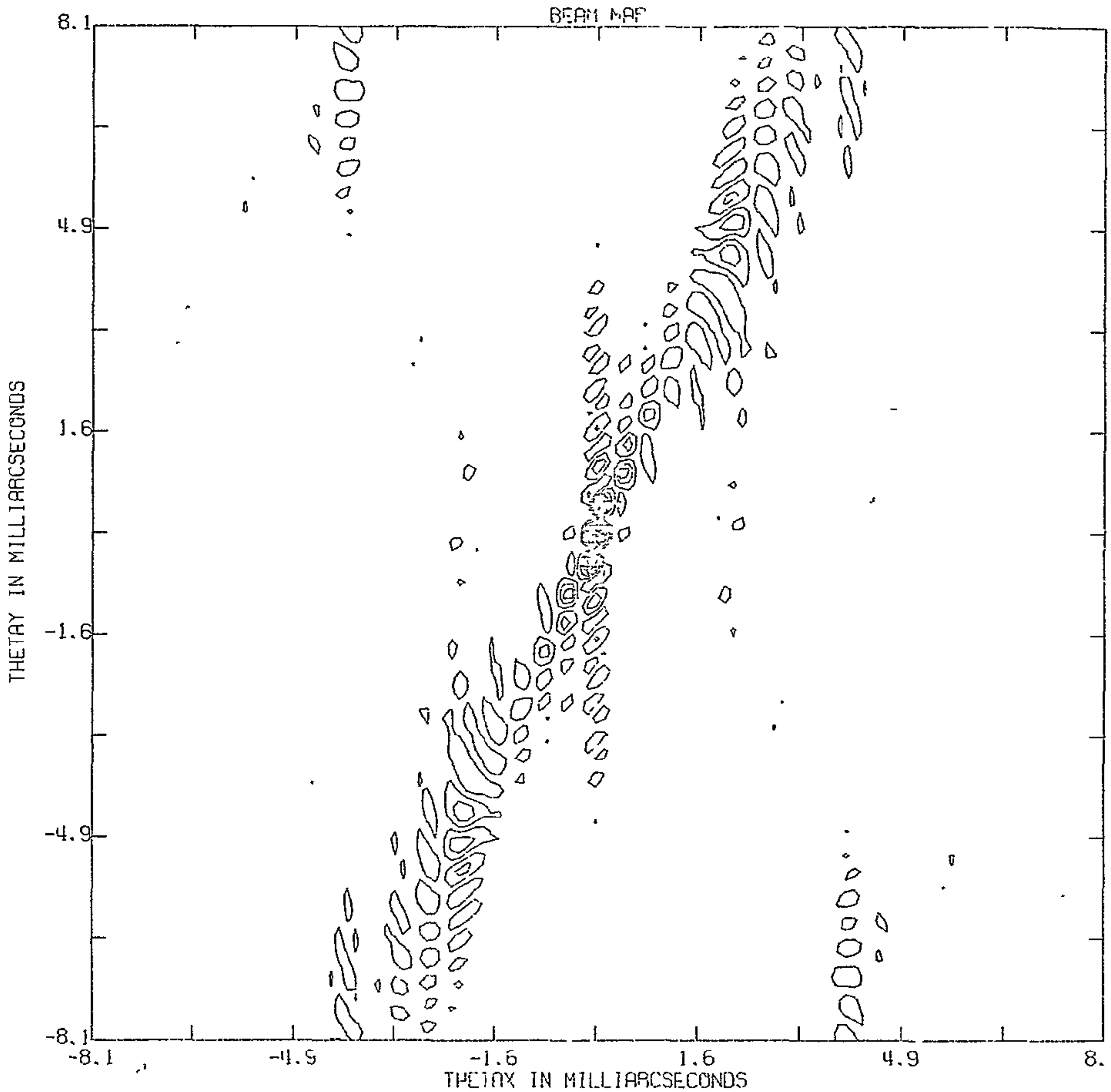


Figure 3-3k: 3C273; $\Omega = 0°$.

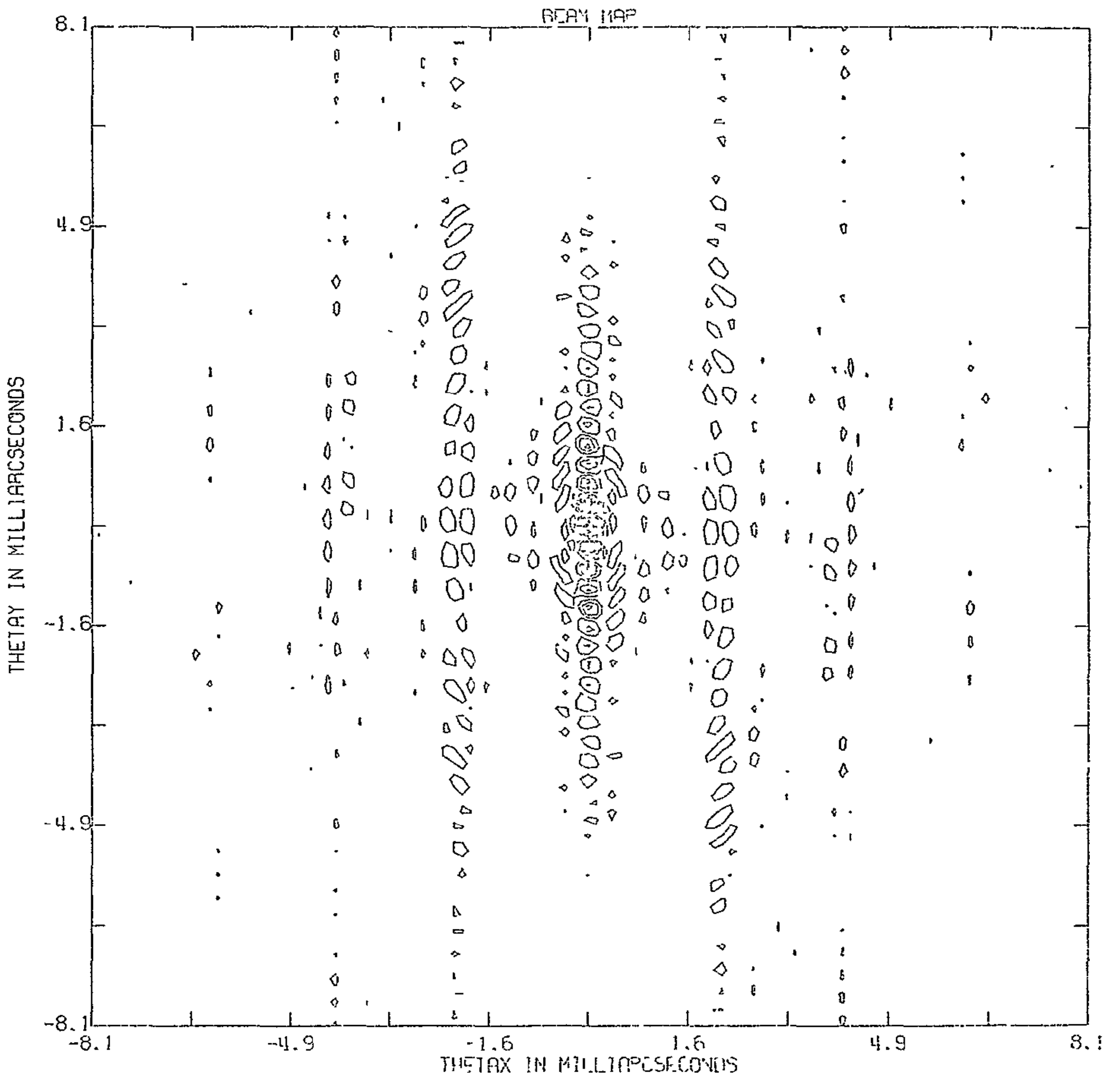


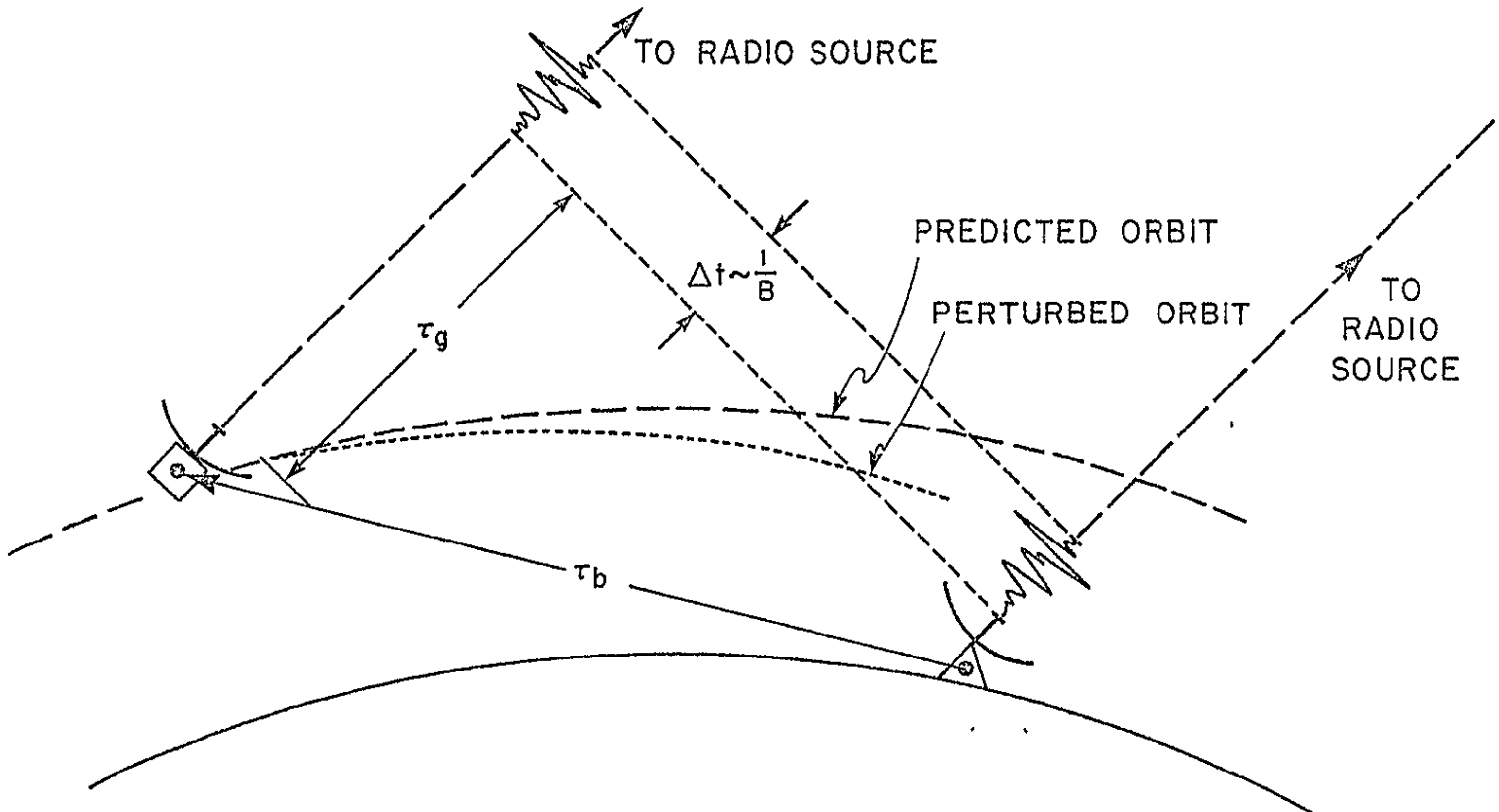
Figure 3-31: 3C273; Ω -90°

Thus, from these examples, we see that a VLBI terminal in space could improve the efficacy of the observing program enormously. Our studies indicate that the cost of a modest space terminal required to achieve this improvement is certainly no greater than the cost of installing and staffing an additional large ground-based radio telescope. Further, because a space terminal inherently provides better coverage and more available baselines, it would make possible results that never could be realized practically with any number of ground-based stations at any price.

3.1.2 Determination of Experiment Feasibility

The initial spacecraft orbit will have errors, and it is essential to examine the orbital precision required for space VLBI. It is easy to show that the VLBI system has a "bootstrap" capability that overcomes orbital error estimates even when these are large. The essential VLBI technique is the "fringe rate-time delay search", a standard procedure that is often required in ground-based VLBI when a station has a timing error or an error in frequency setting. An example of this is shown in Figure 3-4, shich shows in schematic form a pair of VLBI antennas, one in space and one on the earth, receiving signals that have amplitudes $e_s(t)$ and $e_G(t)$, respectively. (The VLBI technique is <u>coherent</u> interferometry, in contrast to the Hanbury Brown-Twiss incoherent interferometry method).

For the moment, we consider both antennas as fixed. The incoming noise signal from the cosmic radio source obeys gaussian random statistics in all known cases, and so the correlation time



SPACE-TO-EARTH VLBI SYSTEM

Figure 3-4

of the signal is the inverse of the bandwidth. For a continuum source, the receiver bandwidth determines the correlation time, while for a line source the linewidth is the effective bandwidth. The usual reduction procedure consists of cross-correlating the two time series, $e_G(t)$ and $e_S(t)$, and forming an average over some short period of time centered on a given time t_i:

$$R_i(\tau) = \left\langle e_G(t)\ e_S(t + \tau)\right\rangle_{t_i}$$

Clearly, the correlation amplitude will be small unless τ is approximately the geometrical time delay, τ_g, to within the correlation time. We thus can make a search in delay time, looking for maximum correlation, if τ_g is only approximately known, and obtain a greatly improved measurement of τ_g for the time t_i. This is the basis for the geodetic applications of VLBI: a set of time delays for various radio sources at different declinations and hour angles permits a solution for the baseline vector, τ_B.

Now, consider the effect of earth rotation, or (equivalently) spacecraft motion. The two signals will constructively and destructively interfere as τ_g moves through wavelength intervals, so the set of cross-correlations, R_i, will oscillate sinusoidally in time. Thus the phase and amplitude of the interference fringes are given by the set of R_i's, which thus yield the fourier component corresponding to the projection of the baseline $\tau_B(t_i)$ on the plane normal to the source direction.

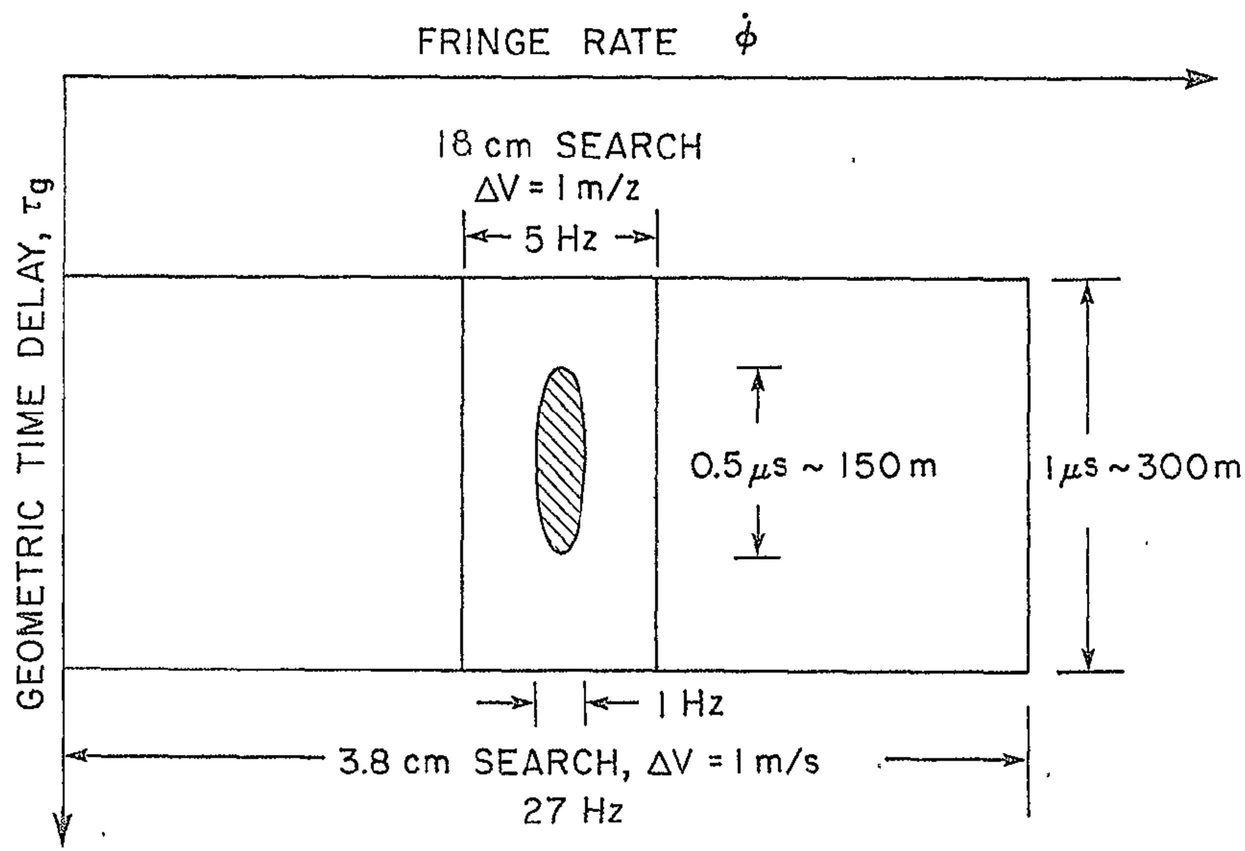
One can easily see, however, that a further parametric fit is required. The finite signal-to-noise ratio of the set of cross-correlations, R_i, require an averaging process to recover the fringe amplitude and phase. Numerous procedures can be folllowed, but what one usually performs is, in effect, a cross-correlation of a fringe pattern at the expected fringe frequency with the series $R_i(t_i)$. The fourier component is thus the best fit in amplitude and phase, over an averaging time long enough to yield a significant answer (10σ, for example). If the wrong fringe frequency is used, and the error over the integration time is an appreciable fraction of 2π radians, the derived fringe amplitude will be reduced. Even for ground-based VLBI, such errors must be searched for, since errors in frequency setting, baseline, or source position all can be manifest as an error in fringe frequency. Thus one searches in fringe frequency and in time delay, with a strong source, to establish the parameters of the system.

A specific example can be cited, using the Mark II VLBI processor as an example. A single reduction pass yields 288 simultaneous values of delay τ_g, and five different values of fringe frequency, $\dot{\phi}_k$. The correlation time for the Mark II system is 0.5 μs, and so, for a 10-second average, the fringe amplitude and phase will be determined in a single pass through the processor if the fringe frequency is known to within about 0.5 Hz and the time delay, τ_g, is known to within 140 μs (10 km distance equivalent). Thus one can derive, in a time approximately equal to the original observing time, the optimum parameters $\tau_o, \dot{\phi}_o$. Much more extensive searches for initial parameters have been carried out routinely with the Mark II system.

Now consider the real case of a moving spacecraft. Even though the projected baseline is changing more rapidly, no real difference exists in the data reduction procedure. For the earth-based case, the projected baseline is changing at a rate of about 0.5 km/s because of the rotation of the earth. The satellite is moving 16 times faster, so the fringe frequencies are 16 times more rapid, but this requires only modest changes in present reduction procedures. The mean spacecraft position is initially known to some accuracy, as is the spacecraft velocity. When one initially questions satellite experts, they give estimates for the expected errors in orbital parameters that are small, but as one presses for worst-case examples, the error limits tend to enlarge. In no case, however, does it seem likely that the error in spacecraft position and velocity for a given time will exceed 300 meters or 1 km/sec. The search parameters, for an observing frequency of 1.6 GHz and an averaging time of 1 second, are shown schematically in Figure 3-5, where we show the range of parameters τ, $\dot{\phi}$ to be searched, compared to the required precision to get the desired correlation.

The total fringe frequency-time delay space to be searched in this example is only 14 times the size of the correlation box, and the correlation maximum would be determined in a single reduction pass through the Mark II VLBI processor. At 3.8 cm, with 1 second averaging, the range to be searched is larger but only three passes through the processor would be needed. In fact, even at 1.3 cm, with a Mark III system of 20 MHz bandwidth, the search in $(\tau,\dot{\phi})$ is an easy one. Once system parameters have been calibrated on strong sources, weaker sources that require longer integration can be studied.

Next, one must examine the effects of unexpected perturbations



FRINGE RATE $\dot{\phi}$
18 cm SEARCH
$\Delta V = 1$ m/z
5 Hz
GEOMETRIC TIME DELAY, τ_g
0.5 μs ~ 150 m
1 μs ~ 300 m
1 Hz
3.8 cm SEARCH, $\Delta V = 1$ m/s
27 Hz

Figure 3-5

on the orbit. We consider the effects of uncertainty in the gravitational field, Δ_g; atmospheric drag, Δa_a; radiation pressure, Δa_r; and internal perturbations caused by attitude control jets, crew motions (if on a manned platform) etc.

The effects can be estimated easily by considering the perturbed orbit shown in Figure 3-4. If the actual orbit deviates from the ephemeris orbit by an appreciable fraction of a wavelength during the integration period, the fringe phase will drift, i.e. there will be a perturbation in the apparent fringe rate. If the displacement is very small compared to a wavelength, the effect is negligible, and a value for the fringe amplitude and phase are directly obtained by standard methods. If the displacement is comparable to a wavelength or larger, one must search in fringe frequency for the maximum correlation, that is, one will derive the perturbed fringe frequency, from which the orbital perturbations would be inferred. The expected effects, it turns out, are surprisingly small.

The uncertainties in the gravitational field of the earth, Δg, are presently of the order of 10^{-3} cm/sec^2. In a 10 second integration, the spacecraft would move 0.5 mm, a negligible amount even if the observing wavelength is 1.3 cm. In a 50 second integration, the unpredictable motion might amount to 1.25 cm, which would cause problems at 1.3 cm, but not for 3.8 cm or 18 cm. Ordinarily, one would not integrate for longer than 50 sec, since spacecraft motion carries one over an appreciable part of the fourier transform plane, and 10 sec is a good nominal value for an eventual space-based system having appreciable collecting area. The conclusion is, therefore, that the uncertainties in g are no problem, and in fact one might expect useful new information on the earth's gravitational field.

A spacecraft with an area-to-mass ratio of 0.2 cm^2/g at 360 km altitude could be expected to experience unexpected accelerations of the order of 3×10^{-4} cm/sec^2 from atmospheric drag, and 10^{-6} cm/sec^2 from radiation pressure. These are substantially smaller than gravitational corrections, and we therefore conclude that no serious problems would be caused by such perturbations.

Internally caused accelerations, such as crew movement if the spacecraft is manned and jet-caused motions from attitude control or leakage are not entirely negligible. Further study of these problems should be undertaken. For the space shuttle, it is known that transient accelerations of 10^{-3} to 10^{-4}g can occur, although the rms values should be less. Control of crew movement during observation, detection of transient spacecraft acceleration by inertial means, and control of gas venting and leakage are all feasible means of control. The problems all appear tractable, but must be examined in further studies.

We conclude, therefore, that none of perturbations are sufficiently serious to prevent VLBI observations in space.

3.1.3 The Ultimate Limits of VLBI

The uncertainties introduced by refractive effects in the earth's atmosphere have been well studied in earth-based VLBI problems, and in the space-based case, there are no new problems. For earth-based VLBI systems, the radio telescopes are looking through independent samples of the earth's atmosphere, generally at such different elevations that the differential electrical phase-shift due to atmospheric refraction is comparable to the total effect itself. Thus, having one telescope in space can only ease the problem.

The "seeing" limitations imposed by the interstellar medium itself are not entirely negligible, however, and must be considered further. Observations of the distant H_2O masers have shown that scattering effects in the interstellar medium can amount to no more than 2 x 10^{-4} arc-sec at 1.35 cm wavelength, for a path traversing 14 kpc in the plane of the galaxy, since that is the size observed for H_2O masers in W49. The path length through the interstellar medium is only of the order of 100 pc toward the galactic poles, so scattering would be much less. The most drastic assumption is that the scattering angle varies as the square root of the path length, so one would expect that the average scattering, at high galactic latitude, would amount to approximately 10^{-5} arc-sec. The interstellar medium is not uniform, and one can expect that some regions would be more transparent. Furthermore, it does not seem likely that the observed disc sizes of H_2O masers in W49 are entirely determined by scattering. One can reasonably conclude, therefore, that 1.35 cm observations should permit angular resolution of the order of 5 x 10^{-6} arc-sec at high galactic latitudes.

We have summarized the parametric possibilities in Figure 3-6. The resolution limits of K-(1.3 cm), X -(3.8 cm) and L -(18 cm) sources are shown. The 1.3 cm system would realize the estimate limiting resolution with an orbit that goes out to 40 earth radii,

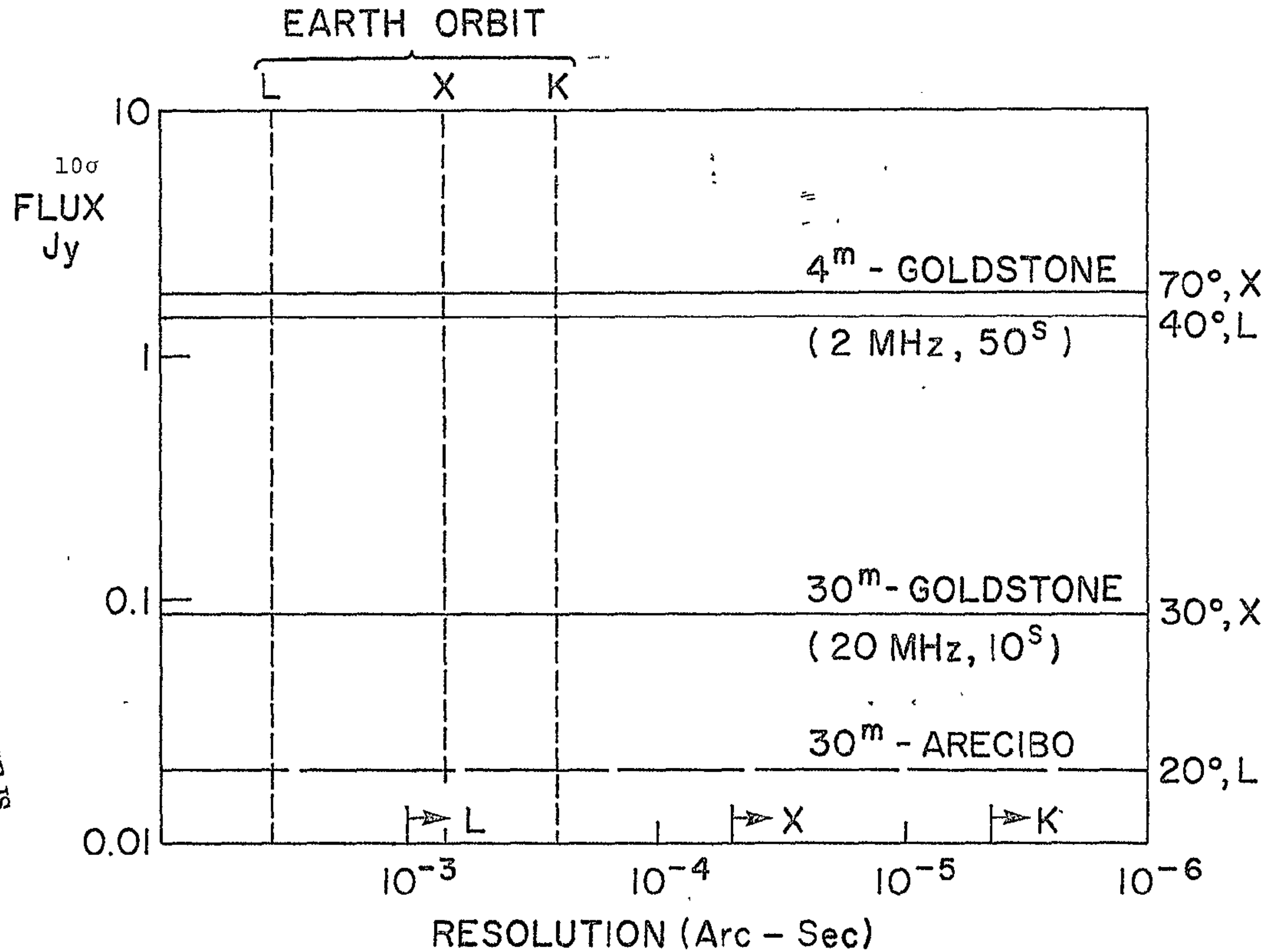


Figure 3-6

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although it may well turn out that the scattering caused by the interstellar medium is less severe than the conservative limits that we have used. Much larger orbits, and correspondingly greater angular resolution, would then be possible. By going to still shorter wavelengths, one can gain in angular resolution still further, and there seem to be no technological barriers in doing so.

Figure 3-6 also contains estimates of the sensitivity of various possible systems. A reasonable program that we have used as a model might consist of an initial prototype system, using a 4 m telescope that would fit in the bay of the space shuttle, and which would be easily pointed since its intrinsic beamwidth is large. When used with the Goldstone 210-ft telescope, the system would achieve a 10σ signal-to-noise ratio for a 1.8 Jy point source at 3.8 cm wavelength, if the system noise temperature of the orbiting station was 70° K, and at 18 cm the sensitivity would be 1.4 Jy for a 40° K receiving system. Some two dozen sources could be studied by such a prototype system.

A larger orbiting antenna, plus better noise performance, would be desired for the next stage. For a 30 m telescope, 30° K X-band receiver, and 20 MHz bandwidth, the sensitivity would be .08 Jy for a 10-sec integration (using shorter integrations for more detailed mapping). Over a thousand sources could be studied by such a system.

Finally, we show a different class of system, in which the enormous receiving area of the Arecibo telescope would be used. The instrument can only operate to zenith angles of 20°, so complete mapping of sources is not achieved, but a high-resolution sample (and in fact good sampling to baselines of half an earth diameter) would give angular size information on sources at the .02 Jy level. Many thousands of sources, some undoubtedly at enormous redshifts, could be studied by such a VLBI system.

3.2 Implementation

The definition of an optimum system configuration for a VLBI terminal in space requires a selection from a plethora of possibilities, with major choices ranging from minimal space hardening of existing equipments so that they can be used in the relatively benign environment of the Shuttle, to the periodic replacement of major subsystems in a large array radio telescope fabricated in space. We have elected primarily to pursue the former 'fix it up and fly it' philosophy. The reason is that this approach appears to offer by far the best benefit/cost ratio. First, it obviously is cheaper. Second, it involves minimum development risk. Third, it provides for a gradual learning process which is particularly appropriate for a continuously evolving and dynamic field like VLBI. And, fourth, it enhances the possibility of making useful scientific progress at the earliest possible time.

The following subsections, relating to the implementation of a VLBI terminal in space, therefore are weighted heavily by a desire to define a minimal cost and minimal risk configuration that can provide performance adequate to ensure a useful scientific advance.

3.2.1 Antenna

Ideally, of course, one would like to have an antenna comparable to those now employed in ground based radio telescopes: a properly contoured dish with a diameter of the order of 30 meters, for example. In Figure 3-6 of the previous section, one can see that with reasonable system parameters, the system sensitivity would be of the order of 0.08 Jy. Such a system would be a good goal to work toward, but a less expensive trial system should be the first step in the program.

The penalty associated with the use of a smaller antenna can be adduced simply: recalling from section 1.3 that the induced signal is proportional to $(A_1 A_2)^{0.5}$ where A_1 and A_2 are the effective areas of the two receiving antennas, we see that the system sensitivity is proportional directly to the diameter of one antenna. Thus, relative to the assumed configuration, the use of a spaceborne antenna with a diameter of 3.6 meters would degrade the system sensitivity by about one order of magnitude, yielding a noise threshold of approximately 1 Jy.

This performance level is adequate to permit the resolution of some of the outstanding and important scientific enigmas, and would be very useful. Recalling that the rationale for a VLBI terminal in space is not an improvement in system sensitivity, but rather, an improvement in coverage of the transform plane, and thus improved resolution of astronomical objects that are visible easily with the present ground based system sensitivities, it is apparent that an almost commonplace antenna would suffice.

One candidate is a copy of the communications antenna used on the Voyager spacecraft. This four meter diameter graphite-epoxy dish has a surface contour accurate within 0.01 cm, or less than one-hundredth of the shortest wavelength of interest. The quoted reproduction cost for such a dish is less than $300,000.

But the additional performance penalty for another dramatic reduction in cost is modest indeed. A simple four meter diameter spun aluminum dish with a surface contour accurate to 0.3 cm can be obtained for less than $3,000. For proper focusing of the antenna beam, the average surface deviation of the dish should be less than about one-tenth of the wavelength involved so such a dish would be effective for wavelengths greater than about 3 cm. Thus a simple $3,000 dish would permit operation at all but the two or three shortest of the eight wavelengths customarily used for VLBI measurement

3.2.2 Receiver

The most critical parts of the receiver are the low noise front end and the first mixer which heterodynes the signal so that the bandwidth interval of immediate interest is centered on a standard IF frequency. Once over this hurdle, the remainder of the receiver, the IF and video amplifiers, are relatively uncritical and, in large measure, standardized.

The wavelengths of interest in VLBI work extend from 1.3 cm in K-band, through X-band and S-band, to 21 cm in L-band; the corresponding frequency range is from 23 to 1.4 GHz. Parametric amplifiers (paramps) are almost universally used except at the very shortest wavelengths where crystal mixers or masers may be more effective. Each of the eight specific wavelengths of interest requires a unique paramp front end for the receiver.

While the bandwidths, noise temperatures, and gains required for a VLBI terminal in space are not beyond the state of the art, there is a very limited selection of immediately available hardware and, for that matter, not much expertise that is directly applicable. Space qualified hardware is concentrated primarily in S-band, particularly 2.3 GHz, and X-band, particularly 8.2 GHz, where it is used in telemetry and communication systems; but in these systems narrow bandwidths are the rule rather than the exception, and in the overall design of the system it often is cheaper to increase the transmitter power by one or two dB than to reduce the receiver front end noise temperature by another few degrees. Appropriate low noise, wide bandwidth, front ends are, of course, used in all the existing radio telescopes, but the designers of these are generally not much concerned with size, weight, mechanical integrity, power consumption, or cooling problems.

We anticipate, therefore, a need for some custom design and development work in this area. Budgetary estimates obtained from various potential vendors having the required mix of RF and space packaging skills indicate a unit cost ranging from $20,000 to $80,000 for each of the eight VLBI wavelengths eventually desired. It may be noted, however, that the packaging is an inherent part of the design of equipments operating at centimeter wavelengths so the front ends necessarily take the form of separate packages. Thus, it is not vital to have all of the desired front ends in an initial installation; one could advantageously start with two or three wavelengths and expand the system by adding separate boxes later.

3.2.3 Clock

In each VLBI terminal an atomic frequency standard is used as a master clock for the sampling and switching operations and, most importantly, as the reference source for a frequency synthesizer from which all local oscillator frequencies are derived. It is the absolute time and frequency synchronization provided by this means which makes VLBI possible.

The atomic frequency standard must have a frequency stability that permit coherent integration of the observed signal; this requires that the total phase variation should not exceed one radian at the signal frequency during one sampling interval. Typically, the desired coherent integration time is about 50 seconds, so the clock stability required ranges from two parts in 10^{12} for observations at 1.4 GHz (21 cm) to one part in 10^{13} for the highest observed frequency of 23 GHz (1.3 cm).

A cesium clock developed for the Navigation Technology Satellite and Navstar programs is available for $50,000. The stability of this clock is entirely adequate for the two or three lowest frequencies of interest but at the higher frequencies the allowable integration time would be unacceptably short.

Incorporating a carefully selected sample of the latest design cesium tube in this instrument would improve the stability by a factor of two or three. This would permit unrestricted operation at all but the two or three shortest wavelengths. It would just barely permit operation at all wavelengths, although with a slightly reduced integration time, and hence somewhat reduced sensitivity, at the two shortest wavelengths of interest.

Although this solution is less than ideal, it is the approach we recommend at this time because the next level of improvement is quite expensive.

A hydrogen maser frequency standard has been space qualified and flown for a gravitational redshift experiment by the Smithsonian Astrophysical Observatory under NASA contract NAS8-27969. This instrument demonstrated a frequency stability of better than one part in 10^{14}, a stability adequate to permit unrestricted operation of a VLBI terminal with a very comfortable design margin. The costs of duplicating the hydrogen maser and its associated systems has been estimated to be approximately $0.5 M.

In addition, a prototype hydrogen maser frequency standard/ clock system compatible with the NTS series spacecraft has been developed by the Hughes Research Laboratories under Navy Contract N00014-75-C-1149 for use in Phase III of the NAVSTAR/Global Positioning System (GPS). Initial life tests indicate an operational life in excess of five years and frequency stability better than one part in 10^{14}. This system has been proposed to be flown on the NTS-3 satellite in 1981. The estimated cost ($5.2 M) for a similar system place it out of the realm of possibilities for all but a permanent VLBI station in space.

3.2.4 Onboard Data Processing

During a VLBI observation realtime data processing is limited to those activities necessary to ensure that the two or more isolated but cooperating terminals are observing the same source at the same time, and that the data is sampled and recorded in a standard format. The data sampling process is controlled automatically by the VLBI terminal instrumentation: inherently it must be controlled by the atomic frequency standard that is a part of the equipment. Time synchronization is ensured by annotating the output data stream with time reference codes derived from the same atomic frequency standard. Thus, the only realtime problem is that the antenna beam must be pointed accurately toward a preselected radio signal source.

The simplest means of ensuring that the antenna beam is pointed accurately is to use the receiver in a radiometric mode as a wideband total power detector. This is accomplished easily by using an internal switch to connect the front end of the receiver alternately to the antenna and to an internal calibration noise source, another internal switch being used to synchronously demodulate the receiver output so that a measure of received power is available to the controller. This apparatus also is required for self test and calibration of the receiver and so already is a normal part of the VLBI terminal instrumentation.

Using the receiver in this manner as a total power radiometer is a sufficient solution to the antenna steering problem if the signal intensity is large enough to permit an unequivocal measure of signal power: this will be the case for most of the targets of immediate interest. The antenna is first pointed by offsetting from inertial axes or optically visible stars. The direction of the antenna beam then can be refined by executing a small raster scan while observing the total power output integrated over a very few seconds. The point of maximum power then defines precisely the optimum antenna beam direction.

As experience is gained with a VLBI network incorporating a spaceborne terminal, it is likely that progressively more attention will be given to the weaker radio sources. With some of these it may not be practical to steer the antenna properly on the basis of a total power measurement alone because the required integration times would become inconveniently long. For this type of target, offset guidance and star tracking must be performed in real time.

For weak maser sources the antenna can be accurately pointed by computing the power spectra of received signal as the antenna is raster scanned. The maser sources have characteristically narrow spectra and can be readily identified against the background noise. It may be that the central computer of the host vehicle will have sufficient computing capacity available and so will be able to perform the power spectrum calculations, although this is not likely due to the very fast data processing rates that are required. It is likely, therefore, that the spaceborne VLBI terminal eventually will have to include a special purpose processor to perform the autocorrelation and fast fourier transform calculations that will be needed to facilitate taking real-time spectra of masers for checking system performance. The high speed digital correlation techniques required for this purpose are well understood and pose no special problems. In any case, this requirement is somewhere in the future: a simple radiometric power measurement will suffice for all of the targets of immediate interest.

3.2.5 Telemetry

Telemetering, and subsequently recording, the data in a form compatible with the existing VLBI data processing computers is, perhaps, one of the more formidable obstacles to a VLBI terminal in space. This is partly because of a synchronization requirement discussed below, but mainly because of the large volume of high rate data that has to be handled. The handling of high rate digital data is well understood, and the TDRSS* will provide more than adequate capacity: the problem is that a four megabit per second data stream has to be telemetered without interruption for intervals of a few tens of minutes, a requirement which may usurp a major share of the telemetry system capability while VLBI observations are in progress. Our parochial view, of course, is that the scientific return amply justifies this, but we recognize that other experimenters who are sharing the telemetry link may be narrow minded.

The synchronization difficulty alluded to above arises because of the manner in which VLBI data is recorded. The *(sic)* Mk II system that is currently used employs a helical scan magnetic tape recorder. One frame of data, comprising a serial string of 66,000 bits with a frame duration of about 1/60th of a second, is recorded each time the rotating head makes a complete pass across the two inch wide magnetic tape. A synchronizing code is recorded as the first item in each such pass: this is used later to phase lock a servomechanism so that the tape can be played back at the correct rate. The second item recorded in each pass is a frame count number which unambiguously relates the subsequent data to a time synchronizati code that is recorded on a separate track on the magnetic tape. This time synchronization is a *sine qua non* because the whole essence of VLBI is that one has to measure the absolute time difference between the receipt of the same signal at two or more independent terminals.

The data sampling and recording process is straightforward in

*Tracking and Data Relay Satellite System a conventional VLBI ground terminal where the receiver, the atomic frequency standard, and the tape recorder are all part of the same equipment. The frequency standard provides an absolute time reference for a clock which controls the bit sampling time and the frame sampling time, and which intersperses the frame count at the right instant so that it forms the first record on each pass of the rotating recording head. It is important to maintain this same recording format so as to avoid any need to change existing data reduction equipments. With a telemetry link interposed between the receiver and the recorder, therefore, time codes must be multiplexed with the data stream at the transmitter, and, at the receiver, the time codes must be demultiplexed and the data stream passed through a first-in, first-out buffer which allows the data rate to be synchronized with the motion of the rotating head.

None of this is particularly difficult, but it does require a first-in first-out buffer accomodating 66,000 bits and operating at a 4 megabit per second rate: a facility that is not a normal part of either the telemetry system or a conventional VLBI terminal. Further, in a system in which a telemetry link is interposed between the receiver and the recorder, the frame sampling rate and the motion of the rotating head of the recorder are necessarily unsynchronized, and since the recording head velocity is not well controlled this causes a small loss of data: we estimate about five per cent, which is not serious but not negligible.

3.2.6 Guidance

Inherently, VLBI observations require the cooperation of two

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isolated radio telescopes, and scheduling constraints dictate that radio signal sources that are to be observed must be selected some weeks before the observations are made. Further, results of VLBI observations are not known until some weeks after the actual observations because these results come from a lengthy correlation of two separate recordings. Consequently, there is almost no realtime decision making or target selection to be performed, and the guidance problem is simply that of pointing the antenna beam in a specified direction at a specified time.

Now the antenna beamwidth is given by:

$$\Theta \simeq \frac{2.1 \quad 10^4}{f \quad D}$$

where Θ is the 3 dB beamwidth in degrees

f is the operating frequency in Megahertz

D is the antenna dish diameter in meters

As discussed earlier, an inexpensive four meter dish would permit operation at wavelengths down to about 3 cm, that is, at frequencies up to about 10 GHz; the corresponding minimum antenna beamwidth then would be about 0.5 degrees. This is compatible with the performance of the Shuttle Orbiter inertial measurement unit which is expected to provide a three sigma initial pointing capability of slightly better than 0.5 degrees. Thus, one could be assured that the selected target would be within the antenna beamwidth, and final antenna pointing could be achieved using the total power measurement discussed earlier.

The use of a larger dish would change the situation in two respects. First, a larger dish would have to be deployed rather than being attached rigidly to the Shuttle bay. And, second, the antenna beamwidth decreases in inverse proportion to the size of the dish, making the guidance problem more demanding. For example, a 36 meter, accurately contoured, dish operating at 1.3 cm has an antenna beamwidth of about 0.025 degrees, or 1.5 arcminutes. While not requiring the pointing accuracy of a few arcseconds that will be provided by the Shuttle Instrument Pointing System, initial pointing of such an antenna would require a star tracker similar to that employed in, for example, the third Small Astronomy Satellite, HEAO-A and C.

The guidance problem, therefore, falls into one of two broad categories. Assuming that body flexures are calibrated, an inexpensive dish fastened rigidly to the Shuttle bay can be pointed with entirely adequate precision by the main Shuttle guidance system. An autonomous deployed antenna, however, would require a dedicated star tracker that must be an integral part of the antenna structure so as to avoid flexure and mechanical distortion problems.

3.2.7 Operational Considerations

Data from the VLBI terminal would be handled by the Spacelab Command and Data Handling (C&DH) system. Primary scientific data, for post flight analysis and evaluation, and operational data, for monitoring and control of the terminal during the mission, would be carried by separate down links from the Orbiter.

Operational data can be handled by the Spacelab Experiment Data Bus and its associated S-Band link. Individual experiments, such as the VLBI terminal, would obtain access to this bus via one or more Remote Access Units (RAUs). The RAUs provide commands and timing signals (including GMT and Mission Elapsed Time) to the experiment and accept analog and digital data in a variety of formats. Since the bus will be computer controlled, the experiment data system will be highly flexible with regard to data formatting and control of the experiment.

Primary scientific data can be handled by the Spacelab High Rate Multiplexer (HRM) and TDRSS Ku-Band data link. This link handles a maximum data rate of 50 MBpS. As presently envisioned, the HRM will allocate this total rate between as many as sixteen users with varying maximum data rate requirements. The input ports of the HRM have maximum data rates which are related in binary ratios: 2, 4, 8, and 16 MBpS*.

HRM data will flow through the TDRSS ground station at White Sands, NM to Goddard Space Flight Center (GSFC) and to the Spacelab Payload Operations Control Center (POCC) at Johnson Space Center (JSC). Data transfer between these locations will be under the control of NASCOM (the NASA Communications Network) and will flow by means of the DOMSAT system.

GSFC will record all HRM scientific data for post-flight processing and distribution. JSC will process and display a sample of the HRM data and all available operational data at the Spacelab POCC**.

Experiment data would be demultiplexed and displayed at a console in the POCC. The VLBI experiment group would be able to

* Spacelab Payload Accommodations Handbook, May 1976

**This information and that which follows comes from a discussion of POCC capabilities with JSC personnel & W. Lenoir Astronaut Office directly control the VLBI experiment from a keyboard on this console. Certain critical commands, those which might affect safety or interfere with other instruments or the operation of the Orbiter, can be "locked out" by the command computer. These critical commands would be issued only with the approval of the Mission Operations Control Center.

Guided by the quick look data available here, the experiment group can make real-time decisions affecting the experiment and will be able to revise its observing plan as the results of the on-going experiment dictate.

There remains in this operational scenario a large number of unknowns. Mission planning has not yet progressed sufficiently to allow all POCC requirements to be fully defined. The established POCC baseline, which allows the experimenter to interface with his experiment directly, to control it from a dedicated keyboard and to observe his quick look data in real time is a straightforward and highly attractive approach. If the approach can be maintained as the POCC and Spacelab requirements become more fully defined we will achieve a highly workable operational scientific instrument system. If mission requirements ultimately dictate that most or all instrument operations must flow through a mission operations controller then an effective means of interaction between the scientific team and the controllers needs to be implemented in order to ensure the high quality of the scientific results.

3.2.8 Payload Specialist Usage

The role of the Payload Specialist (PS) on Spacelab missions is not well defined at the time of this report. Potential roles for the PS range from that of an on-orbit technician who would respond to voice to commands from the ground to that of a PhD scientist who would control his instrument personally and make on-the-spot changes to his experiment plan in response to the incoming data.

We can see the possibilities in either role. For VLBI observations, however, we believe that the former role is more appropriate. In VLBI, the final scientific results will not beome available until some time after the flight and therefore the observing plan will be largely predetermined. As is discussed above, the observing activity will be centered in the POCC and it is there that we anticipate making the real time operational decisions.

We do see an important role for the payload specialist during pointing operations. In slewing from one source to another or in fine pointing of the VLBI antenna the PS would be able to interact directly with the flight crew and thereby optimize the pointing process. Such pointing operations would probably be done with reference to a VLBI instrument star tracker, not to radio sources, and could use star map computer programs which are presently under consideration for inclusion in the Orbiter program set.

4.0 CONCLUSIONS

We have shown that significant improvements in angular resolution of celestial radio sources are achievable with an orbiting VLBI terminal. The vastly improved coverage of the fourier transform plane enables mapping of compact celestial sources with finer resolution, less ambiguity, and more efficiency than can ever be achieved by earth-based VLBI systems. Such a system would permit detailed studies of quasars, BL Lacertae objects, galaxies with active nuclei, Seyfert galaxies, interstellar masers, binary stars and other phenomena of galactic and extragalactic origin.

While there are a large number of possible configurations for a space-borne VLBI terminal, we advocate a "phased growth" philosophy beginning with a modest four-meter dish hard mounted to a Spacelab pallet, hydrogen frequency standard, and low-noise L and S band paramp receivers. This approach enables the earliest possible experience in space VLBI techniques and offers by far the best benefit/cost ratio. It provides for a gradual learning process and the opportunity for substantial scientific results while avoiding major developments by adapting existing designs to flights on the Shuttle. Later improvements such as larger deployable antennas, lower noise pre-amplifiers at shorter wavelengths, and wider bandwidths can be incorporated as experience and funding permit.