Phasing the Very Large Array on Galileo in the Presence of Jupiter's Strong Radio Emission

J. S. Ulvestad
Navigation Systems Section

Work is in progress to determine the feasibility of using the Very Large Array (VLA) radio telescope to receive telemetry from Galileo during its close encounter with Io on December 7, 1995. The VLA was used previously to receive telemetry from Voyager 2 at Neptune. However, Jupiter's strong radio emission is an additional complication in the case of the Galileo encounter. This article analyzes the effect of Jupiter's radio emission on the phase-adjustment procedure ("autophasing") used to maintain coherence among the 27 VLA antennas. Results of an experiment designed to mimic the Io encounter are presented. As expected, Jupiter's strong radio emission has a considerable effect on the autophasing procedure. A simple emission model is found to give a good approximation to the fringe-visibility plots derived from the VLA data, and that successful model is used to estimate the VLA's ability to autophase on Galileo during the Io encounter. The effect of Jupiter should be small for projected baselines longer than ~800 m, and completely negligible for projected baselines longer than ~1.1 km.

The most extended configuration of the VLA (the **A** *configuration) probably can be used successfully for telemetry reception during the Io encounter. Further analysis and testing of the effect of correlated noise from Jupiter is necessary before a final decision can be made about the feasibility of using the second largest (***B***) configuration of the VLA for reception of Galileo telemetry. Use of the* **B** *configuration could simplify the upgrades needed to support the Io encounter. Tests to help choose the preferred VLA configuration could be performed by using the VLA to observe the Magellan spacecraft at Venus during July and October 1991.*

Examination of the effects of planet noise on the VLA have implications beyond the use of that telescope for supporting the Io encounter. The effects of planet radio emission on spacecraft data received by antenna arrays are relevant to choosing the exact locations of antennas that might be built by the Deep Space Network in coming years.

I. Introduction

The Galileo encounter with Io, scheduled for December 7, 1995, requires reception of 8.4-GHz (X-band) telemetry at 134.4 kilobits/sec for approximately 4 hours. The Galileo Array Study Team was formed in the spring of 1990 to determine how the Deep Space Network (DSN) could provide sufficient confidence in the data return from the Io encounter. The report of that team was given in [1]. An important conclusion was that use of the Very Large Array (VLA) radio telescope [2,3] would provide a powerful enhancement to the DSN reception capability for the Io encounter. The VLA already has been used successfully by the DSN, as it was arrayed with the Goldstone Deep Space Communications Complex to return telemetry from the Voyager 2 encounter with Neptune [4]. The expected use for the Io encounter would differ in that the VLA would be used in a stand-alone mode, rather than having its signal arrayed with that of the Goldstone Complex.

The VLA, located southwest of Socorro, New Mexico, consists of 27 25-m antennas, nine on each arm of a Y-shaped configuration. These antennas are ~60 percent efficient at 8.4 GHz and are equipped with receivers having zenith system temperatures of ~30 K [5]. The spacings between adjacent antennas along each arm increase with distance from the center of the array. Four major configurations are employed: **A, B, C,** and **D**. The respective total lengths of each arm in these configurations are 21 km, 6 km, 2 km, and 0.6 km.

The VLA would use the spatially unresolved signal from the Galileo spacecraft to adjust the phase calibration of each antenna in order to maintain coherence among the different antennas of the array. A detailed investigation of this procedure for the Voyager 2 Neptune encounter was reported in [6]. The "autophasing" procedure relies upon the assumption that the received signal on each interferometer baseline is dominated by a point source, so that phase residuals are dominated by system noise and propagation effects, rather than by extended radio emission. More discussion of the meaning of autophasing and the phase residuals is found below, in Section II.

The presence of the strong radio emission of Jupiter places constraints on the ground configuration. This planet is an extended radio source with a flux density of ~8 to 20 Jy[1] at 8.4 GHz; the exact strength depends on the variable Earth–Jupiter distance. In an observing bandwidth of ~8 MHz, which was the value used for the Voyager encounter with Neptune, Jupiter's signal will be considerably stronger than that expected from Galileo when the spacecraft arrives at the planet. Therefore, autophasing can be corrupted by the presence of Jupiter. However, Jupiter is an extended radio source; as baseline lengths are increased, the spatial resolution of Jupiter's emission reduces Jupiter's effect on the autophasing process. In addition to its effect on autophasing, Jupiter's radio emission can affect the signal-to-noise ratio (SNR) of the telemetry stream obtained by adding the signals of the individual antennas. The effect of Jupiter will be to cause some correlation between the noise at antennas that are located close to each other. This correlated noise would be more harmful than uncorrelated noise; analysis of its effects is beyond the scope of this article.

On September 28, 1990, Jupiter passed approximately 2 arcmin from the natural radio source 0839+187. This radio source has an 8.4-GHz flux density near 1 Jy, similar to the expected Jupiter-encounter value for Galileo in an 8-MHz bandwidth; also, like Galileo and other spacecraft, it is an unresolved source as seen by the VLA.

This article presents an analysis of the effect of Jupiter on VLA autophasing on the Galileo spacecraft. Section II defines interferometer phases and elaborates on the autophasing process. Section III contains a calculation of the relative strengths expected for Jupiter and Galileo on the day of Io encounter. Section IV analyzes the theoretical effect of the resolution of Jupiter on autophasing using the VLA. Section V describes VLA observations of Jupiter's close passage to 0839+187 on September 28, 1990; a model that adequately reproduced the fringe visibility during that passage is described. In Section VI, that model is used to predict the effects expected on the day of Io encounter in 1995. Section VII contains a discussion of the results of the simulations and their impact on the selection of the VLA configuration for the Io encounter. Possible further VLA experiments are described in Section VIII. Broader implications for the locations of antennas in future DSN antenna arrays are discussed briefly in Section IX. Finally, the results of this work are summarized in Section X.

II. The Meaning of Phases and Autophasing

In order to understand the VLA phase-adjustment process and the experiment described below, it is necessary to describe the meaning of "phase" and "autophasing" in interferometric observations. A two-element interferometer measures the amplitude and relative phase of the cross-correlation of a signal for a pair of antennas; the VLA

---
[1] 1 Jy = 10^{-26} W m^{-2} Hz^{-1}

is a set of 351 simultaneously operating two-element interferometers. The measured phase on each baseline is affected by the geometry of the observations, propagation effects, instrumental effects, and system noise. Both the propagation effects and many of the instrumental effects are antenna-based in nature; i.e., they are peculiar to a particular antenna and common to all two-element interferometers including that antenna. Therefore, standard calibration methods use measured interferometer phases to determine phase offsets peculiar to each antenna. The normal interferometer mode of the VLA involves no attempt to adjust phases in real time, since those phases carry information about the structure of a radio source that is being mapped. Instead, calibration is accomplished by making observations of another (point) radio source, which are used later to solve for the phase calibration of the individual antennas. During post-observation data analysis, that calibration is applied to the source that is to be mapped.

Autophasing differs from the interferometer mode of the VLA because it attempts to make all the antennas coherent on a particular source by means of a quasi-real-time phase calibration. This is done for telemetry reception and for very long baseline interferometry in order to make the VLA mimic a single antenna whose collecting area is equivalent to that of a 130-m-diameter radio telescope. The calibration is made during the observations by assuming that the source being observed is a point source. Then the phase contributed by the source structure should be negligible. The interferometer phases on each baseline are used to construct a least-squares solution that finds the phase calibration peculiar to each antenna, and then remove the antenna-dependent effect from the data in (near) real time. Phases are corrected by means of a feedback loop delayed by a few seconds to tens of seconds. Both the 351 measured baseline phases and the 27 individual antenna phase calibrations will be referred to below.

III. Relative Strengths of Jupiter and Galileo

At the time of the Io encounter, the distance from the Earth to Galileo and Jupiter will be 6.2 astronomical units (AU), or 9.3×10^8 km. The total flux density of Jupiter at 8.4 GHz should be approximately 8.4 Jy (scaled from values given in [7]). About 6.7 Jy would be in the planet's atmospheric emission, with another 1.7 Jy in the radiation belts. A 25-m VLA antenna has a sensitivity of 0.110 K/Jy at 8.4 GHz [5]. Therefore, the antenna temperature contributed by Jupiter will be about 0.9 K on the day of Io encounter. This is a small fraction of the system temperature of an individual antenna; thus, Jupiter should add only a small amount to the random thermal noise at each antenna.

For Voyager, an 8-MHz observing bandwidth was used for autophasing. In that bandwidth, the total power received from Jupiter during the Io encounter would be 6.7×10^{-19} W m^{-2}. However, the centimetric radio emission of Jupiter is unpolarized, whereas the spacecraft signal is all in a single circular polarization. Thus, in comparing the spacecraft strength to Jupiter, only a single circularly polarized VLA channel should be considered; the received power from Jupiter in such a channel will be only half the total power. Taking this factor into account and considering the scaling with the observing bandwidth $\Delta\nu$, the received power in a single VLA channel will be

$$P_J = 3.4 \times 10^{-19} \left(\frac{\Delta\nu}{8 \text{ MHz}}\right) \text{ W m}^{-2} \qquad (1)$$

For Galileo, estimates for the low-power mode of the high-gain antenna are a transmitter power of 40.5 dBm with a mean gain of 48.7 dBi in the direction of Earth. Spacecraft power is expected to be inadequate for use of the high-power mode of the transmitter, so the low-power mode is assumed throughout this article. At a distance of 6.2 AU, the expected received power is

$$P_G = 7.7 \times 10^{-20} \text{ W m}^{-2} \qquad (2)$$

This value assumes that the total observing bandwidth used at the VLA will be wide enough to contain all significant power from various harmonics of the Galileo telemetry sidebands. Therefore,

$$\frac{P_J}{P_G} = 4.4 \left(\frac{\Delta\nu}{8 \text{ MHz}}\right) \qquad (3)$$

Equation 3 holds for $\Delta\nu \gtrsim 5$ MHz, which is wide enough to encompass almost all the power in the sidebands; at smaller bandwidths, the received power in the Galileo signal would begin to be reduced.

At this stage, it should be noted that VLA observations of Galileo probably will use a different setup than for the Voyager–Neptune encounter. Specifically, rather than operating the VLA correlator in its continuum mode for the autophasing, the correlator will be used in the spectral-line mode. The different setup is related to the need to eliminate significant telemetry gaps in VLA stand-alone data for a data rate that will be more than six times the rate delivered from Voyager at the Neptune encounter. Consideration of the details of the setup of the back end of the VLA are beyond the scope of this article, but those details will influence the final choice of the effective autophasing bandwidth, $\Delta\nu$.

IV. Predicted Effect of the VLA's Spatial Resolution of Jupiter

At VLA rise time on the day of the Io encounter, Galileo and Jupiter will be separated by 0.85 arcmin, well within the primary beam of a single VLA antenna, which has a full-width at half maximum of ~5 arcmin at 8.4 GHz. If Jupiter were a point source, its signal would be considerably stronger than that from Galileo (cf. Section III above); the VLA autophasing procedure would make the antennas mutually coherent on Jupiter, but then they would not be in phase for Galileo. Therefore, the Galileo telemetry signal from the 27 antennas would not be combined coherently, and the effective gain of the VLA would not give an adequate SNR for the spacecraft telemetry.

Interferometers having a long enough baseline can resolve away the bulk of Jupiter's disk, so that the autophasing procedure would respond primarily to the point-like radio emission from Galileo. To evaluate the baseline length required, consider the complex fringe visibility for an interferometer with baseline $\vec{b}$. This interferometer observes an extended radio source whose intensity distribution is $I(\vec{r})$, where $\vec{r}$ is the angular position in the radio source relative to a reference point within the source. The amplitude of that fringe visibility, multiplied by the total power from the source, gives the correlated power observed by the interferometer. The complex fringe visibility is given by

$$V = \frac{1}{A_0 I_0} \int_S A(\vec{r})\, I(\vec{r})\, e^{-2\pi i \vec{b}\cdot\vec{r}/\lambda} d\Omega \qquad (4)$$

(e.g., [8]). In Eq. (4), $A(\vec{r})$ is the effective area of an individual antenna in the direction given by $\vec{r}$, A_0 is the effective antenna area along the pointing direction, I_0 is the ~~maximum~~ total intensity of the radiation from Jupiter, λ is the observing wavelength, S is the source area that contributes to the integral over the solid angle Ω, and i is the imaginary number representing $\sqrt{-1}$.

Assume that the VLA antennas' effective areas are constant over the radio source, since the individual antenna beamwidths are much larger than Jupiter's disk. Further, let the distribution of emission be uniform over the Jovian disk (angular radius r_J) and zero elsewhere. Then $A(\vec{r})I(\vec{r}) = A_0 I_0$ for $r \le r_J$. [The assumption that $I(\vec{r})$ is constant may lead to an overestimate of Jupiter's effect on the autophasing by up to 20 percent, since it ignores the fact that some of the radio emission comes from more extended radiation belts.] Then

$$V \approx \int_0^{r_J} r dr \int_0^{2\pi} e^{-2\pi i \vec{b}\cdot\vec{r}/\lambda}\, d\theta \qquad (5)$$

where θ is the angle between $\vec{r}$ and the projection of $\vec{b}$ on the sky plane. If D is the projected baseline length as seen from the direction of Jupiter, Eq. (5) reduces to

$$V \approx \int_0^{r_J} r dr \int_0^{2\pi} e^{-2\pi i D r \cos\theta/\lambda}\, d\theta \qquad (6)$$

Note that D is the *projected* baseline perpendicular to the line of sight to Jupiter; the projected baseline, rather than the actual physical separation of two antennas, is the relevant quantity for interferometry. The integral in Eq. (6) gives a first-order Bessel function, J_1. Defining $D_\lambda \equiv D/\lambda$ to be the projected baseline length in units of wavelengths, the effective power from Jupiter would be

$$P_{\text{eff,J}} = P_J|V| = P_J \frac{|J_1(2\pi D_\lambda r_J)|}{\pi D_\lambda r_J} \qquad (7)$$

Suppose the effective power from Jupiter were less than 20 percent of the power received from Galileo on a particular VLA interferometer. Then Jupiter would affect the phase on that baseline by less than 0.2 rad. Summing two antennas out of phase by such a small angle gives a very small amplitude loss for the Galileo telemetry (cf. [6]). Hence, a reasonable condition for successful autophasing is

$$\frac{P_G}{P_{\text{eff,J}}} \ge 5 \qquad (8)$$

Combining Eqs. (3), (7), and (8) leads to the following condition for successful autophasing:

$$\frac{|J_1(2\pi D_\lambda r_J)|}{\pi D_\lambda r_J}\, \frac{\Delta\nu}{8\ \text{MHz}} \le 0.046 \qquad (9)$$

This equation holds as long as $\Delta\nu$ is not so small that a significant fraction of the Galileo signal power is excluded from the autophasing bandwidth. Examination of the values of the Bessel function (e.g., [9]) shows that, assuming $\Delta\nu = 8$ MHz, the requirement given by Eq. (9) is met for $2\pi D_\lambda r_J \geq 10$ (r_J in radians). On December 7, 1995, the angular radius of Jupiter will be 15.2 arcsec (74 μrad). This implies that, for 8.4-GHz observations, the projected interferometer spacing should be larger than 0.77 km. Many of the projected baselines in the VLA **C** configuration, used for the Neptune encounter, are shorter than this. Projected baselines will tend to be shortest when Galileo rises at the VLA, since the spacecraft clears the 8-deg elevation limit at an azimuth similar to that of the southeast arm of the VLA. Thus, the analysis shows that the VLA must be arranged in the larger **B** or **A** configuration for autophasing to be successful at the Io encounter.

V. Test Observations of Jupiter's Close Passage to 0839+187

A. The Observations

On September 28, 1990, at 1000 Universal Time (UT), Jupiter passed less than 2.1 arcmin from the natural radio source 0839+187. This natural source is a primary calibrator at the VLA, unresolved on all baselines at 8.4 GHz. Since Jupiter rose at the VLA at 0920 UT, there was an opportunity to use this close passage to test the effect of Jupiter on the ability of the VLA to autophase on the nearby point radio source. The distance to Jupiter was approximately 6 AU, making its flux density and angular size slightly larger than those expected for the Galileo encounter with Io. Approximately 70 minutes of VLA time were scheduled on September 28, from 0955 to 1105 UT. At that time, the VLA was in a **B**/**C** hybrid configuration (north arm in the **B** configuration, others in the **C** configuration). Projected antenna spacings ranged from about 70 m to 6.7 km (2,000 to 190,000 wavelengths).

During the tests, a point-source calibrator (0851+202) about 3 deg from the field of interest was observed in normal interferometer mode (with no phase feedback loop) and in autophasing mode in order to set an approximate flux density scale and to check the system performance. (See Section IV above for a further description of these observing methods.) The field including 0839+187 and Jupiter also was observed in both modes in order to supply data for autophasing simulations and to provide real-time autophasing data. Finally, an autophasing observation was made with the VLA split into two subarrays, one containing only antennas with mutual baselines longer than 850 m and the other containing many antennas near the central hub of the VLA, with a mix of long and short baselines. This last observation was meant to test the real-time performance of the autophasing procedure when only the longer antenna spacings were included.

Figure 1 shows an image of 0839+187 and Jupiter, calibrated using the observations of the nearby calibrator 0851+202. This image has undergone a deconvolution process to remove the effects of sidelobes in the synthesized VLA beam. The apparently elongated shape of the point source is caused by asymmetry in the response function of the VLA due to the north arm of the VLA being much longer than the other two arms during these observations. The *peak* flux density of the point source was a factor of ~7 higher than that of Jupiter because of the resolution of Jupiter with the longest VLA baselines. However, the *total* flux density of Jupiter was much higher than that of the point source.

B. Test Results

The results of the observations of 0839+187 initially were confusing. The SNR of more than 15 to 1 in a 5-sec integration on 0839+187 would have given phase residuals on the order of 4 deg on each baseline if system noise were the limiting factor. During observations in the autophasing mode, the displayed residual phases for each *antenna* indicated that the individual antennas had small phase residuals, as though the autophasing were working well. However, the phases on many individual *baselines* were quite large and remained relatively constant, sometimes in the vicinity of 60 deg. A listing of the phases on all baselines after the experiment indicated high values in many cases. In particular, interferometer phases on baselines that included any one of three antennas that were moderately close to the center of the array were on the order of 90 deg. Baselines involving only the few antennas closer to the center and those farther out had phases that were less than 20 deg.

The real-time antenna phase listing was misleading because the "residuals" displayed actually were just the differences between the antenna phases at the current integration and those predicted based on past integrations. These residuals accurately depict the system performance when the dominant error consists of dynamic phase fluctuations due to the troposphere or to other causes. However, in the situation where there is extended radio emission, there are phase "errors" caused by the erroneous assumption that the radio source being observed is a point source. In that case, the antenna phase solutions may not fluctuate greatly from one integration to the next even though phase coherence is not being maintained on the radio source of interest. The feedback loop would not generate phase coherence on the point source, even though the lack of fluctuations would cause the reported residuals to be small.

In the post-observation data processing, attempts were made to solve for the complex antenna gains (amplitude and phase) from the normal interferometry data. This procedure is identical to the real-time process used in autophasing, but without a feedback loop. The solutions gave enormous errors; convergence sometimes did not occur. (Unfortunately, similar failures of convergence are not reported in real time during autophasing.) Often, no individual phase solutions were reported for the same three antennas that had shown the large baseline phases in the post-experiment listings of the autophasing data. This may have been due to the confusion caused by the mixture of short and long baselines involving these antennas, with the short baselines dominated by Jupiter and the long baselines dominated by 0839+187. Figure 2 shows a portion of the reported errors from the least-squares program that attempts to compute antenna gains; this output is from an individual 5-sec integration made in normal interferometry mode at 1025 UT. The huge amplitude and phase closure errors show that autophasing would not have worked adequately.

Off-line gain solutions also were computed for the normal interferometry data using various limitations on the baseline lengths. Elimination of all baselines whose projections were shorter than 20,000 wavelengths (0.71 km) gave decent results, since the longer baselines detected very little correlated flux from Jupiter. Figure 3 displays reported errors (with closure limits of 5 percent in amplitude and 5 deg in phase) for the gain solutions with this minimum baseline length, using the same 5-sec integration as in Fig. 2. Although the baseline limitation eliminated some of the 351 baselines from the phase solution, the returned solution gave individual phases for each of the 27 antennas, since even the antennas near the center of the VLA had projected baselines longer than the specified cutoff when combined with the outermost antennas. As long as the solution for each antenna is not limited by a poor SNR on the individual baselines, the antenna solutions derived from a subset of all possible baselines should be adequate. For Galileo at Jupiter, the total received power on an individual baseline will be ~15 times higher than it was for Voyager 2 at Neptune, so an adequate SNR for phase determination will be achievable without using all the VLA baselines.

When the VLA was split into two subarrays performing autophasing independently of each other, the subarray containing only baselines longer than 850 m (most well over a kilometer) performed quite well. No phase residuals larger than 15 deg were observed either in the real-time autophasing or in the listings generated in the post-processing of the data. Again, this validated the prediction that projected baselines longer than ~0.7 to 0.8 km (20,000 wavelengths) would be adequate to remove most of the effects of Jupiter.

C. Simulations of the Test Observations

A useful tool in understanding the robustness of autophasing is a plot of the amplitude of the fringe visibility *versus* baseline length (a "visibility plot"). If such a plot is made for interferometer observations when Jupiter is in the field of view, baselines short enough to see a significant correlated amplitude from Jupiter also would have their phases affected by the Jupiter emission. Thus, the effects of Jupiter on autophasing can be estimated by looking at visibility plots.

Figure 4 is a visibility plot derived from a 9-minute observation of 0839+187 and Jupiter, using the normal interferometer mode. On baselines shorter than about 35,000 wavelengths (1.25 km), the effects of Jupiter are noticeable; the effect is greater than ~20 percent for baselines shorter than about 20,000 km, as expected. Oscillations in the correlated amplitude are related to alternating constructive and destructive interference between Jupiter and the point source, and die out as baselines become long enough to resolve Jupiter completely. For baselines longer than 35,000 wavelengths, the flatness of the plot is a result of the absence of significant correlated flux from Jupiter. These baselines "see" only the point source 0839+187, indicating that autophasing would perform well in this regime.

Figure 5 shows a visibility plot for a simulation of the observation considered in the preceding paragraph. A simple model was used for the brightness distribution of the point source and Jupiter. The size of Jupiter's disk and the source separation were fixed by Jupiter's actual angular diameter and the positions of the point source and the planet, while the baselines sampled were those actually used to acquire the test data illustrated in Fig. 4. The flux densities of the sources in the simulation were adjusted to give a good qualitative correspondence between Figs. 4 and 5. The final model included a point source of flux density 0.93 Jy and a uniform disk of total flux density 6.0 Jy.[2] The absolute flux densities in the model are more

[2] Jupiter was actually somewhat stronger than 6.0 Jy, but its effective flux density was reduced because of the 2.5-arcmin half-power half-widths of the VLA antenna beams at 8.4 GHz.

uncertain than their ratio, since the amplitude calibration was based on a highly variable radio source whose strength was known only to ~10 percent accuracy. For each point, 0.054 Jy of noise (computed noise level for the parameters used in the test observations) was added with random phase.

Figure 6 is a comparison of the plots from Figs. 4 and 5, and shows the good correspondence between the real data and the simulation. Differences can be accounted for by the crude method by which noise was added in the simulation, the fact that different subsets of the real projected baselines were selected for the two plots, and the over-simplification of the uniform disk model for Jupiter.

VI. Simulations of the Io Encounter

The good correspondence between the real and simulated visibility data in the 1990 test indicated that a simple emission model could serve well as a predictor of the visibility function to be expected from the combined emission of Galileo and Jupiter on encounter day, December 7, 1995. The 1990 test was performed with Jupiter at a distance of 6 AU, giving it an angular size similar to that at the time of the Io encounter, when it will be 6.2 AU from Earth. Further, the model value of 6.5 for the ratio of the flux density of Jupiter to that of 0839+187 on September 28, 1990 was somewhat larger than the expected ratio of 4.4 for the Jupiter/Galileo ratio on the day of the 1995 encounter [cf. Eq. (3)], assuming an 8-MHz bandwidth. Thus, the test results give a reasonably conservative approximation of the expectations for the Io encounter.

On December 7, 1995, when Galileo and Jupiter rise at the VLA, a little less than 3 hours prior to Galileo's closest approach to Io, Jupiter will be located about 51 arcsec from Galileo. Figure 7 shows the predicted visibility plot for the model of Galileo and Jupiter, assuming use of the **B** configuration of the VLA, in which each of the three VLA arms has a total length of ~6 km. This plot was derived in the same way as the simulation displayed in Fig. 5, which was shown to be a fairly good representation of reality. More than a third of the baselines will have projected lengths shorter than 30,000 wavelengths and show some effect due to Jupiter. About 15 to 20 percent of the baselines, those shorter than ~20,000 wavelengths, show an effect greater than 20 percent. The shortness of the projected baselines is partly due to the fact that the spacecraft and Jupiter will be at −23 deg declination at the encounter. Therefore, they rise nearly along the azimuth of the southeast arm of the VLA, giving considerable foreshortening of many baselines. If Jupiter's center and Galileo were located at the same point, Fig. 7 would look like a superposition of a constant and a Bessel function $J_1(x)/x$ (where x is proportional to the baseline length), the respective Fourier transforms of a delta function and a uniform disk. In fact, the plot is somewhat more complicated because Galileo will not be directly in front of Jupiter, so that Jupiter and Galileo will be beating against each other as Jupiter is being resolved.

Figure 8 shows the visibility plot for the same model as for Fig. 7, with the exception that the VLA antennas are assumed to be in their most extended arrangement, the **A** configuration. The baselines are more than three times longer than those in Fig. 7, and less than 10 percent of the baselines would be short enough to be affected significantly by Jupiter.

Figure 9 is a plot similar to Fig. 7 for the **B** configuration, except the assumed VLA bandwidth is 4.7 MHz instead of 8 MHz. The narrower bandwidth corresponds to the situation in which six spectral-line channels of 781 kHz each, centered on the Galileo carrier, are used for the phase adjustment process. Since Galileo's signal is restricted in frequency, whereas Jupiter is a broadband emitter, this bandwidth gives a higher SNR for Galileo and a lower SNR for Jupiter. The effective bandwidth cannot be made much smaller than ~5 MHz without reducing the total power from Galileo.

Using the 4.7-MHz bandwidth in Eq. (9) and evaluating the Bessel function, it appears that Jupiter should cause an effect of 20 percent or more only for baselines shorter than about 10,000 wavelengths (350 m). Figure 9 confirms the analytic approximation; about 8 percent of the baselines will be shorter than the critical length. Figure 10 is a plot made using the same assumptions for observations using the VLA **A** configuration. It shows a significant effect from Jupiter on fewer than 10 baselines.

Two hours after Galileo and Jupiter rise at the VLA, Galileo will have moved within 19 arcsec of Jupiter's center, appearing just off the limb of the planet. The spacecraft and Jupiter will be at 25 deg elevation. The projected baselines will be somewhat longer for the higher spacecraft elevation. Calculations show that, as expected, Jupiter's effects on the visibility function will be less pronounced even though it is closer to the spacecraft; this is a direct consequence of the increase in the projected baseline lengths. Thus, the limiting case in selection of the appropriate VLA configuration is the situation at the spacecraft rise time.

VII. Selecting the Proper VLA Configuration for the Io Encounter

The purpose of the VLA tests and simulations has been to select the appropriate parameters for reception of telemetry from Galileo at the Jupiter encounter. There are two issues to be considered. One is the autophasing of the VLA antennas, while the other is the problem of correlated noise from Jupiter in the summed signal from all the antennas. Problems with the autophasing can be reduced by setting a software limit on the minimum projected length for the baselines used in the autophasing procedure. However, even though this will enable the phase adjustment to converge on antenna solutions that maintain coherence of the signal from Galileo, the antennas close to the center of the array also may have small relative phase for some portion of the signal from Jupiter. Therefore, they will be affected by correlated noise from Jupiter that will degrade the SNR of the telemetry stream. Because of the correlated component of the noise, the effect of Jupiter on the system's sensitivity will be greater than predicted from the 0.9 K increase in system temperature at the individual antennas. Although the details of correlated noise are beyond the scope of this article, the correlated noise will be minimized when the effective Galileo/Jupiter power ratio is maximized. If no baselines show an effect in the visibility plot, there should be little effect from correlated noise. An ideal situation would result from a selection of parameters such that the visibility plots (see Figs. 7–10) would be dominated by Galileo and show little effect from Jupiter.

Consider the effect of Jupiter on the visibility function. Equation (8) specifies that Jupiter should contribute less than $\sim$20 percent to the total amplitude of the fringe visibility. If Jupiter contributes less than that amount on a given baseline, its contribution to the autophasing error for that baseline will be only $\sim$12 deg, and the correlated-noise contribution should be correspondingly small. As is evident from Fig. 7, assuming an 8-MHz bandwidth and observations using the **B** configuration, roughly 20 percent of the 351 baselines show too large an effect due to Jupiter. Therefore, this set of parameters may be inadequate for telemetry reception from Galileo. Figure 10 shows that for a 4.7-MHz bandwidth and the **A** configuration, only a few baselines will show bad effects due to Jupiter, so this set of parameters could be used for telemetry reception.

The remaining uncertainty is whether both the **A** configuration and the reduced bandwidth are necessary, or if only one change from the parameters of Fig. 7 would suffice. Inspection of Fig. 9 shows that, with a 4.7-MHz bandwidth and the **B** configuration, fewer than 10 percent of the baselines show a contribution of more than 20 percent due to Jupiter. For the **A** configuration and the 8-MHz bandwidth, Fig. 8 shows a 20 percent effect on about 5 percent of the baselines. These baselines can be eliminated easily in the autophasing solution, but the degradation of telemetry by Jupiter's correlated noise still must be evaluated.

The ideal choice would be to use the largest available configuration and smallest possible autophasing bandwidth for the Io encounter. However, making the reliability adequate for the **A** configuration would cost more than for the smaller **B** configuration, because of the decaying power-distribution system at the VLA; cable replacement would be needed to the end of the **A** configuration (21-km arms) instead of only to the end of the **B** configuration (6-km arms). Therefore, the feasibility of using the **B** configuration merits further study. Using the narrowest possible autophasing bandwidth would put more severe operational constraints on the spacecraft frequency predictions in order to prevent loss of the telemetry SNR due to the exclusion of significant sidebands.

The limiting factor for VLA observations of the Io encounter probably will be the correlated noise. The effect on autophasing could be reduced by software limits on the baseline lengths used in the autophasing solutions and/or by including a model of the Jovian emission in the autophasing process. However, the correlated noise could be more difficult to eliminate. At first glance, it would seem that the effect of the noise could be bounded by the increased noise expected on a single large antenna due to the system-temperature increase caused by Jupiter. However, the situation may be worse. A single large antenna samples all projected baselines included within the aperture, whereas an array of smaller antennas samples only a limited set of projected baselines. For example, a single 35-m antenna would have a system-temperature increase of only $\sim$1.8 K due to Jupiter at a distance of 6 AU. But if the same aperture area is made up of two 25-m antennas, and the observing geometry is unfavorable, it is possible that destructive interference and correlated noise could cause the spacecraft signal to disappear completely, equivalent to an infinite increase in system temperature! Further investigation of the correlated noise should be conducted to choose the best configuration for the Io encounter.

VIII. Possible Future VLA Tests

Tests of autophasing in the larger VLA configurations, and particularly tests of the effects of correlated noise, should be conducted. Either a natural radio source containing both point and extended components, or a close passage of Jupiter to another bright, compact radio source might be used to evaluate the noise in the summed signal of all the antennas. However, use of a natural radio source would not give a particularly accurate representation of the distribution of emission from Galileo and Jupiter. The best "near miss" between Jupiter and a strong point source (P 1352−104) will not occur until late 1993, when the VLA is scheduled to be in the **A** configuration. Even then, the angular separation between Jupiter and the compact radio source will be nearly twice as large as the separation in the 1990 test, nearly as large as the half-power beamwidth of the individual antennas at 8.4 GHz.

Observation of a spacecraft with discrete telemetry sidebands could be more useful than observing a natural radio source with a wideband noise-like signal. However, use of a spacecraft probably would provide additional benefits only if the telemetry signal were extracted and the signal properties (SNR, bit error rate, etc.) were studied. Without telemetry extraction, a test involving spacecraft observations would be similar to a test involving observations of a natural, pointlike radio source.

An ongoing test opportunity exists involving the Magellan spacecraft, which transmits an 8.4-GHz signal to Earth from its orbit around Venus. Appropriate selection of observing parameters probably could be made to mimic the situation when Galileo encounters Jupiter. Parameters that need to be considered include the VLA configuration, the Magellan declination, the Earth–Sun–Venus angle, the Venus flux density, the apparent angular size of Venus, and the spacecraft transmission times compared to its rise times at the VLA. Depending on phase angle, Venus has a brightness temperature of ~600 K at 3.6 cm [10], between three and four times that of Jupiter. At an Earth–Venus distance of 8.3×10^7 km, Venus has the same angular size (~15 arcsec) that Jupiter will have when Galileo arrives in 1995; therefore, it would have three to four times Jupiter's flux density. At this distance, the *total* Earth-received power from Magellan will be approximately 200 times that expected from Galileo on December 7, 1995. However, it may be possible to mimic Galileo's Io encounter by selecting the appropriate passband for observations of Magellan, so that only a small fraction of the total power is detected.

In July and October 1991, Venus will have the appropriate angular size of 15 arcsec and the VLA will be in the **A** (July) and **B** (October) configurations. Although Venus will not be at the right declination to get the same projected baselines as for Galileo's Io encounter, this still would be the best time to do further autophasing tests and investigations of the correlated noise problem. Results of such tests can enable a final decision to be made about the feasibility of using the **B** configuration for Galileo's Jupiter encounter.

IX. General Considerations for DSN Antenna Siting

This article has addressed the issue of the proper VLA configuration for the Io encounter at some length. However, the work done also has a significant impact on the general question of the siting of new antennas for the DSN. Future deep-space telecommunications may rely more heavily on arrays of smaller antennas than on single large antennas such as the 70-m antennas currently in operation at each DSN complex. Indeed, arraying of a variety of antennas for telemetry reception has been used for 20 years; the chronology of that arraying was summarized in Table 1 of [4].

Inevitably, future spacecraft supported by the DSN will visit planets that are strong radio emitters at the planned telecommunication frequencies of 8.4 GHz and 32 to 34 GHz. The general trend for those spacecraft will be for them to involve orbiters that may spend years in the vicinity of a single planet. The Cassini spacecraft, which will arrive at Saturn a few years after the turn of the century, is an example of a candidate for support from a new generation of antenna arrays. It is essential that the geometry of those arrays take into consideration the effect of planetary radio noise, which can hinder the coherent phasing of the antennas, the reception of telemetry, and the adequacy of the SNR on radiometric data such as Doppler tracking. If the antenna sites are selected primarily for operational convenience, they may not be used to full advantage for spacecraft in planetary orbits. Antenna separations should be large enough that the effects of planetary radio emission can be reduced to insignificance by appropriate observing and data analysis techniques.

X. Summary

An analysis has been performed to determine the ability of the VLA to autophase on the Galileo spacecraft in the presence of the strong 8.4-GHz radio emission from Jupiter. This autophasing process must be successful in order for signals from the individual VLA antennas to be added coherently. The total power from Jupiter is expected to be about 4.4 times that from Galileo in a single, 8-MHz-bandwidth, circularly polarized channel. Calculations show that projected interferometer baselines longer than ~0.8 km will be necessary in order to resolve Jupiter adequately so that the autophasing is successful.

A VLA test has been performed that simulated the Galileo–Jupiter encounter that will occur in late 1995. This test showed that the autophasing process was corrupted severely when antennas were spaced closely enough to see a large amount of correlated emission from Jupiter. The corruption became relatively insignificant for projected interferometer baselines longer than 800 meters, in good agreement with the predictions. A simple model of the structure of the radio emission gave good success in reproducing the observed fringe visibility.

A simple emission model has been used to predict the fringe visibility and the effects of Jupiter at the Galileo encounter. Results show that the **A** configuration of the VLA should be adequate to resolve Jupiter enough to minimize both autophasing problems and correlated noise in the telemetry stream. The **B** configuration may be adequate for autophasing if the effective bandwidth is reduced to ~5 MHz, but further analysis must be done to investigate the effects of the correlated noise. Observations of the Magellan spacecraft in orbit around Venus could provide important information about the feasibility of use of the VLA **B** configuration for data return from Galileo at Jupiter. Such tests could be done in July and October of 1991.

The tests using the VLA may have a broader applicability for the DSN. The problems of receiving telemetry and radiometric data from planetary orbiters in the presence of radio-emitting planets are relevant to the selection of sites for individual antennas in future arrays that might be built by the DSN.

Acknowledgments

The author thanks Roger Linfield for using his occultation-prediction software to identify the close passage between Jupiter and 0839+187 and for searching for similar events with Venus, Jupiter, and Saturn in the 1991 to 1995 period. The author also thanks Rachel Dewey and Don Brown for carefully reading and commenting on a draft of this article.

References

[1] J. W. Layland, P. E. Beyer, D. W. Brown, R. W. Burt, R. C. Clauss, J. M. Ludwinski, B. D. Madsen, J. C. McKinney, F. D. McLaughlin, D. J. Mudgway, N. A. Renzetti, J. S. Ulvestad, and R. J. Wallace, "Galileo Array Study Team Report," *TDA Progress Report 42-103,* vol. July–September 1990, Jet Propulsion Laboratory, Pasadena, California, pp. 161–169, November 15, 1990.

[2] A. R. Thompson, B. G. Clark, C. M. Wade, and P. J. Napier, "The Very Large Array," *Astrophysical Journal Supplement Series,* vol. 44, pp. 151–167, October 1980.

[3] P. J. Napier, A. R. Thompson, and R. D. Ekers, "The Very Large Array: Design and Performance of a Modern Synthesis Radio Telescope," *Proceedings of the IEEE,* vol. 71, pp. 1295–1320, November 1983.

[4] D. W. Brown, W. D. Brundage, J. S. Ulvestad, S. S. Kent, and K. P. Bartos, "Interagency Telemetry Arraying for Voyager Neptune Encounter," *TDA Progress Report 42-102,* vol. April–June 1990, Jet Propulsion Laboratory, Pasadena, California, pp. 91–118, August 15, 1990.

[5] J. S. Ulvestad, G. M. Resch, and W. D. Brundage, "X-band System Performance of the Very Large Array," *TDA Progress Report 42-92*, vol. October–December 1987, Jet Propulsion Laboratory, Pasadena, California, pp. 123–137, February 15, 1988.

[6] J. S. Ulvestad, "Phasing the Antennas of the Very Large Array for Reception of Telemetry from Voyager 2 at Neptune Encounter," *TDA Progress Report 42-94*, vol. April–June 1988, Jet Propulsion Laboratory, Pasadena, California, pp. 257–273, August 15, 1988.

[7] G. L. Berge and S. Gulkis, "Earth-Based Radio Observations of Jupiter: Millimeter to Meter Wavelengths," in *Jupiter*, edited by T. Gehrels, Tucson: University of Arizona Press, pp. 621–692, 1976.

[8] A. R. Thompson, "The Interferometer in Practice," in *Synthesis Imaging in Radio Astronomy*, edited by R. A. Perley, F. R. Schwab, and A. H. Bridle, Astronomical Society of the Pacific Conference Series, vol. 6, pp. 11–37, 1989.

[9] S. M. Selby, ed., *Standard Mathematical Tables*, 21st edition, Cleveland, Ohio: Chemical Rubber Company, p. 538, 1973.

[10] W. M. Kaula, *An Introduction to Planetary Physics: The Terrestrial Planets*, New York: Wiley and Sons, 1968.

Figure captions for Article D

Fig. 1. X-band image of Jupiter and the radio source 0839+187, as taken by the VLA on September 28, 1990.

Fig. 2. Reported amplitude (percent) and phase (*d*) errors from the least-squares solution attempting to compute VLA antenna gains, during a 5-sec integration on 0839+187 when it was near Jupiter. All baselines were used in the solution. Only errors involving antennas 1 and 2 are shown.

Fig. 3. Reported errors from the least-squares solution attempting to compute VLA antenna gains, during interferometry observations of 0839+187 when it was near Jupiter. Only baselines with projected lengths longer than ~~30,000~~ 20,000 wavelengths were used. The original data were the same as the data used for Fig. 2. Errors involving antennas 1 and 2 are shown.

Fig. 4. Visibility plot for VLA observations of 0839+187 and Jupiter on September 28, 1990.

Fig. 5. Visibility plot computed from a simple emission model for the VLA test observations on September 28, 1990.

Fig. 6. Comparison of ~~(a)~~ data (Fig. 4) and ~~(b)~~ simulation (Fig. 5) for the VLA observations on September 28, 1990.

Fig. 7. Simulated visibility plot for observations of Galileo and Jupiter at their rise time (8 deg elevation) at the VLA on December 7, 1995. An 8-MHz bandwidth and use of the VLA B configuration are assumed.

Fig. 8. Simulated visibility plot for observations of Galileo and Jupiter at their rise time (8 deg elevation) at the VLA on December 7, 1995. An 8-MHz bandwidth and use of the VLA A configuration are assumed.

Fig. 9. Simulated visibility plot for observations of Galileo and Jupiter at their rise time (8 deg elevation) at the VLA on December 7, 1995. A 4.7-MHz bandwidth and use of the VLA B configuration are assumed.

Fig. 10. Simulated visibility plot for observations of Galileo and Jupiter at their rise time (8 deg elevation) at the VLA on December 7, 1995. A 4.7-MHz bandwidth and use of the VLA A configuration are assumed.

FIG. D-1 TOP RED. TO 53%

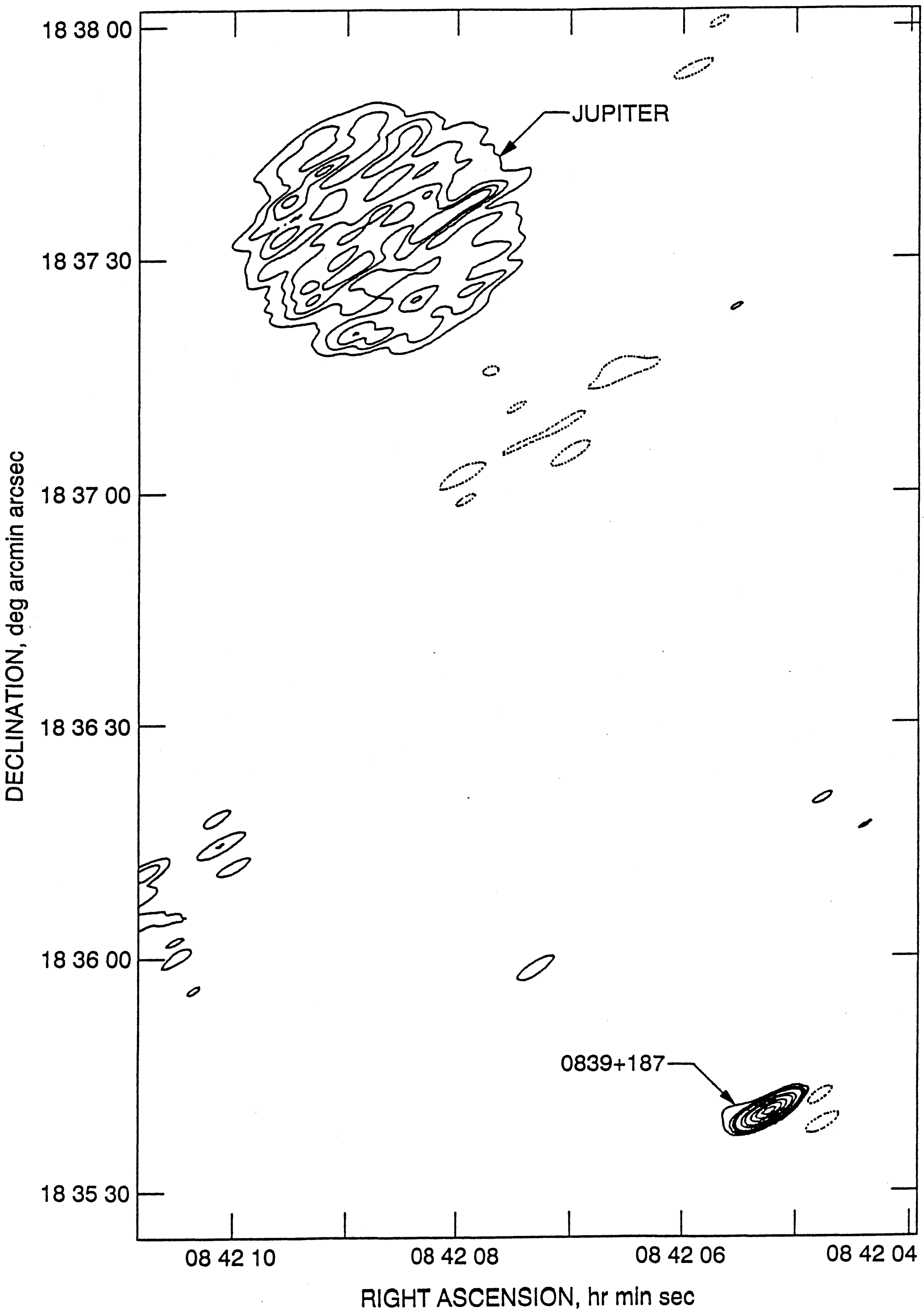


FIG. D-3 2 TOP RED. TO 67%

Closure errors at 0/10 25 0.0839+187

1-2	184%	−3d	1-4	−47%	−9d	1-5	135%	158d
1-6	163%	1d	1-7	220%	−9d	1-8	137%	2d
1-9	84%	22d	1-10	158%	−31d	1-11	732%	4d
1-12	327%	16d	1-13	165%	2d	1-14	167%	13d
1-15	170%	−6d	1-16	114%	−17d	1-17	421%	−133d
1-18	−35%	−22d	1-19	−48%	101d	1-20	606%	45d
1-21	141%	11d	1-22	178%	−2d	1-23	162%	−7d
1-24	−35%	−37d	1-25	113%	−11d	1-26	155%	−8d
1-27	190%	−4d	1-28	−1%	85d	2-4	−35%	2d
2-5	180%	165d	2-6	174%	3d	2-7	237%	−3d
2-8	190%	−3d	2-9	88%	1d	2-10	169%	−1d
2-11	129%	1d	2-12	212%	−5d	2-13	165%	−4d
2-14	180%	10d	2-15	167%	2d	2-16	98%	−6d
2-17	501%	−116d	2-18	−21%	−29d	2-19	−13%	92d
2-20	234%	3d	2-21	184%	4d	2-22	198%	4d
2-23	200%	2d	2-24	−31%	−32d	2-25	183%	−14d
2-26	224%	14d	2-27	206%	4d	2-28	30%	85d

FIG. D-3 TOP RED. TO 82%

Closure errors at 0/10 25 0.0839+187

1-7	13%	–5d	1-8	–11%	3d	1-21	0%	11d
2-16	–16%	6d	2-18	11%	0d	2-19	–11%	–3d
2-20	17%	–3d						

FIG. D-4

TOP

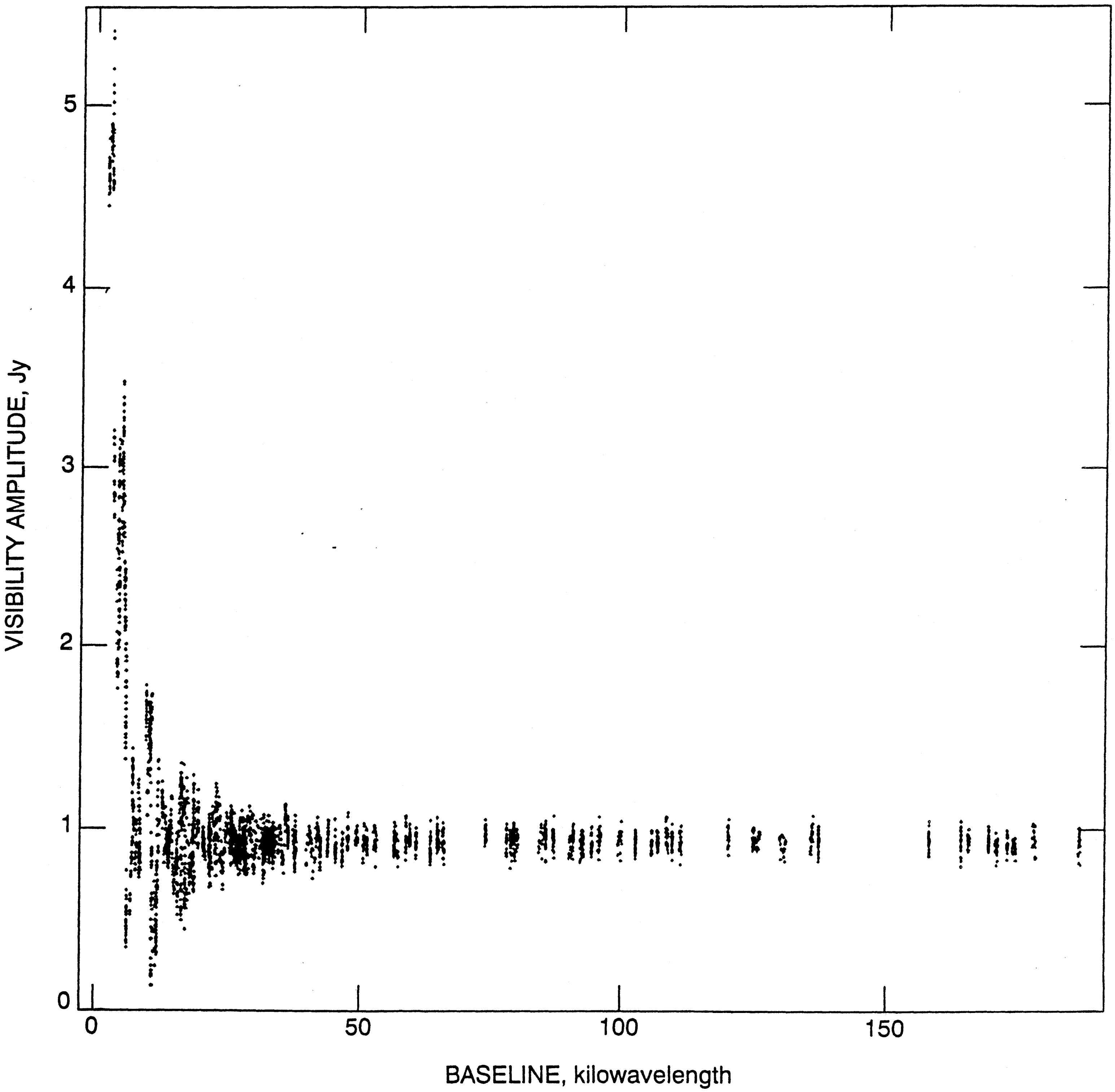

VISIBILITY AMPLITUDE, Jy
0
1
2
3
4
5
0
50
100
150
BASELINE, kilowavelength

FIG. D-5   500   RED. TO 52%

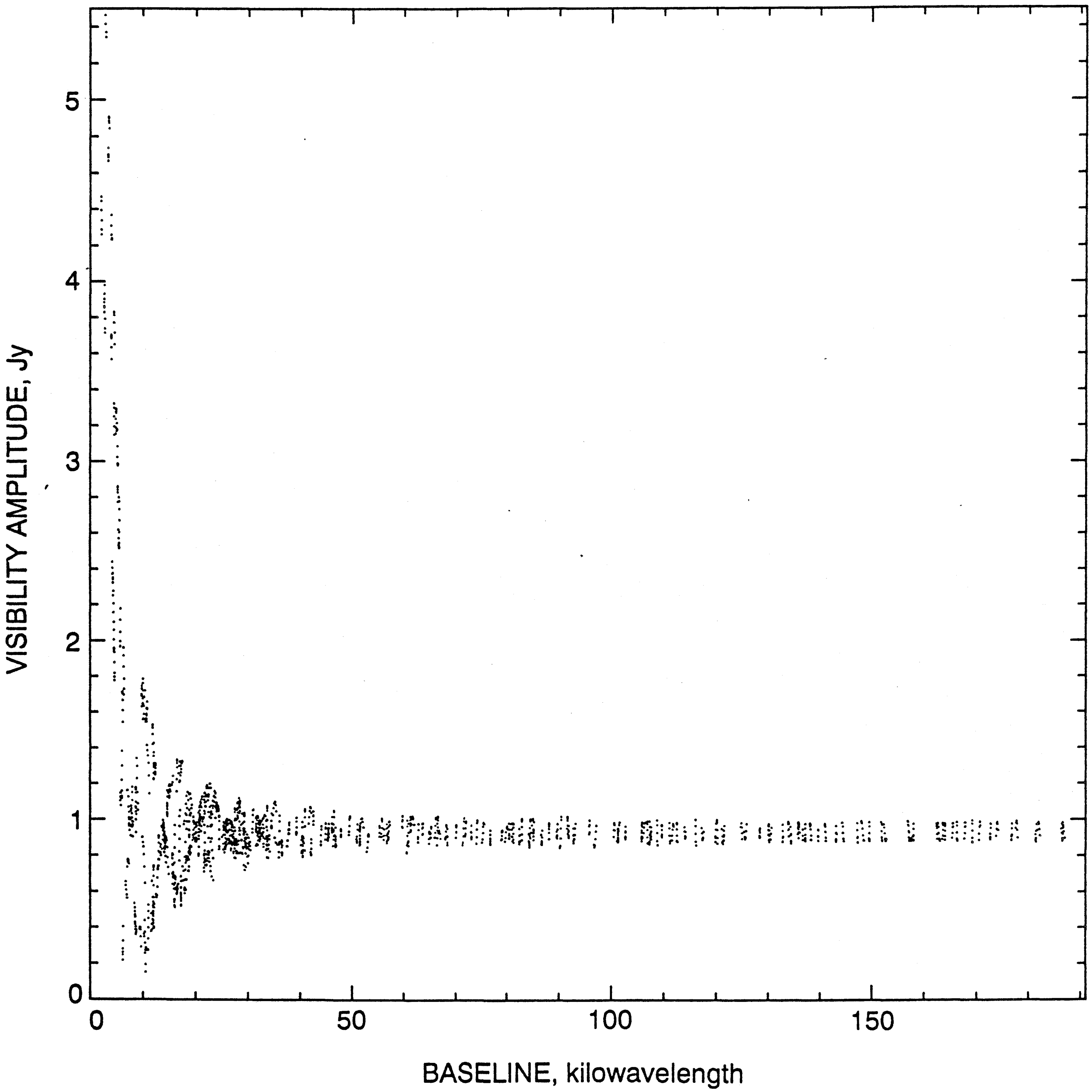


FIG. D-6 TOP RED. TO 54.5%

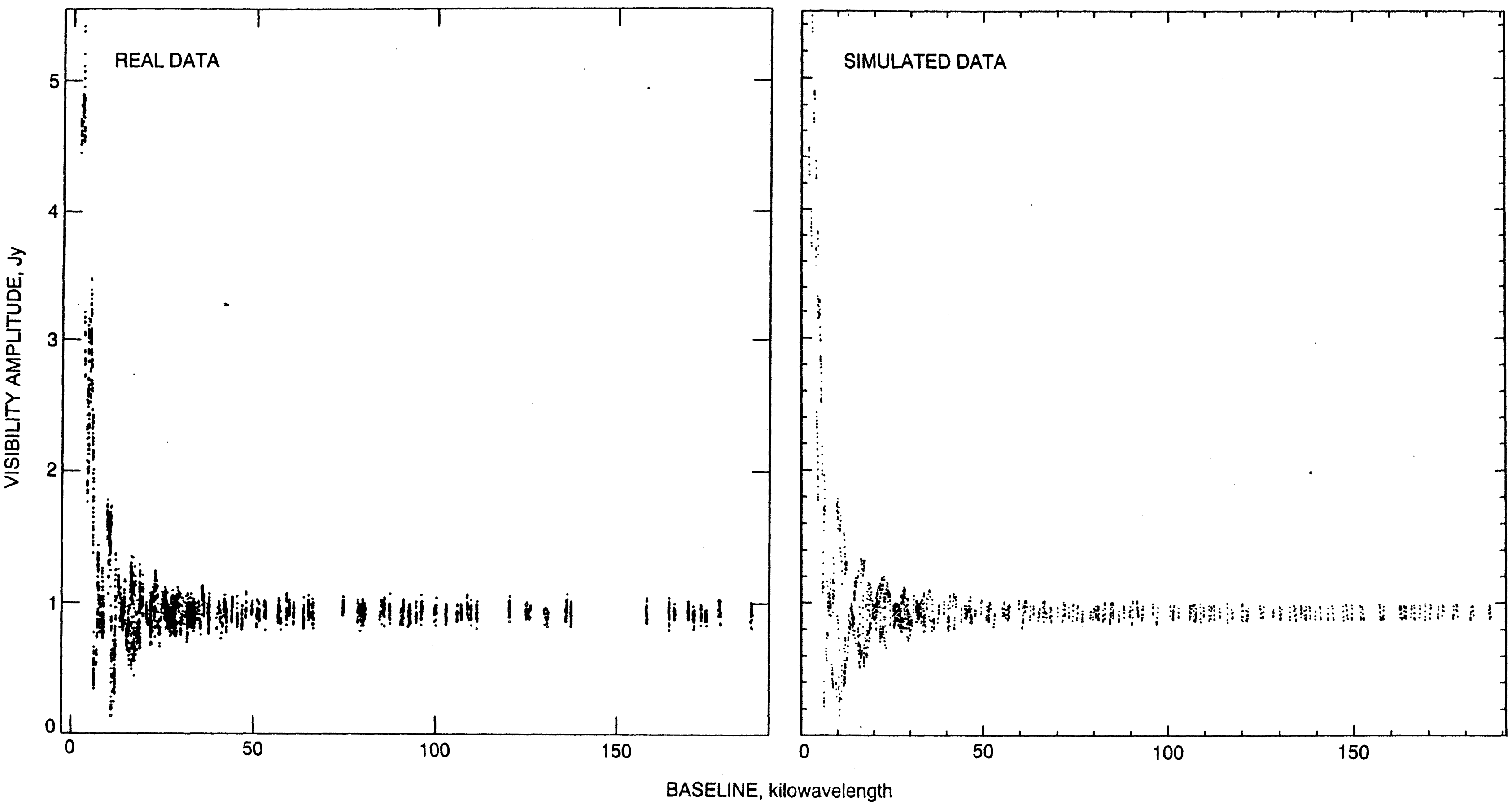
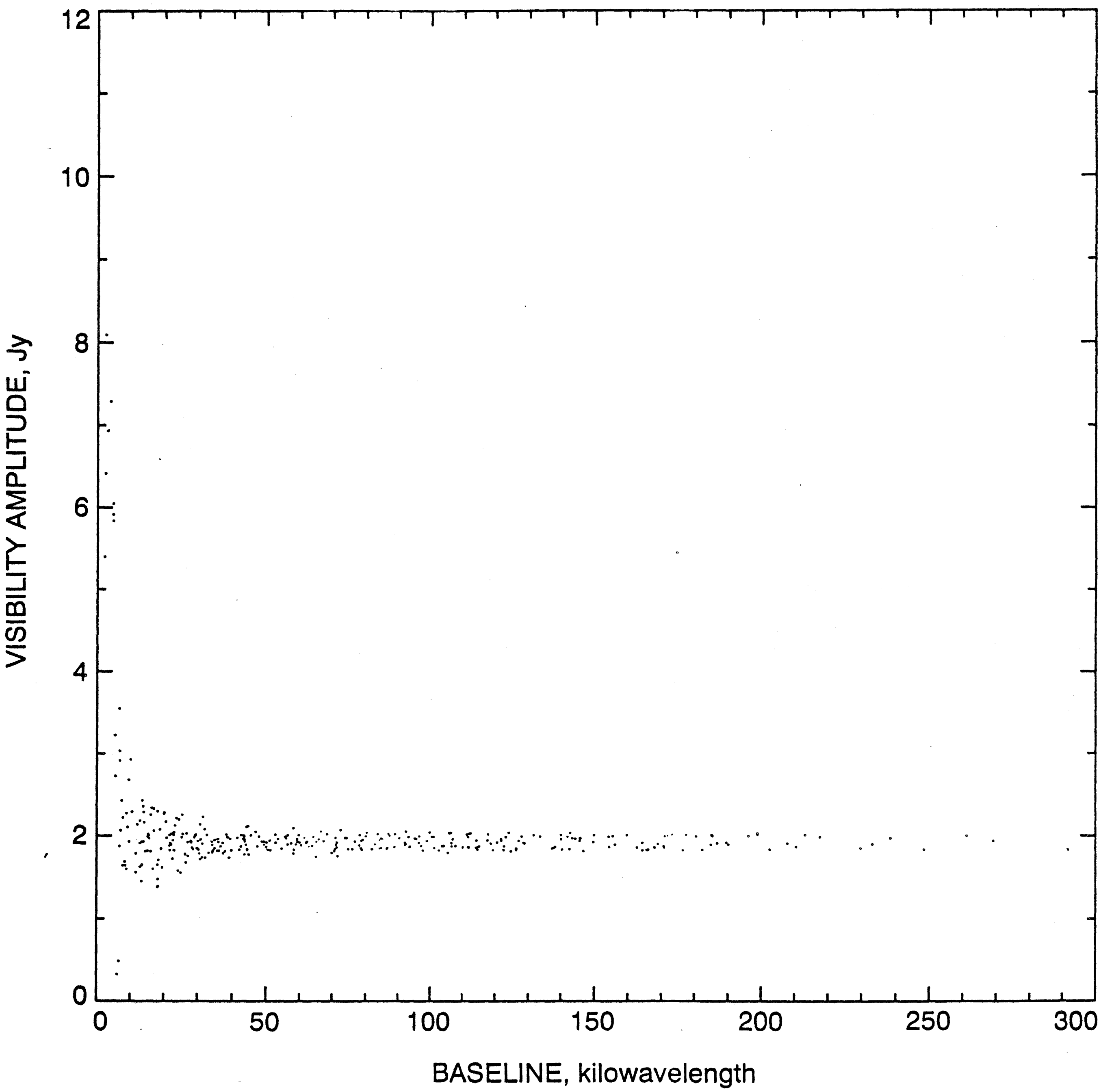
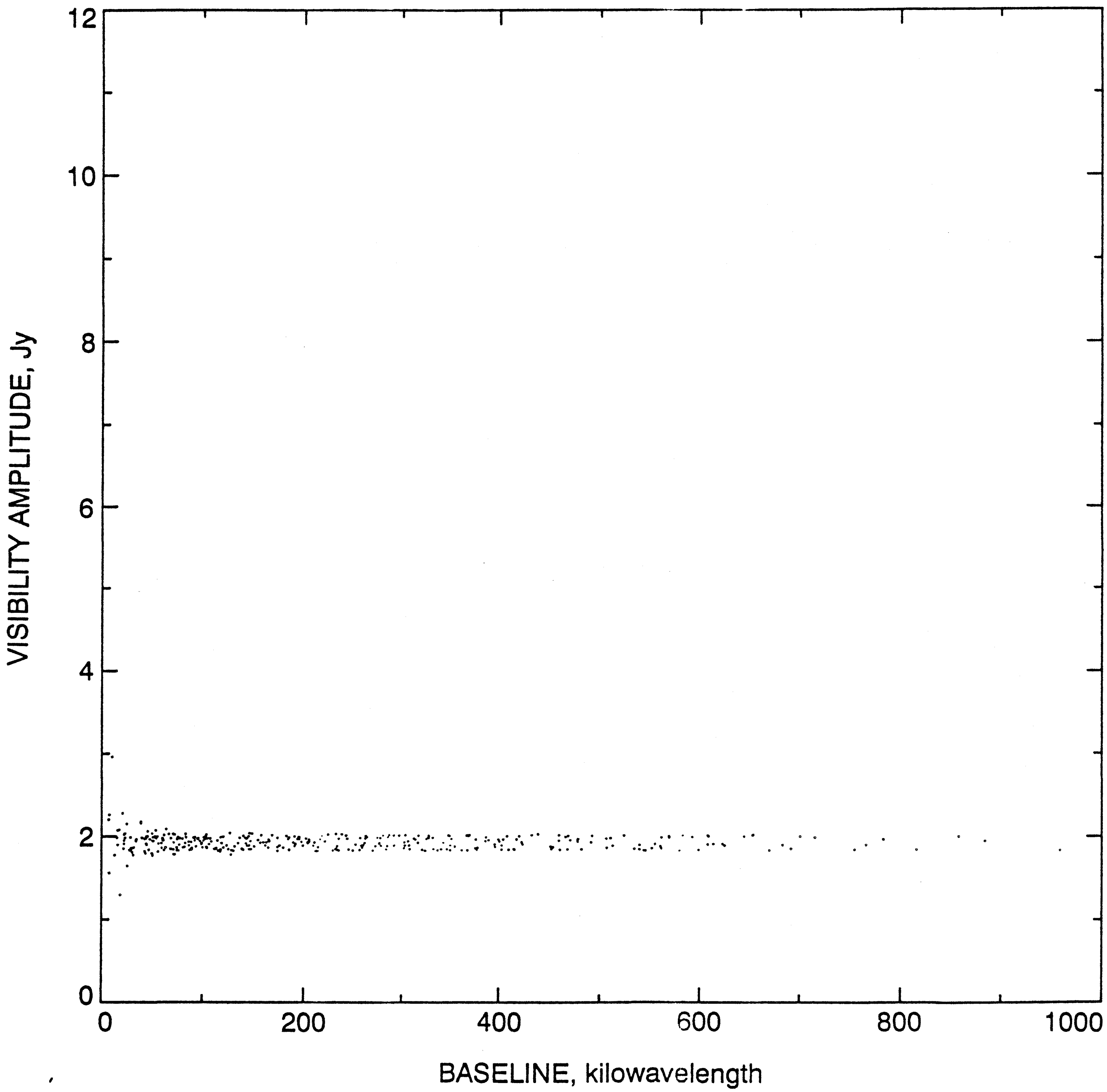


FIG. D-7 TOP



VISIBILITY AMPLITUDE, Jy
0
2
4
6
8
10
12
BASELINE, kilowavelength
0
50
100
150
200
250
300

FIG. D-8



VISIBILITY AMPLITUDE, Jy
0
2
4
6
8
10
12
0
200
400
600
800
1000
BASELINE, kilowavelength

FIG. D-9 TOP RED. TO 50%

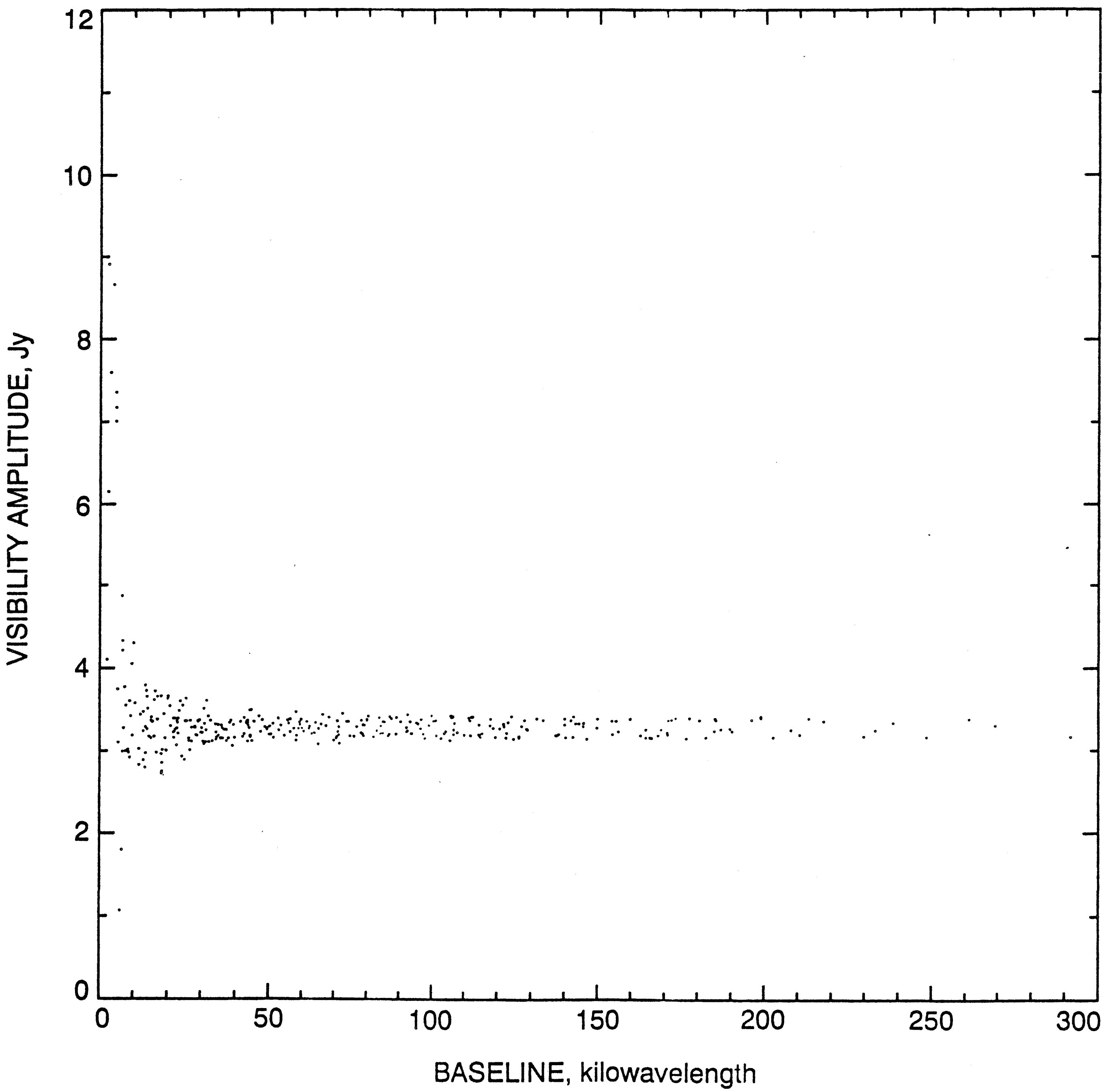
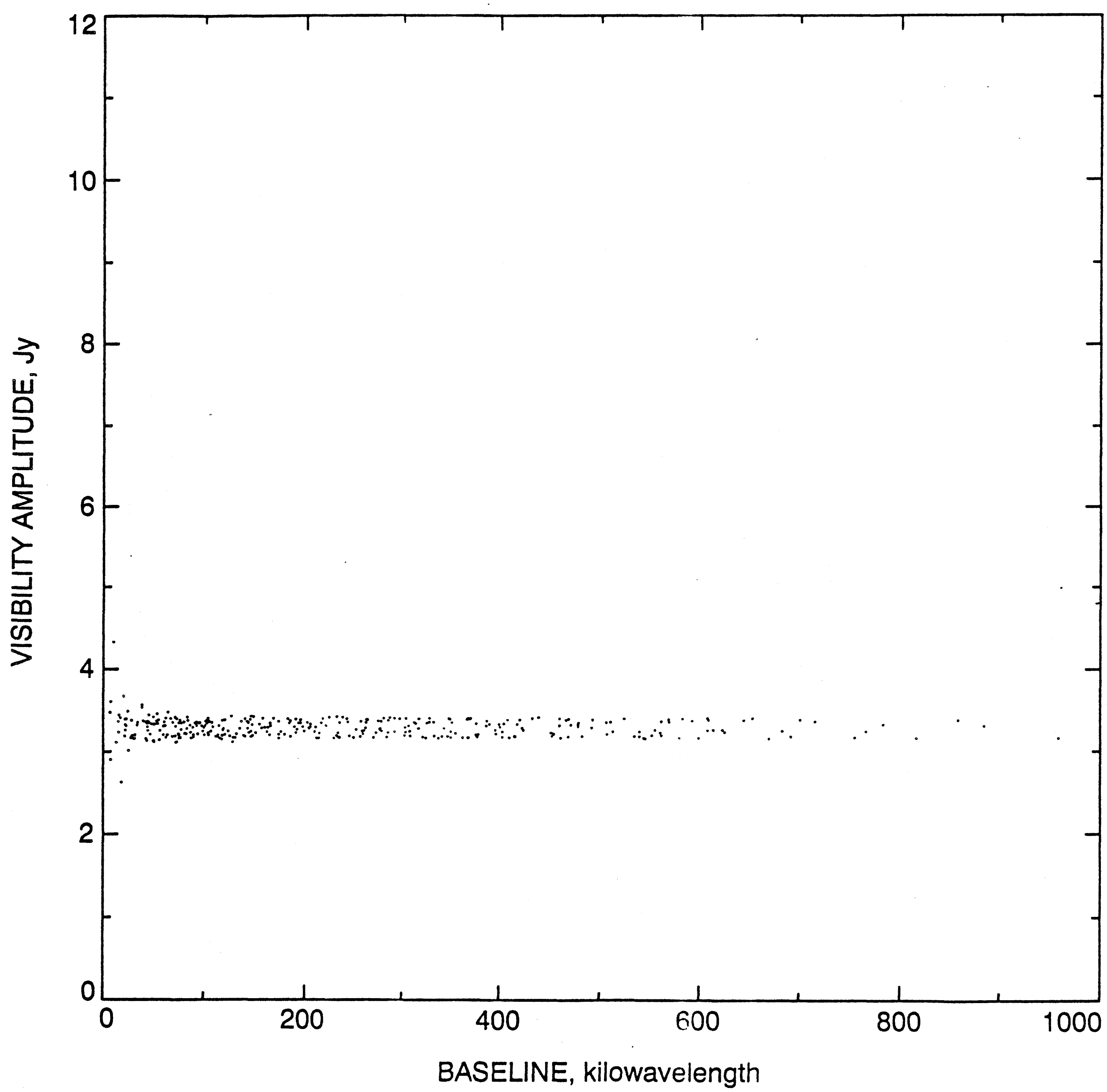


FIG. D-10



12
10
8
6
4
2
0
VISIBILITY AMPLITUDE, Jy
0
200
400
600
800
1000
BASELINE, kilowavelength