VLB ARRAY MEMO No. 488

# THE RESPONSE OF THE VERY LONG BASELINE ARRAY TO INTERFERING SIGNALS

Patrick C. Crane

11 September 1985

## I. Introduction

Radio astronomy studies the nature of the Universe, based upon the reception of radio waves of cosmic origin. These cosmic emissions constitute the "cosmic background noise" of communications engineering. The emissions are random, noise-like signals that are indistinquishable from the noise generated in the receivers or from the Earth and its atmosphere. Furthermore, the intensity of cosmic radiation is usually much weaker than that of the noise (the weakest cosmic signal detected is about -234 dBW/m$^2$.)

The National Radio Astronomy Observatory began construction of a new radio telescope, the Very Long Baseline Array (VLBA), in May 1985; construction should be completed by 1992. The characteristics of the VLBA have been described by Kellermann and Thompson (1985). Like any other radio telescope the VLBA will be sensitive to radio interference but several features of its design will greatly reduce its sensitivity to such interfering signals.

In the following sections I will summarize the responses of a single antenna and an aperture-synthesis radio telescope to interfering signals, followed by a discussion of the response of the Very Long Baseline Array.

## II. A single antenna

The harmful interference level for observations with a single antenna has been analyzed in CCIR Report 224-5: The harmful interference level is that level of interference which equals 0.1 of the rms noise level which sets the fundamental limit of the data. For a total-power receiver the harmful interference level is given by

$$F_i = \frac{0.4\pi f^2 k T_s \sqrt{B}}{c^2 G_s \sqrt{2t}} ,$$

where f is the observing frequency; k, Boltzman's constant; $T_s$, the system temperature; B, the observing bandwidth; c, the speed of light; $G_s$, the gain, with respect to an isotropic antenna, of the antenna in the direction of arrival of the interfering signal; and t, the total integration time. As derived in the report, the harmful interference levels, for continuum observations with modern receivers and an integration time of 2000 seconds, range between -202 and -114 dBW/m$^2$ at 20 MHz and 235 GHz, respectively.

## III. An aperture-synthesis radio telescope

As discussed by Thompson (1982a), two effects reduce the sensitivity to interfering signals of an aperture-synthesis radio telescope:

The first is an averaging effect that applies to any interfering signal. The motion of an astronomical source across the sky results in changes in the relative phases of the signals received at the antennas, so that if the signals from any pair of antennas are multiplied together, the output voltage will vary quasi-sinusoidally with time. The frequency of the output signal is called the natural fringe frequency and depends upon the spacing of the antennas and the position of the radio source on the sky (it ranges between a few milliHertz and tens of Hertz for existing radio telescopes.) On the other hand, a terrestrial source of interference is fixed with respect to the earth, and the corresponding output voltage will be constant. If the data are averaged for a time T, the interfering signal will be reduced by a factor of sinc($\pi$fT), where f is the natural fringe frequency. Thompson's complete analysis includes the variations with the position of the source and the spacings of the antennas, and the harmful interference level for a twelve-hour observation time is given by

$$F_i = \frac{0.4\pi f^2 k T_s \sqrt{2\omega_0 B}}{c^2 G_s} \sqrt{\frac{L}{\lambda}} ,$$

where $\omega_0$ is the angular rotation velocity of the earth and L is a measure of the physical size of the array.

The second effect mentioned above reduces the sensitivity of an aperture-synthesis radio telescope to broadband interfering signals. Because the signals from cosmic radio sources have the characteristics of broadband noise, such a telescope introduces computer-controlled delays to equalize the time delays from the source through the antennas to the multipliers and to maintain the coherence of the signals. For broadband interference entering the antenna sidelobes, the delays will generally differ from those of the cosmic signal, and the interfering signal will be decorrelated by an amount given by sinc($\pi B t_d$), where $t_d$ is the delay inequality. The maximum delay inequality is given by twice the delay corresponding to the maximum baseline. Obviously, for an interfering signal arriving from the same general direction as the cosmic signal, the delay inequality may be near zero. The decorrelation factor is not amenable to a general analysis, but will vary significantly with bandwidth, declination of the radio source, and the configuration.

## IV. The Very Long Baseline Array

The Very Long Baseline Array (VLBA) will be much less sensitive to interfering signals than any other radio telescope, primarily because of its vastly greater geographical scale: Because the antenna spacings in the VLBA range between 200 and 8000 km (L is about 3950 km), the natural fringe frequencies are much greater (of the order of kiloHertz) than for other aperture-synthesis radio telescopes, and the averaging effect reduces the sensitivity to interfering signals by about a factor of 10,000 over a single antenna. Also the delay inequalies and the decorrelation factor are corresponding greater. Finally, except for an interfering signal originating from a satellite, such a signal is unlikely to be present at a harmful level at more than one antenna.

More significant for the VLBA will be the degradation of its performance by the addition of uncorrelated power at the individual antennas which effectively increases the noise level. The harmful level for such interference is estimated to be one percent of the system noise level (Thompson 1982b), or

$$F_i = \frac{0.04\pi f^2 k T_S B}{c^2 G_S} .$$

At much higher levels interfering signals occurring anywhere within the passband of the front-end receiver will cause gain compression and other nonlinear behavior. The harmful levels for such interference depend upon the design of the receiver but can be estimated for each observing band.

Table 1 presents the harmful interference levels for the thirteen observing bands planned for the VLBA, which were calculated for a $G_S$ of 1 and bandwidths of 8 MHz (1.6 MHz at 75 MHz). The estimates of the interference levels that will cause one-percent gain compression are from Thompson and Schlecht (1985). We see that the averaging effect increases the harmful interference levels of the VLBA to values comparable to those which will increase the system noise level by one percent. The 70-dB differences between the interference levels adding one percent to the system noise level and causing one-percent gain compression allow considerable leeway for processing at the IF.

## V. Conclusions

The Very Long Baseline Array is far less sensitive to interfering signals than any other radio telescope. The sites of the VLBA antennas have been selected, furthermore, to minimize the potential for terrestrial sources of interference, but the VLBA will be particularly susceptible to interfering signals from air- and satellite-borne transmitters. A transmitter in geostationary orbit, isotropically broadcasting one watt, produces a signal level of -162 dBW/m$^2$ at the earth's surface. Allowing for a more powerful transmitter or more antenna gain at the receiver or transmitter, we see that such a transmitter could easily interfere with the VLBA.

Table 2 lists the VLBA observing bands and the adjacent and overlapping U.S. frequency allocations (international and U.S. footnotes are noted in parentheses when appropriate.) Most of the allocations for radio astronomy are adjacent to or share allocations for aeronautical radionavigation, mobile-satellite, radionavigation-satellite, meteorological-satellite, and broadcasting-satellite. Radio astronomers have already encountered problems with the U.S. Global Positioning System and the corresponding Soviet GLONASS system.

## VI. References

CCIR, "Interference protection criteria for the radio astronomy service," RECOMMENDATIONS AND REPORTS, vol. II, Geneva: Int. Telecommun. Union, Rep. 224-5, pp. 497-506, 1982.

K.I. Kellermann and A.R. Thompson, "The Very Long Baseline Array," SCIENCE, 229, pp. 123-130, 1985.

A.R. Thompson, "The response of a radio-astronomy synthesis array to interfering signals," IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, AP-30, pp. 450-456, 1982a.

A.R. Thompson, "Frequency protection for the Transcontinental Radio Telescope," VLBA MEMO NO. 81, 1982b.

A.R. Thompson and E. Schlecht, "Dynamic range and interference thresholds in the front-end and IF units," VLBA ELECTRONICS MEMO NO. 39, 1985.

TABLE 1. VLBA OBSERVING BANDS AND HARMFUL INTERFERENCE LEVELS

| FREQUENCY (MHz) | EFFICIENCY | TSYS (K) | RECEIVER | 10% NOISE ($dBW/m^2$) | 1% SYSTEM ($dBW/m^2$) | 1% GAIN ($dBW/m^2$) |
|---|---|---|---|---|---|---|
| 73.0- 74.6 | 0.50 | 1000 | GAsFET | -168 | -158 | |
| 312.0- 342.0 | 0.50 | 126 | GAsFET | -157 | -147 | -72 |
| 580.0- 640.0 | 0.49 | 84 | GAsFET | -152 | -143 | -67 |
| 1350.0- 1750.0 | 0.67 | 28 | Cooled GAsFET | -150 | -140 | -59 |
| 2150.0- 2350.0 | 0.71 | 33 | Cooled GAsFET | -142 | -136 | -55 |
| 4600.0- 5100.0 | 0.73 | 35 | Cooled HEMT | -134 | -129 | -49 |
| 5900.0- 6400.0 | 0.72 | 38 | Cooled HEMT | -131 | -127 | -47 |
| 8000.0- 8800.0 | 0.72 | 49 | Cooled HEMT | -126 | -123 | -44 |
| 10200.0-11200.0 | 0.71 | 48 | Cooled HEMT | -124 | -121 | -42 |
| 14400.0-15400.0 | 0.70 | 54 | Cooled HEMT | -119 | -117 | -39 |
| 21700.0-24100.0 | 0.65 | 70 | Cooled HEMT | -114 | -113 | -35 |
| 42300.0-43500.0 | 0.64 | 75 | Cooled SIS | -107 | -107 | -30 |
| 86000.0-92000.0 | 0.42 | 300 | Cooled SIS | -93 | -94 | |

TABLE 2. VLBA OBSERVING BANDS AND U.S. FREQUENCY ALLOCATIONS

| Specified Band (Accessible Band) | Frequency Allocations | |
|---|---|---|
| 73.0- 74.6 MHz | 54.0- 72.0 MHz | Broadcasting |
| | 72.0- 73.0 MHz | Fixed, Mobile |
| | 73.0- 74.6 MHz | RADIO ASTRONOMY |
| | 74.6- 74.8 MHz | Fixed, Mobile |
| | 74.8- 75.2 MHz | Aeronautical Radionavigation |
| | 75.2- 76.0 MHz | Fixed, Mobile |
| | 76.0- 108.0 MHz | Broadcasting |
| 312.0- 342.0 MHz | 225.0- 328.6 MHz | Fixed, Mobile |
| | 322.0- 328.6 MHz | Radio Astronomy (644) |
| | 328.6- 335.4 MHz | Aeronautical Radionavigation |
| | 335.4- 399.9 MHz | Fixed, Mobile |
| 580.0- 640.0 MHz | 512.0- 608.0 MHz | Broadcasting |
| | 608.0- 614.0 MHz | RADIO ASTRONOMY |
| | 614.0- 806.0 MHz | Broadcasting |
| 1350.0- 1750.0 MHz | 1240.0- 1300.0 MHz | Radiolocation |
| (1300.0- 1800.0) | 1300.0- 1350.0 MHz | Aeronautical Radionavigation |
| | 1330.0- 1400.0 MHz | Radio Astronomy (718) |
| | 1350.0- 1400.0 MHz | Radiolocation |
| | 1400.0- 1427.0 MHz | RADIO ASTRONOMY<br>Earth Exploration-Satellite (1)<br>Space Research (1) |
| | 1427.0- 1429.0 MHz | Fixed, Mobile (6)<br>Space Operation (2) |
| | 1429.0- 1435.0 MHz | Fixed, Mobile |
| | 1435.0- 1530.0 MHz | Mobile (7) |
| | 1530.0- 1544.0 MHz | Maritime Mobile-Satellite (3) |
| | 1544.0- 1545.0 MHz | Mobile-Satellite (3) |
| | 1545.0- 1559.0 MHz | Aeronautical Mobile-Satellite (3) |
| | 1559.0- 1610.0 MHz | Aeronautical Radionavigation<br>Radionavigation-Satellite (3) |
| | 1610.0- 1626.5 MHz | Aeronautical Radionavigation |
| | 1610.6- 1613.8 MHz | Radio Astronomy (734) |
| | 1626.5- 1645.5 MHz | Maritime Mobile-Satellite (2) |
| | 1645.5- 1646.5 MHz | Mobile-Satellite (2) |
| | 1646.5- 1660.0 MHz | Aeronautical Mobile-Satellite (2) |
| | 1660.0- 1660.5 MHz | RADIO ASTRONOMY<br>Aeronautical Mobile-Satellite |
| | 1660.5- 1668.4 MHz | RADIO ASTRONOMY<br>Space Research (1) |
| | 1668.4- 1670.0 MHz | RADIO ASTRONOMY<br>Meteorological Aids |
| | 1670.0- 1690.0 MHz | Meteorological Aids<br>Meteorological-Satellite (3)<br>Radio Astronomy (US211) |
| | [illegible].0- 1700.0 MHz | Meteorological Aids<br>Meteorological-Satellite (3) |
| | [illegible]- 1710.0 MHz | Fixed<br>Meteorological-Satellite (3) |
| | 17[illegible]0.0- 1850.0 MHz | Fixed, Mobile |

| | | |
|---|---|---|
| | 1718.8- 1722.2 MHz | Radio Astronomy (US256) |
| 2150.0- 2350.0 MHz | 1990.0- 2110.0 MHz | Fixed, Mobile |
| (2100.0- 2600.0) | 2110.0- 2200.0 MHz | Fixed |
| | 2200.0- 2290.0 MHz | Fixed (8), Mobile (8) |
| | | Space Research (3,4) |
| | 2290.0- 2300.0 MHz | Space Research (3,5) |
| | | Fixed, Mobile (6) |
| | 2300.0- 2310.0 MHz | Radiolocation |
| | 2310.0- 2390.0 MHz | Radiolocation, Mobile |
| | 2390.0- 2450.0 MHz | Radiolocation |
| | 2450.0- 2500.0 MHz | Fixed, Mobile |
| | 2500.0- 2655.0 MHz | Broadcasting-Satellite |
| | | Fixed |
| | | Radio Astronomy (US269) |
| | 2655.0- 2690.0 MHz | Broadcasting-Satellite |
| | | Fixed |
| | | Radio Astronomy |
| | 2690.0- 2700.0 MHz | RADIO ASTRONOMY |
| | | Earth Exploration-Satellite (1) |
| | | Space Research (1) |
| 4600.0- 5100.0 MHz | 4400.0- 4500.0 MHz | Fixed, Mobile |
| | 4500.0- 4800.0 MHz | Fixed, Mobile |
| | | Fixed-Satellite (3) |
| | 4800.0- 4990.0 MHz | Fixed, Mobile |
| | 4825.0- 4835.0 MHz | Radio Astronomy (US203,778) |
| | 4950.0- 4990.0 MHz | Radio Astronomy (US257) |
| | 4990.0- 5000.0 MHz | RADIO ASTRONOMY |
| | 5000.0- 5250.0 MHz | Aeronautical Radionavigation |
| | | Radio Astronomy (US211) |
| 5900.0- 6400.0 MHz | 5850.0- 5925.0 MHz | Radiolocation |
| | | Fixed-Satellite (2) |
| | 5925.0- 6425.0 MHz | Fixed |
| | | Fixed-Satellite (2) |
| 8000.0- 8800.0 MHz | 7750.0- 7900.0 MHz | Fixed |
| (7900.0- 8900.0) | 7900.0- 8025.0 MHz | Fixed-Satellite (2) |
| | | Mobile-Satellite (2) |
| | 8025.0- 8175.0 MHz | Earth Exploration-Satellite (3) |
| | | Fixed |
| | | Fixed-Satellite (2) |
| | 8175.0- 8215.0 MHz | Earth Exploration-Satellite (3) |
| | | Fixed |
| | | Fixed-Satellite (2) |
| | | Meteorological Satellite (2) |
| | 8215.0- 8400.0 MHz | Earth Exploration-Satellite (3) |
| | | Fixed |
| | | Fixed-Satellite (2) |
| | 8400.0- 8450.0 MHz | Fixed |
| | | Space Research (3,5) |
| | 8450.0- 8500.0 MHz | Fixed |
| | | Space Research (3) |
| | 8500.0- 9000.0 MHz | Radiolocation |
| 10200.0-11200.0 MHz | 9500.0-10550.0 MHz | Radiolocation |
| | 10550.0-10600.0 MHz | Fixed |

| | | |
|---|---|---|
| | 10600.0-10680.0 MHz | Earth Exploration-Satellite (1) |
| | | Fixed |
| | | Space Research (1) |
| | | Radio Astronomy (US277) |
| | 10680.0-10700.0 MHz | RADIO ASTRONOMY |
| | | Earth Exploration-Satellite (1) |
| | | Space Research (1) |
| | 10700.0-11700.0 MHz | Fixed |
| | | Fixed-Satellite (3) |
| | | Radio Astronomy (US211) |
| 14400.0-15400.0 MHz | 14200.0-14500.0 MHz | Fixed-Satellite (2) |
| | 14470.0-14500.0 MHz | Radio Astronomy (US203,862) |
| | 14500.0-14714.5 MHz | Fixed |
| | 14714.5-15136.5 MHz | Mobile |
| | 15136.5-15350.0 MHz | Fixed |
| | | Radio Astronomy (US211) |
| | 15350.0-15400.0 MHz | RADIO ASTRONOMY |
| | | Earth Exploration-Satellite (1) |
| | | Space Research (1) |
| | 15400.0-15700.0 MHz | Aeronautical Radionavigation |
| | | Radio Astronomy (US211) |
| 21700.0-24100.0 MHz | 19700.0-20200.0 MHz | Fixed, Mobile |
| (20000.0-26300.0) | | Fixed-Satellite (3) |
| | 20200.0-21200.0 MHz | Fixed-Satellite (3) |
| | | Mobile-Satellite (3) |
| | 21200.0-21400.0 MHz | Earth Exploration-Satellite (1) |
| | | Space Research (1) |
| | | Fixed, Mobile |
| | 21400.0-22000.0 MHz | Fixed, Mobile |
| | 22000.0-22210.0 MHz | Fixed, Mobile (6) |
| | 22010.0-22210.0 MHz | Radio Astronomy (874) |
| | 22210.0-22500.0 MHz | RADIO ASTRONOMY |
| | | Fixed, Mobile (6) |
| | | Earth Exploration-Satellite (1) |
| | | Space Research (1) |
| | 22500.0-22550.0 MHz | Fixed, Mobile |
| | | Broadcasting-Satellite |
| | | Radio Astronomy (US211) |
| | 22550.0-23000.0 MHz | Fixed, Mobile |
| | | Inter-Satellite |
| | | Broadcasting-Satellite |
| | 22810.0-22860.0 MHz | Radio Astronomy (879) |
| | 23000.0-23550.0 MHz | Fixed, Mobile |
| | | Inter-Satellite |
| | 23070.0-23120.0 MHz | Radio Astronomy (879) |
| | 23550.0-23600.0 MHz | Fixed, Mobile |
| | 23600.0-24000.0 MHz | RADIO ASTRONOMY |
| | | Earth Exploration-Satellite (1) |
| | | Space Research (1) |
| | 24000.0-24050.0 MHz | Amateur |
| | | Amateur-Satellite |
| | | Radio Astronomy (US211) |
| | 24050.0-24250.0 MHz | Radiolocation |
| | 24250.0-25250.0 MHz | Radionavigation |
| | 25250.0-27000.0 MHz | Fixed, Mobile |

| | | |
|---|---|---|
| 42300.0-43500.0 MHz | 40500.0-42500.0 MHz | Broadcasting-Satellite |
| | | Broadcasting |
| | | Radio Astronomy (US211) |
| | 42500.0-43500.0 MHz | RADIO ASTRONOMY |
| | | Fixed, Mobile (6) |
| | | Fixed-Satellite (2) |
| | 43500.0-45500.0 MHz | Fixed-Satellite (2) |
| | | Mobile-Satellite (2) |
| 86000.0-92000.0 MHz | 84000.0-86000.0 MHz | Fixed, Mobile |
| | | Broadcasting-Satellite |
| | | Broadcasting |
| | | Radio Astronomy (US211) |
| | 86000.0-92000.0 MHz | RADIO ASTRONOMY |
| | | Earth Exploration-Satellite (1) |
| | | Space Research (1) |
| | 92000.0-95000.0 MHz | Fixed, Mobile |
| | | Fixed-Satellite (2) |
| | | Radiolocation |
| | 93070.0-93270.0 MHz | Radio Astronomy (914) |

---

(1) Passive
(2) Earth-to-Space
(3) Space-to-Earth
(4) Space-to-Space
(5) Deep Space only
(6) Except aeronautical mobile
(7) Aeronautical telemetering
(8) Line-of-Sight