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THE RESPONSES OF THE VERY LARGE ARRAY AND THE VERY LONG BASELINE ARRAY TO INTERFERING SIGNALS

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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 Very Large Array (VLA) radio telescope was constructed by the National Radio Astronomy Observatory (NRAO) between 1973 and 1980, and was formally dedicated on 10 October 1980. The design and performance of the VLA have been described by Napier, Thompson, and Ekers (1983). In May 1985 the NRAO began construction of a new radio telescope, the Very Long Baseline Array (VLBA); construction should be completed by 1992. The characteristics of the VLBA have been described by Kellermann and Thompson (1985). Like other radio telescopes both the VLA and the VLBA are sensitive to radio interference but several features of their designs greatly reduce their sensitivities to such interfering signals.

In the following sections I will summarize the response of a single antenna to interfering signals, followed by discussions of the responses of the Very Large Array and 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. The Very Large Array

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

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 the VLA.) 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(πfT), 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 ω_0 is the angular rotation velocity of the earth and L is a measure of the physical size of the array. Characteristic values of L for the VLA and the VLBA are given below.

VALUES OF L FOR VLA AND VLBA

D array	C array	B array	A array	VLBA
436 m	1432 m	4706 m	15459 m	3952 km

The interference component in the VLA image should appear noise-like, although variations in the sidelobe gain or, especially, in the strength of the interfering signal may significantly affect the response of the VLA.

Nevertheless, we can use the above result to estimate the harmful interference levels for the VLA. The VLA presently observes, or is being equipped to observe, at seven bands. Bandwidths of 6.25 to 50 MHz are available for observations of the continuum emission of radio sources, and channel widths as narrow as 381 Hz are available for multi-channel observations of the spectral-line emission of radio sources; the narrower bandwidths are more sensitive to interfering signals. The most compact configuration of the VLA - the D array - is also the most sensitive to interfering signals. Table 1 shows the estimates of the harmful interference levels for the VLA for both continuum and spectral-line observations in the D array and using the narrowest appropriate bandwidth (at 75 MHz the width of the radio-astronomy allocation, 1.6 MHz, is used for the continuum observation.) Table 1 also includes the corresponding CCIR harmful interference levels for continuum observations with a single antenna; we see that the VLA is only 0.01 as sensitive to interfering signals as a single antenna.

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, like the VLA, 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 $\mathrm{sinc}(\pi B t_d)$, where t_d is the delay inequality. The maximum delay inequality is given by twice the delay corresponding to the maximum baseline of 35 km, or 230,000 nanoseconds. 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 Thompson (1982a) examined the response of the VLA to a geostationary satellite on the meridian. He finds that the decorrelation factor ranges between -3 and -35 dB in this instance, varying significantly with bandwidth, declination of the radio source, and the configuration of the VLA.

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 typical antenna spacing in the VLBA is 10,000 that in the D array (compare values of L), the natural fringe frequencies are corresponding greater (of the order of kiloHertz) than for the VLA, and the averaging effect reduces the sensitivity to interfering signals by another factor of 100. 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 occuring 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 2 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 Large Array and, especially, the Very Long Baseline Array are far less sensitive to interfering signals than other radio telescopes. Their sites have been selected, nonetheless, to minimize the potential for terrestrial sources of interference but both are 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, which is already quite comparable to the harmful interference levels for the VLA, without allowing for a more powerful transmitter or more antenna gain at the receiver or transmitter. Even the VLBA could see harmful interference.

Table 3 lists the VLBA observing bands - which include the VLA 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

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TABLE 1. VLA OBSERVING BANDS AND HARMFUL INTERFERENCE LEVELS

FREQUENCY (MHz)	EFFICIENCY	TSYS (K)	RECEIVER	CCIR(1) (dBW/m^2)	CONT(1) (dBW/m^2)	SPECT(2) (dBW/m^2)
73.0- 74.6	0.50	1000	GAsFET	-203(3)	-188(3)	-206
312.0- 342.0	0.40	125	GAsFET	-197	-178	-199
1340.0- 1730.0	0.50	50	Cooled GAsFET	-188	-166	-187
4500.0- 5000.0	0.65	50	Cooled GAsFET	-177	-152	-173
8000.0- 8800.0	0.65	40	Cooled HEMT	-173	-147	-168
14400.0-15400.0	0.54	110	Cooled GAsFET	-164	-137	-158
22000.0-24000.0	0.46	150	Cooled GAsFET	-159	-131	-152

(1) 6.25-MHz bandwidth
(2) 381-Hz bandwidth
(3) 1.6-MHz bandwidth

TABLE 2. 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 3. 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 (1300.0- 1800.0)	1240.0- 1300.0 MHz Radiolocation
	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 Earth Exploration-Satellite (1) Space Research (1)
	1427.0- 1429.0 MHz Fixed, Mobile (6) 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 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 Aeronautical Mobile-Satellite
	1660.5- 1668.4 MHz RADIO ASTRONOMY Space Research (1)
	1668.4- 1670.0 MHz RADIO ASTRONOMY Meteorological Aids
	1670.0- 1690.0 MHz Meteorological Aids Meteorological-Satellite (3) Radio Astronomy (US211)
	1690.0- 1700.0 MHz Meteorological Aids Meteorological-Satellite (3)
	1700.0- 1710.0 MHz Fixed Meteorological-Satellite (3)
	1710.0- 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)

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(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