VLB ARRAY MEMO No. 58A

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APPENDIX I

FRONT-END SYSTEM

A number of front-end configurations were considered for the VLB Array receivers. During the course of these deliberations a general design philosophy emerged that is felt will insure a low percentage of down time in a semi-attended operation staffed by personnel not expected to be highly skilled in the operation and maintenance of microwave and cryogenic equipment. We have attempted to achieve reliability through simplicity of design and a high degree of modularity. The resultant commonality of spare parts will reduce operating costs and the initial acquisition cost will be lower than for a system featuring redundant sub-systems to achieve reliability. The proposed design calls for mounting the dual polarization receivers for each frequency on a separate closed cycle refrigerator (CCR). This facilitates the low noise objective by permitting each receiver to be mounted in close proximity to the appropriate feed horn, eliminating transmission line runs to a single large receiver dewar as in the VLA. Additionally, it permits integration of the polarization separating orth-mode junction and the throat section of the feed horn onto the cryogenic refrigerator, thus reducing the noise contribution of these components. The low cost of GASFET amplifiers makes this approach affordable.

Because of feed considerations the two lowest frequency receivers must be located near the prime focus of the antenna. We have considered both uncooled and cooled GASFET amplifiers as well as cooled varactor upconverters followed by a cooled C-band GASFET as receivers for these frequencies. The later system would be similar to one implemented for the NRAO 140-foot and 300-foot telecopes in Green Bank. This system currently offers 40 K system temperature with a 10 K receiver temperature over the frequency band of 300 to 400 MHz. A second band from 500 to 750 MHz is covered with 60 K system temperature and a receiver temperature of 20 K. Noise temperatures in the galactic plane are, of course, higher. System noise, if implemented on the VLB Array, would probably by 10 to 15 K higher because of losses in the transmission lines required to link the single receiver dewar to the feeds located outboard of the subreflector on the support legs. Since the bandwidth offered by upconverters is not needed by the VLB Array at these frequencies, GASFET amplifiers at each frequency are more cost/performance effective. Cooled GASFETs are estimated to provide 30 and 60 MHz bandwidth at 327 and 610 MHz center frequency, respectively, and a receiver temperature using present technology of 10 K, reducing in 1986 to 7 K. The receiver for each frequency could be mounted on a separate CCR and located with the appropriate feed, thus offering an ultimate system temperature with 1986 technology of 42 and 37 K, respectively, exclusive of any noise contribution from the galactic plane. Uncooled GASFET amplifiers are estimated to increase the noise temperature at each frequency by 23 K with 1986 technology.

The uncooled amplifier configuration would be the least costly to acquire and maintain. Cooling both receivers on separate refrigerators would add \$30 K in material and 3 man-months in labor to the front-end cost estimate. Dual channel upconverters/C-band GASFET amplifiers for these two frequencies mounted on a single CCR would increase the front-end cost estimate by \$30 K in material and 5 man-months of labor.

The galactic noise at 327 MHz ranges from $\sim$ 100 K to $\sim$ 1000 K in the region $\pm$ 10° around the galactic plane. The extragalactic component elsewhere in the sky is $\sim$ 15 K, which is included in the system temperature estimate. Comparable positions at 610 MHz are 4 to 5 times smaller [5]. Since VLB experiments at these frequencies are usually done with sources outside the galactic plane, the receiver noise temperature improvement would not be masked by galactic noise for any appreciable number of observations. However, increased sensitivity at these wavelengths is not considered sufficiently important to offset the increased costs of front-end acquisition as well as mechanical considerations for higher load bearing prime focus support legs and prime focus access by cryogenic maintenance personnel.

Ruby masers are the lowest noise microwave amplifiers available. Consideration of these devices for the shorter wavelength receivers is summarized in Table I-1. Experimental performance obtained by the Jet Propulsion Laboratory with traveling wave masers (TWM) is indicated for 2.3, 8.4, and 15.4 GHz [1]. Experimental performance for NRAO reflected wave masers (RWM) are included at 22.2 GHz and 43 GHz [2]. Performance at other frequencies is extrapolated from these values. The projected improvement in TWM performance by 1986 arises from use of a superconducting material as a printed comb structure. This dramatically lowers the forward loss, thus reducing the noise temperature and allowing a tighter pitch slow wave structure for increased bandwidth and tuning range. The half wave printed comb slow wave sturcture, pioneered by JPL, provides a considerable increase in bandwidth and tuning range over the conventional quarter wave comb structure TWM. The RWM, pioneered by JPL/NRAO at 22 GHz [3], offers the widest tuning range and broadest bandwidth of any maser yet reported [4]. The RWM maser could be built at lower frequencies, but the input circulator loss would result in a receiver temperature 2 to 3 times that of a TWM. Obviously, masers could meet the tuning range required from L-band (400 MHz range to cover 21 and 18 cm molecular lines) on through 2-cm wavelength with receiver temperatures 1/10 to 1/25 of that projected for a cooled GASFET amplifier. System temperatures would improve by 30% to 60%.

It is highly desirable to be able to use the frequency synthesis technique to "fill-in" the u-v coverage of this array. This requires the receivers to have a center frequency range of 10% of nominal and be switchable over this frequency in an integration period (on the order of 1 second or less). This requirement precludes the use of masers at most VLB Array frequencies because the tuning rate is limited by the superconducting magnet to several seconds, and the instantaneous bandwidth will be less than that shown in Table I-1 because of limitations of the microwave pump source. The only possible exceptions would be at L-band and at S-band, where the pump frequencies are low enough to provide the projected bandwidth of 200-250 MHz. A further disadvantage of masers is the acquisition cost. The cost increase to replace one cooled GAS-FET receiver with a dual channel maser would be approximately $50 K in materials and 5 man-months in labor. For these reasons masers are only proposed for use at the two shortest wavelengths where the noise temperature improvement is significant enough to warrant the added cost and the loss of the u-v "fill-in" technique is accepted. Also, masers for these two frequencies have already been developed by NRAO, so no additional development costs will be incurred.

We have also considered upconverter/maser type receivers for the microwave frequencies. This type receiver offers maser-like receiver temperatures with wider bandwidth and tuning range than masers alone. NRAO has implemented an upconverter/maser receiver for the 140-foot telescope at Green Bank which achieves system temperatures in the range 30 K to 60 K between 4.6 and 25 GHz. The system employs three upconverters and a single K-band maser mounted on a 4.5 K CCR. The four frequency bands have instantaneous bandwidths of 300 to 500 MHz and tuning ranges of 2.5 GHz to 7 GHz.

Table I-2 is a comparison of receiver temperatures for upconverter/K-band maser type receivers, masers and cooled or uncooled GASFET amplifiers. Although the low noise temperature is attractive, the versatility of the upconverter/maser receiver requires complexity in the hardware implementation which has the disadvantage of high operating cost because of the need for skilled personnel to operate and maintain such a system. Additionally, the tuning speed and bandwidth preclude using the frequency synthesis technique for u-v "fill-in" at all but the L-band and S-band frequencies.

We can consider including upconverters at either of these frequencies on the same CCR with the dual channel K-band maser. The Q-band, K-band, and either S-band or L-band feeds could then be located near enough to one another to make the transmission line losses at the lowest frequency not excessive. The increased acquisition cost for such a system compared to the separate cooled GASFET amplifier would be \$20 K in material and three man-months of labor. Such a system would only provide about 20% improvement in system temperature, which is not considered enough to offset the increased operating cost due to the lower reliability of such a complex receiver. By comparison, the reduction in acquisition cost of not cooling any one of the dual-channel GASFET receivers is estimated to be \$15 K in material and 1.5 man-months of labor. This would result in a doubling of the system temperature at L-band, rising to three times at 2 cm. The system performance improvement in this case justifies the increase in complexity and costs.

For these reasons the proposed receiver complement consists of uncooled GASFET amplifiers near the prime focus for 327 MHz and 610 MHz, cooled GASFET amplifiers at the Cassegrain focus for six receivers between 21 cm and 2 cm and reflected wave ruby masers for the two shortest wavelengths of 1.2 cm and 0.7 cm. Table I-3 compares the cost increase to replace any of those receivers with the lowest noise alternative. Although the system temperature improvement in most cases is significant, the acquisition cost increase is also significant except for the prime focus frequencies of 327 MHz and 610 MHz. The development of traveling wave masers for the other frequencies would also require a sizeable engineering effort, which is not included in the cost column of Table I-3. Additionally, there is always the risk that the projected performance objective will not be achieved in the allotted time when such a significant advance in state of the art is attempted. It should also be pointed out that the lowest noise alternative considered here would preclude use of the u-v "fill-in" technique of frequency synthesis at all frequencies higher than 2.3 GHz. This is due to the limitations of bandwidth and tuning speed of the masers.

BIBLIOGRAPHY

[1] Private communication, R. C. Clauss and D. Trowbridge of JPL, Pasadena, CA.

[2] Private communication, S. Zisk, Haystack Observatory, Westford, MA.

[3] Moore, C. R. and Clauss, R. C., "A Reflected Wave Ruby Maser with K-Band Tuning Range and Large Instantaneous Bandwidth," IEEE Trans. MTT, Vol. MTT-27, p. 249 (March 1979).

[4] Moore, C. R., "A K-Band Ruby Maser with 500 MHz Bandwidth," IEEE Trans. MTT, Vol. MTT-28, p. 149 (February 1980).

[5] Private communication, R. Brown, NRAO, Charlottesville, VA.

TABLE I-1

Experimental and Estimated Performance of Ruby Masers at the VLB Array Frequencies

Frequency (GHz)	Maser Type	Tuning Range (GHz) 1	Bandwidth (MHz) 1	Receiver Temperature (Kelvin)	Experimental System Temperature (Kelvin) 4	1986 System Temperature (Kelvin)
1.55	TWM	0.1 (0.4)	40 (200)	3 (1)		21
2.3	TWM 2	0.1 (0.5)	40 (250)	2 (1)	13.5 2	
5.5	TWM	0.5 (1.5)	100 (300)	3 (1)		21
8.4	TWM 2	0.5 (2.0)	110 (300)	3.5 (1)	19.5 2	
10.7	TWM	1.5 (3.0)	180 (350)	4 (1)		21
15.4	TWM 2	2 (4.0)	20 (400)	9 (1.5)	27 2	
22.2	RWM 3	7	500	10 (7)	50 3	42
22.2	TWM	(4.0)	(500)	(2)		37
43	RWM 3	6	250	35 (30)	90 3	70
43	TWM	(3.0)	(500)	(5)		45

NOTES:
(1) Independent of pump source limitations
(2) JPL Experimental Performance of Traveling Wave Maser [1].
(3) NRAO Experimental Performance of Reflected Wave Maser [2] [4].
(4) Includes noise due to transmission lines, antenna losses and atmosphere.
( ) Values in parenthesis are 1986 projected performance with superconducting half-wave printed comb structure.

TABLE I-2

Noise Temperature for Various Types of Receivers at the VLB Array Frequencies

Frequency (GHz)	Receiver Noise Temperatue (Kelvin)				Additional* Noise (Kelvin)
	GASFET at 300 K	GASFET at 20 K	Upconverter/ K-Band Maser	Ruby Maser	
0.33	40 (30)	10 (7)			35**
0.61	45 (30)	10 (7)			30**
1.55	50 (40)	12 (9)	5	3 (1)	20
2.3	60 (50)	15 (11)	5	2 (1)	20
5.5	90 (70)	20 (17)	5	3 (1)	20
8.4	130 (110)	30 (20)	10	3.5 (1)	20
10.7	170 (140)	35 (25)	10	4 (1)	20
15.4	280 (170)	55 (40)	15	9 (1.5)	25
22.2	470 (200)	130 (60)	10	10 (2)	35
43	--- (800)	--- (200)		35 (5)	40

* Noise due to atmosphere, antenna spillover, and feed losses.

** Exclusive of noise in the galactic plane.

() Values in parentheses are 1986 projections.

TABLE I-3

Cost/System Temperature Improvement Summary for Lowest Noise Alternative Relative to Proposed Front-End System at the VLB Array Frequencies

Frequency (GHz)	Proposed System Temperature (Kelvin)	Lowest Alternate System Temperature (Kelvin)	Cost Increase over Proposed System to Achieve Lowest Temperature		System Temperature Improvement (Percentage)
			Material ($)	Man-Months	
0.33	*75 (65)	*45 (42)	15 K	1.5	40 (35)
0.61	*75 (60)	*40 (37)	15 K	1.5	47 (38)
1.55	32 (29)	23 (21)	50 K	5	28 (28)
2.3	35 (31)	22 (21)	50 K	5	37 (32)
5.5	40 (37)	23 (21)	50 K	5	43 (43)
8.4	50 (40)	24 (21)	50 K	5	52 (48)
10.7	55 (45)	24 (21)	50 K	5	56 (53)
15.4	80 (65)	34 (27)	50 K	5	58 (58)
22.2	45 (45)	45 (37)	None	None	0 (18)
43	75 (70)	75 (45)	None	None	0 (36)

* Exclusive of noise in the galactic plane.

() Values in parentheses are 1986 projections.

Note: The lowest noise alternate precludes the frequency synthesis u-v "fill-in" at all frequencies higher than 2.3 GHz.