A Proposed 1.5m Observing System for the VLA / EVLA

Field and Lab Test Results, Design Updates, and Deployment Plans

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Project Outline

The program may be broken down into five phases over 16 months:

(1) initial design and feasibility assessments at SAO
(2004 AUGUST – 2004 DECEMBER);

(2) construction of prototypes with *off-the-shelf* components
(2004 DECEMBER – 2005 FEBRUARY);

(3) field testing to evaluate antenna, IF, and correlator performance, and to assess receiver/feed design
(2005 MARCH – 2005 JUNE);

(4) redesign of electronics incorporating *custom-made components*; formulation of data processing strategies, all in light of lessons learned
(2005 MAY – 2005 JULY); and

(5) construction and deployment of second generation receiver/feed systems
(2005 AUGUST – 2005 NOVEMBER 30).

D-configuration (150^h approved contingent on performance) begins 2005 November 4 and ends 2006 January 17. Our latest planned readiness date for science observing is 2005 December 5. A proposed deployment schedule for final production receivers is discussed in a later section.

Project Status

(1) Three prototype receiver systems are fielded; number 4 is in use for design tests.
(2) Routine operation in a ~2 MHz band at 195 MHz has been demonstrated (Figure 1).
(3) Performance is adequate for key science.
(4) Impact on VLA L and P-band systems has been shown to be small.
(5) The RFI environment has been characterized and initial mitigation plans laid.
(6) A production receiver design has been completed.
(7) A window for general-user science has been identified (184-186 MHz) and a long-term contingency plan formulated in the event this band becomes unusable due to RFI.

Perspective

The program to outfit the VLA (and EVLA) for operation at 1.5m wavelength is motivated by the high potential reward of the key science. Through our field testing program during spring/summer 2005 it has been possible to test array performance with datasets on the order of 5^h long with 3 baselines. The ultimate scientific goal of the program requires integrations of several hundred hours in the 2007 D-configuration. Time requested for interim late 2005 and early 2006 D-configuration is explicitly intended to demonstrate performance with intermediate integrations of order 50 hours and to support the larger time request. Time in 2005/2006 will also be used to test a theorized (though seemingly unlikely) strong signal case, investigate the crowded fields around proposed targets, and support algorithm testing and development. *This* *work requires a full or nearly full deployment on the array* so that good *u,v* coverage is achieved even with heavy tapers (0.2 kλ) and dedication of 1-3 antennas to RFI monitoring.

Intensive field testing has enabled us to develop a robust RF design (*schematically* similar to that of the P-band receiver), characterize impact on P and L-band system performance, and study logistical constraints related to desired rapid deployment in late 2005. We are prepared to field this design (presented to the recently convened review panel). Secondary changes to mounting of the feed have been proposed to further improve sensitivity. To validate them and to confirm they do not negatively impact the other users, we propose testing in late September or early October, before deployment. (The testing will focus on sensitivity and beam characteristics at 1.5m and P-band). If we are unable to makes tests at that time, we are prepared to integrate testing and the first week of deployment activities, as described in a later section. Alternatively, we can defer the changes to later in 2006.

Clearly work with the proposed 1.5m receiver system carries technical risk; it might not perform adequately to accomplish the key science. However, initial indications are encouraging, and we cannot know how well it will actually perform for high dynamic range imaging until we deploy it. The program will explore a new scientific and technical frontier, and it is hoped to carry with it long-term benefits to the VLA and EVLA projects (i.e., expansion of frequency coverage and science). Uncertainties that remain now will be largely put to rest after the 2005/2006 D-configuration data are reduced.

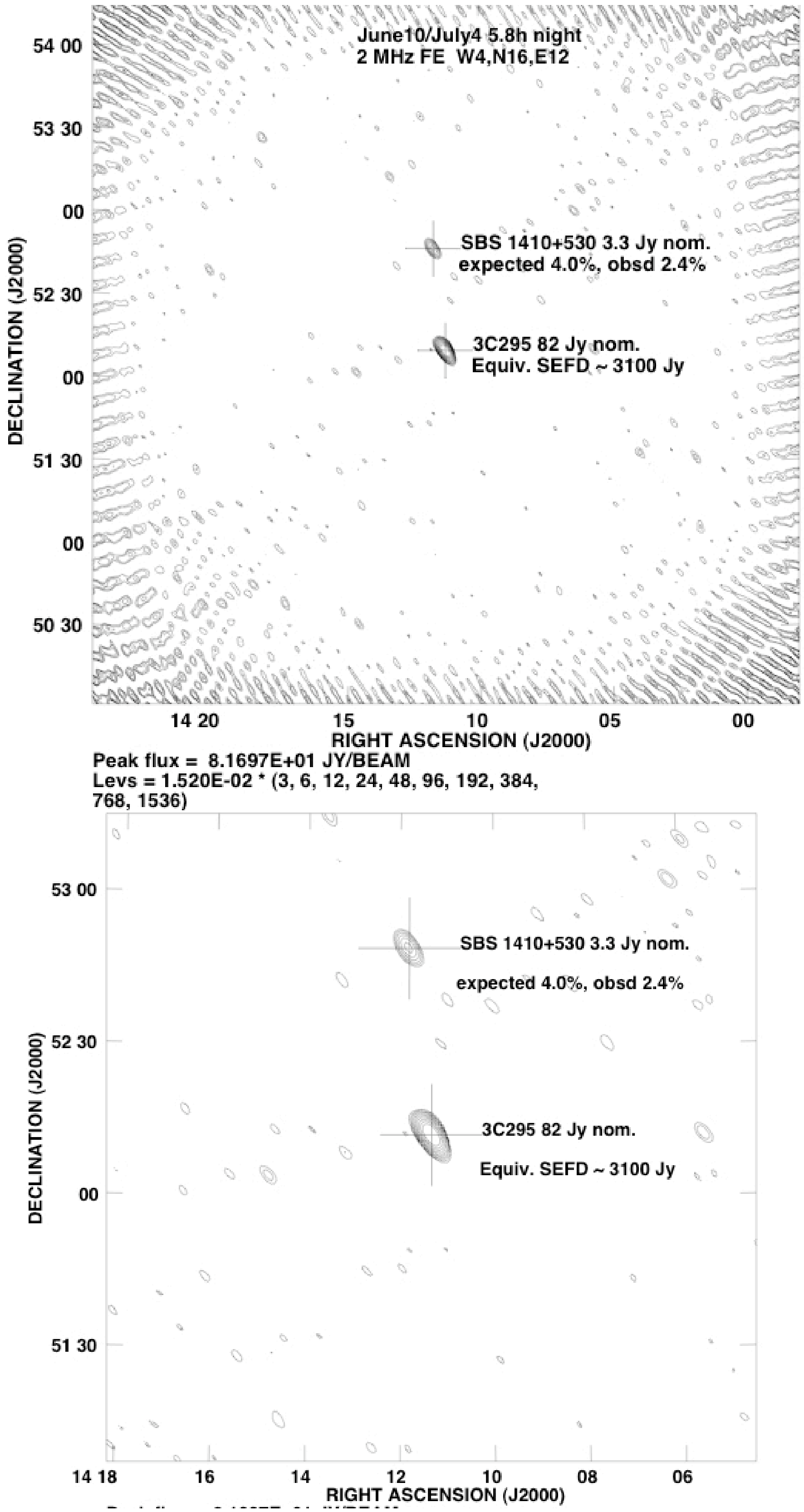

Figure 1—Images of 3C295 at 195 MHz (3 element subarray; 5.8^{h} on source; 2 MHz band. Crosshairs in the expanded view *(bottom)* mark catalog positions.

Field Test Activities

The VHF field testing program has targeted three themes: (1) assessment of antenna and prototype receiver performance at 195 MHz, (2) measurement of impact on L-band and P-band system performance, and (3) characterization of RFI and initial formulation of mitigation strategies.

SAO personnel have worked in Socorro or at the VLA site (day shifts and night shifts) for 10 of the 15 weeks between 2005 March 7 and 2005 June 17, principally using maintenance and software time where available. Test data have also been acquired during regularly scheduled tracks:

- 2005 April: 12^h,
- 2005 May: 12^h,
- 2005 June: 11.5^h (all at night), and
- 2005 July: 15.5^h (all at night)

The pace and direction of work during April and May was dictated by (1) the learning curve for making total-power measurements with the prototype receivers and (2) the delivery schedule for custom-made narrow band tunable front-end filters (~2 MHz at -3 dB). We discovered these were needed to obtain stable performance of the VLA front-end auto-level control system when faced with the rapid time variability of carriers from analog TV stations. The filters are engineering grade and will not be required in the long run.

Prototype receiver performance

SENSITIVITY

Our most reliable means by which to assess interferometer sensitivity (G/T) is measurement of phase RMS (i.e., signal-to-noise ratio) on a source of known flux. (Work with our prototype receivers has demonstrated the difficulty of estimating G/T in total-power mode because hot/cold load measurements cannot be made effectively and calibration of the noise diode signal injection in the prototype receivers is limited.)

Estimates of system equivalent flux density (SEFD) measured during nighttime observation of 3C295 and 3C313/7 on June 2, 10, 21, and July 4 are 2700 - 4400 Jy. For an adopted T_{SYS}~200 K[(1)] at high galactic latitude, the inferred aperture efficiency is ~26% to 35%. We note that this is comparable to the ~30% obtained with the Westerbork 25m dishes and prime focus dipole feeds.

PRIMARY BEAM

The primary beam at 195 MHz has been measured through standard holography on CasA (Figures 2-3). The half-power full width measured in beam cuts is ~4.3° ($1.2\lambda/D$=4.2°), though

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[(1)] We adopt a sky temperature of ~100 K, based on measurements of Haslam et al. (1982) at 408 MHz extrapolated to 195 MHz ($T \propto \nu^{-2.6}$), receiver temperature of ~ 60 K, based on lab characterization of the receiver *minus the feed*, and spillover temperature of ~ 40 K, based on an estimated beam taper of −6 dB at the edge of the VLA dish. Actual system temperatures could be somewhat larger in light of feed losses, which are difficult to measure. However, anticipated performance of final receiver designs is better and will be discussed later.

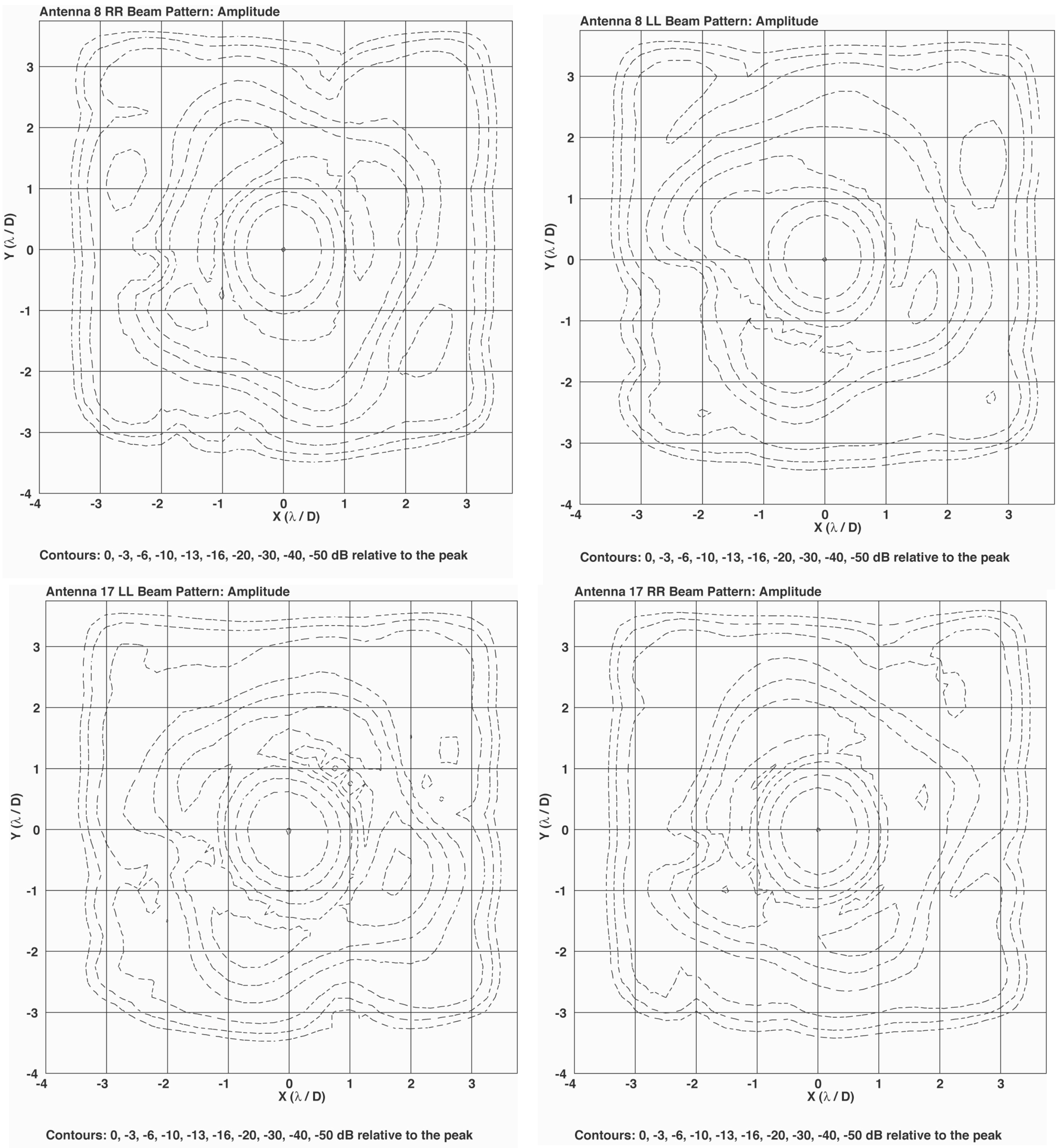

Figure 2—Beam patterns (amplitude) for antennas 8 and 17, RR and LL. The subreflector is rotated to the L-band default position (short side 45° from the downside quadrupod leg). The beam characteristics are repeatable from antenna to antenna.

sidelobe structure is present at about -10dB, some oval distortion is visible. We are collecting follow-up holographic data to better quantify these and other second-order characteristics.

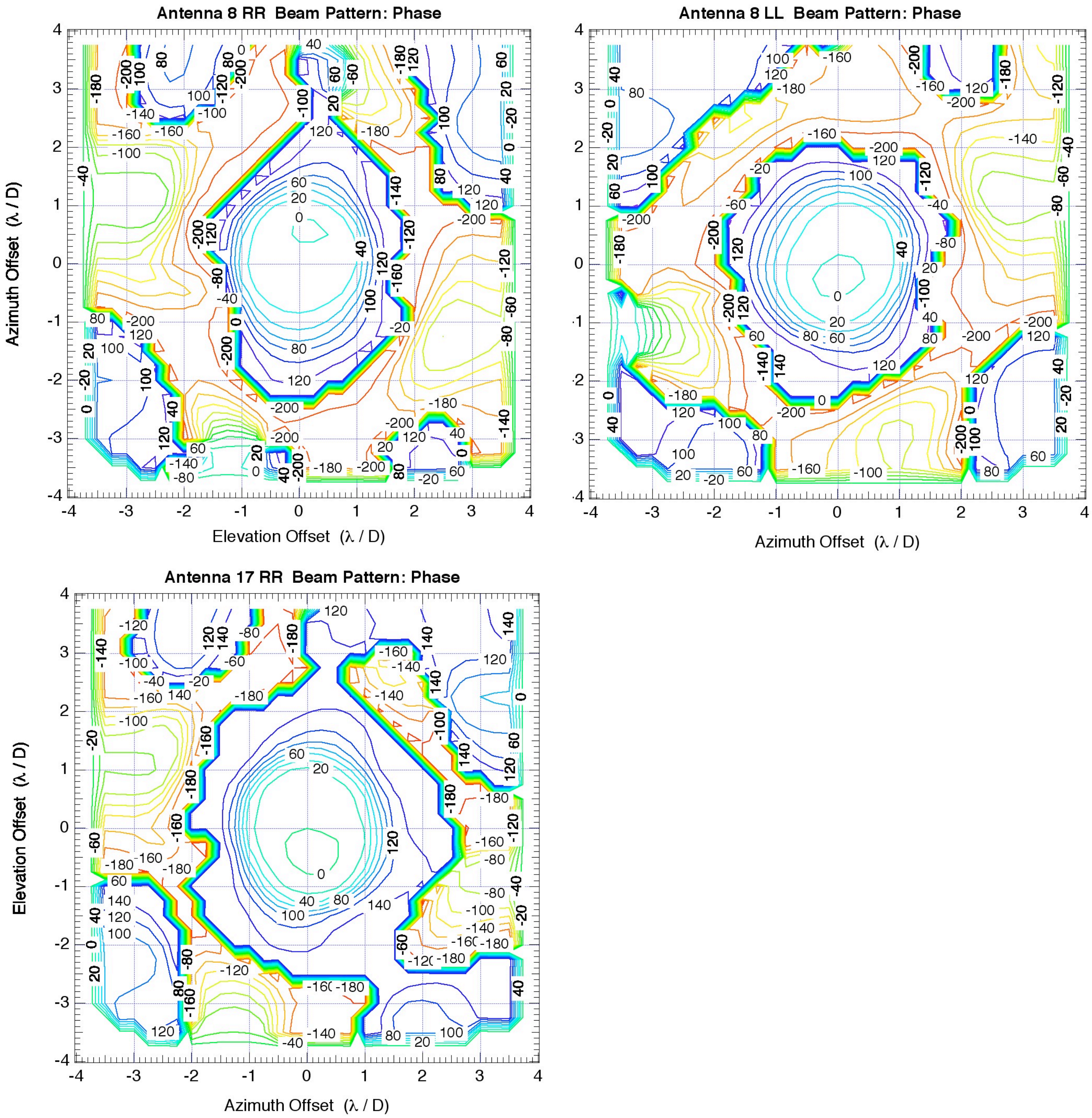

Figure 3—Beam pattern (phase) for antennas 8 and 17, RR and LL. The subreflector position is as in Figure 2.

Polarization Response

The cross polarization response of the 2-band system is expected to be comparable to that of the P-band system because the receiver and feed designs are similar. Attempts to measure polarization response on a single 2-band baseline using the prototype receivers have provided marginal results (e.g., RL/RR or RL/LL~10-40%) because of instrumental effects specific to the prototype design (e.g., possible cross-talk between coaxial baluns and normal variance in the division of signal within the quadrature hybrid). The production receivers should exhibit no worse cross polarization than the P-band receivers *on axis*. Off-axis polarization responses will differ because of larger diffraction effects at 1.5m and differences in sidelobe structure. We will study off-axis response once the production receivers are available, and (1) we are no longer constrained to use our small number of front-end, engineering-grade filters, and (2) we can be more certain of consistent receiver performance and generalizable results.

Proposed Changes to the Prototype Receiver System

The prototype receivers were constructed from off-the-shelf components and enabled rapid implementation of a test system at the VLA. Semi-permanent mounting of 1.5m dipoles, in contrast to the 4m dipoles, has provided an opportunity for low operational overhead and consistency in performance. Experience gained in field work has highlighted critical areas (e.g., RFI suppression in hardware, impedance matching of the feed, and quadrature hybrid placement in the signal path) and enabled design of lower noise, more robust and efficient receivers (Figure 4).

WHAT WILL NOT CHANGE

The VHF receiving systems comprise crossed dipole feed assemblies mounted beneath the sub-reflectors, and RF modules mounted in the barrel cabins. The 1.5m dipoles and central hubs are clamped to the P-band dipole assemblies via removable stand-offs. The 1.5m baluns are located in the central hubs, and ~1m of LMR300 coaxial cable conducts the RF signals to the receiver modules. These are anchored to the reverse side of the mounting plates for the P-band RF modules. The RF cables pass through the on-axis structural supports of the P-band feed

Table 1: Prototype vs Proposed Production Receiver Systems

Component	Change	Driver
Q-hybrid	Move to before LNA; broader band, lower loss component	Purity of polarization; isolation of LNA from mismatches
LNA	Operating point	Higher gain, lower T_{RX}
Noise diode injection	Move to after LNA; off for science observations	Stability; low T_{RX}; preclude leakage into P-band receiver
Lumped-element balun	Replace coaxial balun	Low insertion loss, broad bandwidth
Bandpass filter	Use 8-pole custom filter	Exclusion of TV carriers
High-Q crystal notch filters	Inclusion	Exclusion of TV carriers to enable operation of ALCs and to avoid ringing in spectra
Dipole shorting switch	Inclusion	P-band performance.
Connection to superflex	3 dB pad at 2-band RX out	Damp 3 MHz bandpass ripple in 1.5m AND P-band output
2-band/P-band power and cal on/off control	S/W control of power and cal signal to 2-band and P-band	Noninterference assured. 2-band off for P-band obs. P-band off for 2-band obs. Control power at A-rack input

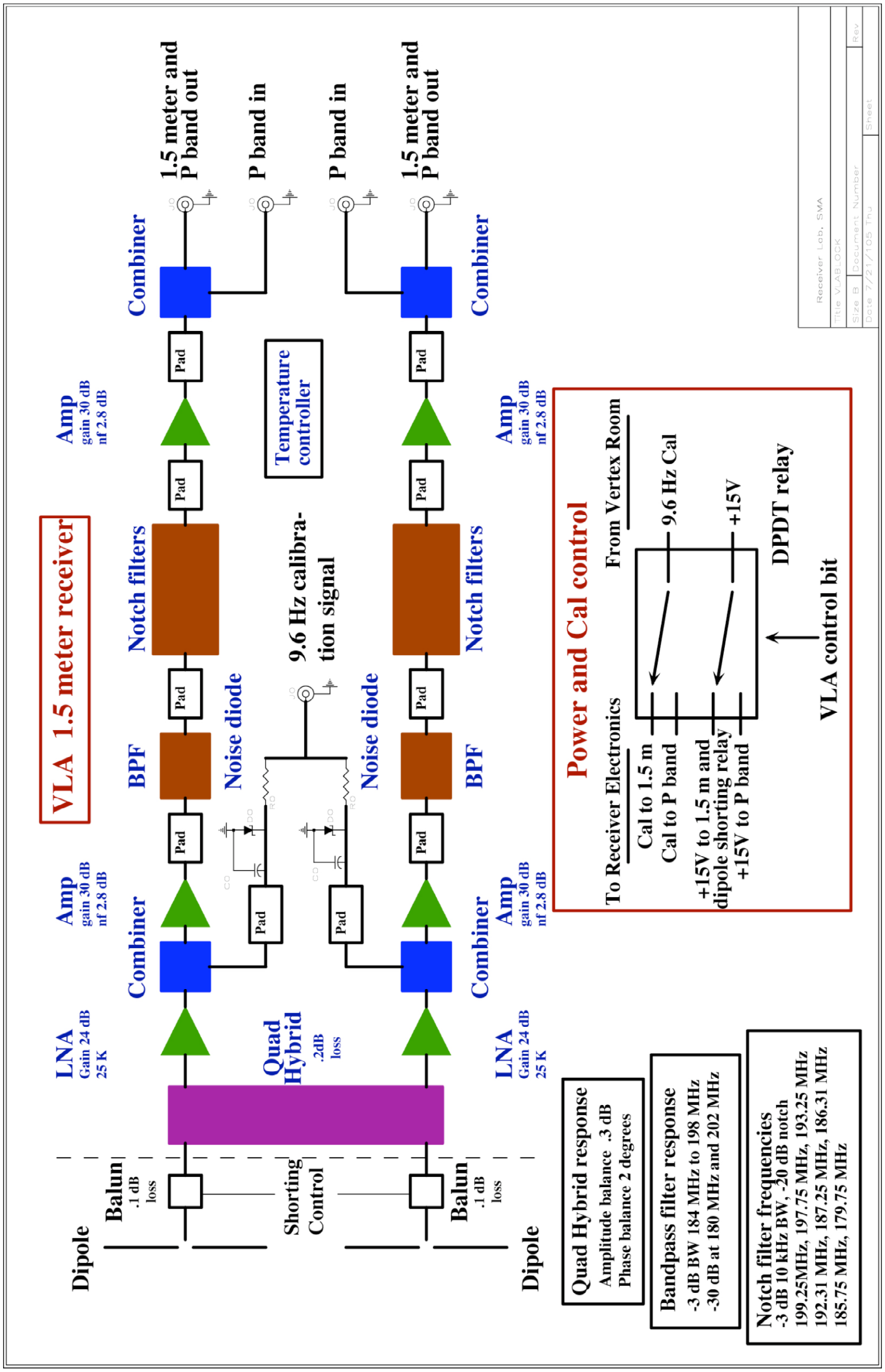

Figure 4—Layout of proposed production receivers. The RF electronics comprise surface mount components in shielded enclosures and weather tight boxes identical to those for P-band. A heater provides temperature control for critical elements, to assure gain stability.

assemblies. The power, calibration control signals, and RF output for the 1.5m and P-band receivers are daisy chained so that existing cables serving the barrel cabins can be used without modification. One control bit is needed.

WHAT WILL CHANGE

Tables 1-3 summarize the differences between prototype and proposed production receiver designs, and the proposed receiver specifications.

Table 2: Specification of the Proposed Production Receiver Systems

Bandwidth	Feed: 193 MHz center; $\Delta\nu/\nu$ ~ 5-8% optimum BP filter: 184-198 MHz @ -3 dB Quadrature hybrid: 160-230 MHz
Gain	84 dB minus pads, filter insertion losses, etc
Notches	TV 7(v), TV8(a), TV9(v), TV10(v,a) TV11(v), DTV9(c), DTV10(c) †
Power out	-67 dBm over 14 MHz at input to A-rack
System noise savings over prototypes	Low noise balun (0.05-0.1 dB) †† Simplification of balun connections (0.01-0.05 dB) Shortened cable between balun and RX (0.01 dB) LNA operating point (10-20K) Noise diode off during science ops (~5-10K) Spill-over (~10K; contingent on feed alteration see later section)

† (v)—video carrier; (a)—audio carrier; (c)—digital carrier

†† 0.1 dB loss contributes ~7K of receiver temperature.

Table 3: Anticipated Performance of VLA/EVLA Antennas and Receivers at 1.5m

Primary beam	~ 4.3° half power full width; 10 dB 1st sidelobe
SEFD	2400 – 4000 Jy (16 cm dipole spacing) 2100 – 3400 Jy (10 cm dipole spacing) †
Cross pol.	Comparable to P-band

† The option and advantages of reduced spacing between 1.5m and 0.92m feeds will be discussed in a later section. The prototype receivers exhibit SEFDs of 2700-4400 Jy with a16 cm dipole spacing.

SENSITIVITY

Design improvements are anticipated to reduce receiver temperature by ~30% and system temperature by ~10%. Contributions will come chiefly from lower loss in the balun, better operating point for the LNA, and switching off the noise diode injection during observing, In the a later section we propose testing a shorter separation between 1.5m and 0.92m dipoles in an effort to recover another 10% in sensitivity (G/T), for a net improvement of ~20% (25% if an anticipated 10K improvement in spillover is achieved) - see Table 3.

Impact on P and L-band System Performance

L-BAND

Impact on L-band T_{SYS} (zenith) and G/T were measured on 2005 May 25 with the 1.5m dipole mounted and dismounted from antenna 8. With the dipole mounted and assuming 10K spill-over, a hot load test yields a T_{SYS} of 29K and a noise cal temperature of 2.03±0.04K for 12 cycles of the cal. Measurements were repeated with the 1.5m dipole dismounted. The cal temperature was this time used to estimate T_{SYS} directly, 30K after subtracting the temperature of the galactic plane, which was close to overhead (Reich et al. 1982, AAS, 48, 219).
Similar measurements at L-band were also made on 2005 March 16, using antenna 6. T_{SYS} with the dipole mounted was 30K and 30K without the dipole, ±1K.

On 2005 May 25, ratios of fringe power for CasA with and without the 1.5m dipole mounted were used to estimate impact on sensitivity. The ratio was measured three times, 0.98, 0.99, and 0.98 with formal uncertainties of 1%. On 2005 March 16 the ratio for CasA was 1.01 with comparable uncertainty.

P-BAND

Impact tests for the P-band system evaluated both loaded and shorted 1.5m dipoles. Lab testing at SAO in 2004 raised expectations that a shorted 1.5m dipole would act as a director, improving the forward gain of the P-band feed. Electromagnetic finite element modeling (using the MMANA package) has also suggested there may be some benefit to shorting the1.5m dipole (Table 4).

Table 4: Model P-band Gain† in Response to Loaded/Shorted1.5m dipole

ν	1.5m loaded	1.5m shorted	Δ
305 MHz	7.35 dB	7.84 dB	0.49 dB
315	7.54	7.79	0.25
325 ††	7.50††	7.54	0.04
335	7.32	7.28	-0.04
345	7.05	6.89	-0.16

† Gains are relative.
†† The 325 MHz gain for a P-band dipole alone is 7.55 dB.

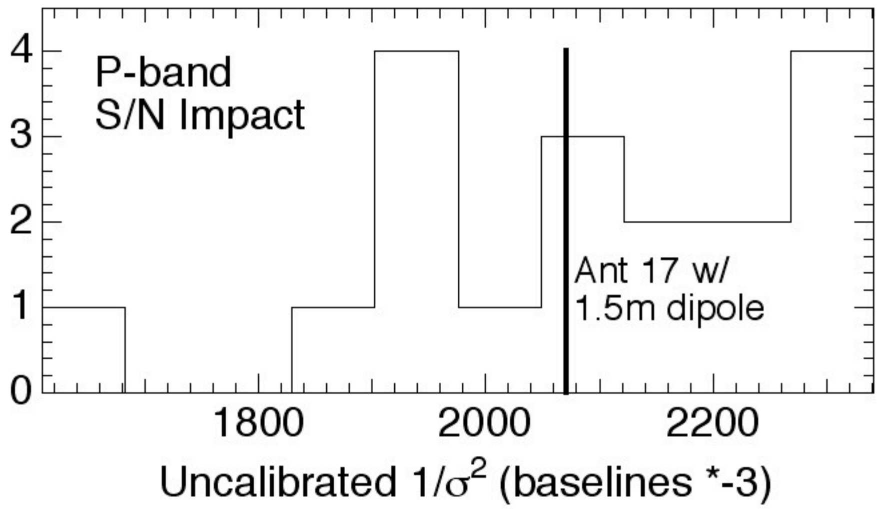

Figure 5—Good performance of antenna 17 with a loaded 1.5m dipole in place, relative to other antennas at P-band.

Loaded 1.5m Dipole
Although field-testing has focused on performance for shorted 1.5m dipoles, basic tests show that antenna 17 has average sensitivity when equipped with a *loaded* 1.5m dipole. 3C295 was observed on 2005 June 21. Comparison of S/N achieved on different baselines to antenna 3 shows that the performance of antenna 17 is comparable to other antennas (Figure 5). Comparison of phase noise measurements at 327 MHz on 2002 April 06 give comparable results. The phase noise on 2005 June 21 is consistent with T_{SYS} / A_e~ 670 K or a ~ 30% efficiency for T_{SYS} ~ 200 K, in agreement with measurements by Perley in early 2005 March, before deployment of the 1.5m dipoles. More accurate measurements for a loaded dipole can be readily made, but for a deployed 1.5m system, operation with a short applied will be the default.

Shorted 1.5m Dipole
We have examined the effect of shorted 1.5m dipoles on P-band beam characteristics (305 and 325 MHz) and sensitivity (305 to 345 MHz). In the first observations, on 2005 June 02 at 325 MHz with 3.125 MHz bandwidth, relative G/T and beam width were estimated from analysis of beamcuts in holography mode along four axes while observing 3C147. The mean ratio of fringe power with the shorted dipole mounted/dismounted was 1.07±0.05. Comparison of −3 dB beam widths indicates a mean 11±3% narrowing of the P-band beam when the shorted dipole is in place.

Full holographic measurements were completed on 2005 July 26 and 27 with the 1.5m dipole shorted and dismounted from antenna 17 (Figure 6). The raster scan covered ~18°. Slices through the beam power pattern at 325 MHz show up to a 10% reduction in −3dB and −10dB beam widths (Table 5a,b). The reduction in beam width is consistent with reduction in defocusing of the P-band system (from 50 cm to 40±3 cm).

Sensitivities in 0.8 MHz bands at band-center frequencies between 305 and 344 MHz were obtained by tracking 3C147 on 2005 July 26 and 27, with the 1.5m dipole shorted and dismounted (Table 5c). A shorted 1.5m dipole improves P-band sensitivity at 335 and 345 MHz significantly, and would support use of broader observing bandwidths in future. No measurable difference is seen at 305 MHz. Some may be present at 325 MHz.

Table 5a: RCP P-band Beam Widths (Shorted 1.5m/No 1.5m)

	PA=90° (*)	PA=45° (*)	PA=0° (*)	PA=-45° (*)
-3 dB	2.39°/2.53°	2.42°/2.53°	2.46°/2.56°	2.42°/2.56°
-6 dB	3.37°/3.61°	3.40°/3.61°	3.44°/3.58°	3.42°/3.61°
-10 dB	4.35°/4.95°	4.46°/4.91°	4.42°/4.70°	4.39°/4.84°

*Position angle defined in terms of elevation (0°) and azimuth (90°)

Table 5b: LCP P-band Beam Widths (Shorted 1.5m/No 1.5m)

	PA=90° (*)	PA=45° (*)	PA=0° (*)	PA=-45° (*)
-3 dB	2.39°/2.42°	2.39°/2.53°	2.46°/2.65°	2.49°/2.56°
-6 dB	3.37°/3.38°	3.33°/3.58°	3.47°/3.75°	3.51°/3.58°
-10 dB	4.28°/4.34°	4.32°/4.77°	4.49°/5.01°	4.53°/4.56°

*Position angle defined in terms of elevation (0°) and azimuth (90°)

Table 5c: Change in P-band Sensitivity due to Shorted 1.5m Dipole

Frequency	**Improvement in sensitivity**				
	1-17	**17-22**	**17-24**	**17-27**	
Short 1.5m					
305 MHz	1.0	1.0	1.3	1.1	
325	1.0	1.3	1.3	1.0	
335	1.6	1.7	1.5	1.8	
344	1.8	1.7	1.8	2.0	
Control	**1-22**	**1-24**	**22-24**	**22-27**	**1-27**
305 MHz	1.21	0.93	0.97	1.4	0.85
325	0.81	0.84	0.84	1.0	0.91
335	1.1	1.1	1.3	0.87	1.1
345	1.1	1.0	0.97	0.98	0.89

† Signal to noise ratio for listed baselines with a shorted 1.5m dipole on antenna 17 divided by the signal to noise ratio when the 1.5m dipole is removed from antenna 17. Numbers larger than unity favor the shorted dipole.

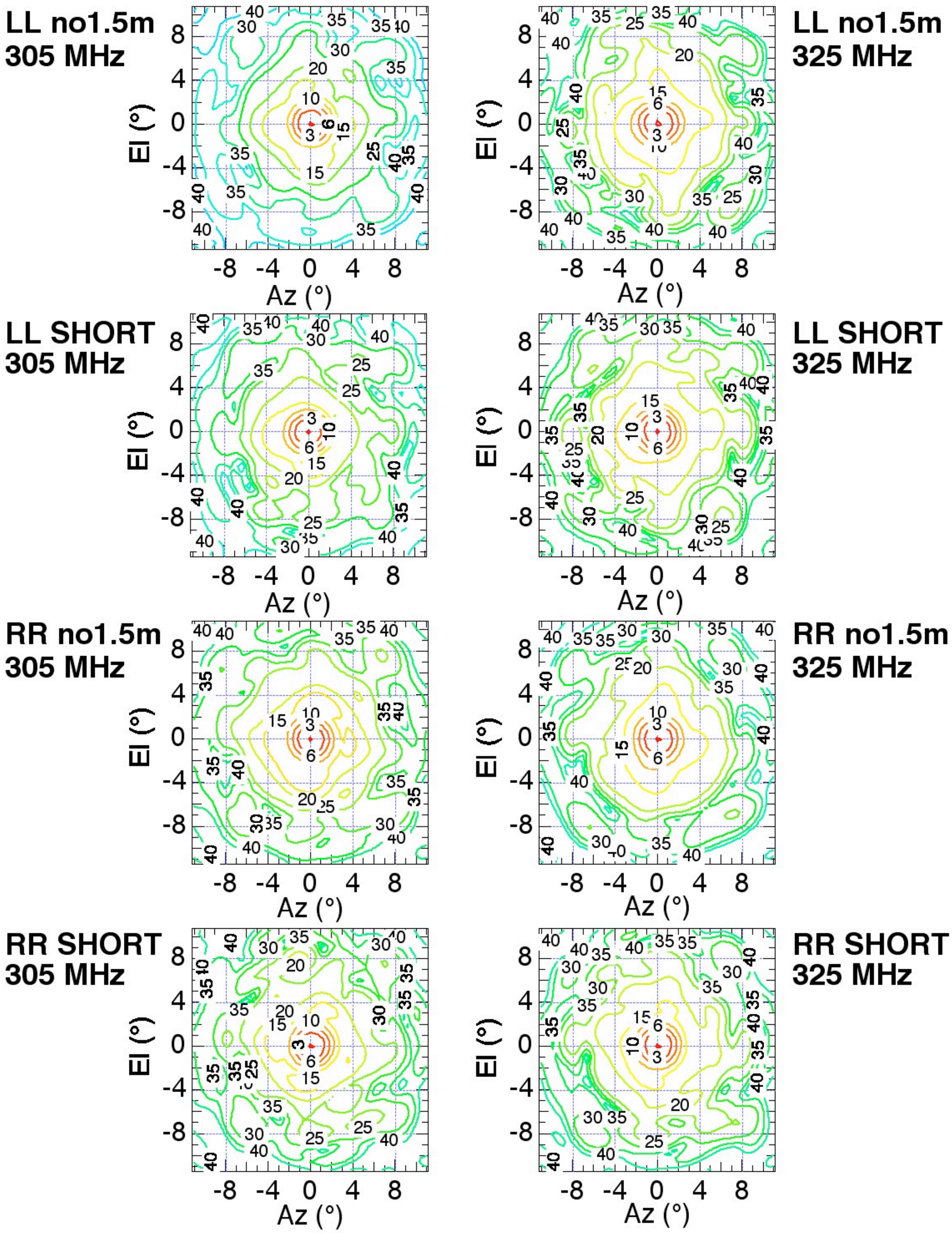

Figure 6—P-band beam patterns for antenna 17 (in dB) without a 1.5m dipole assembly and with a shorted 1.5m assembly in place.

Manpower

USE TO DATE

Bob Smith and *Dan Mertely* have provided the bulk of support within NRAO for field testing. *John McClendon* and the cherry picker operators have also worked on the project, but to a lesser extent. When feasible, we chose to work with Bob Smith because his duties were VLA-related, rather than EVLA-related. This manpower has been needed for operations that require work in the areas that require safety training: barrel cabins and on the reverse side of the sub-reflectors (mounting and receivers and feeds, dismounting feed assemblies for impact testing, DVM or reflection loss sweeps, and basic RF testing such as insertion of pads or terminations). Demand early in the field test program was driven by the need to follow-up inconsistent test results that have since been linked to receiver performance in the presence of unexpectedly heavy RFI. Later in the field test program, activity focused on the vertex cabins and pedestal, where the PI was able to handle most activities, supported by Carilli and Perley when able.

FORECAST

Any future installation program will be designed to minimize demands on NRAO manpower. Structural details of the prototype and production receivers are effectively identical. In terms of noise characteristics, efficiency, and RF performance in the presence of RFI, improvements will greatly simplify and speed testing of the production receivers.

Extensive experience has been gained through the installation of the prototype1.5m receivers. The procedure for production units will be substantially similar. *A practical rate is two receivers per full day for three people plus cherry picker operator.* This requires one person to work a barrel cabin with safety look-out in the dish (4^h) and a second person working in the cherry picker, accompanied by an operator for ($\sim 2^h$). Testing in the barrel cabins will be limited to line voltage measurements, switching tests, and RF continuity tests involving the look-out who will work with a spectrum analyzer in the vertex room. Subsequent receiver performance testing will be conducted through remote control of the antennas and the correlator. There is not now any expectation of a need to make time consuming manual measurements as were made by us in 2005 April and May (e.g., total power with the Milhouse laptop).

Receivers and feeds will be delivered (with documentation) to NRAO after function testing, noise measurements, and vector network analyzer characterization. Confirmation before mounting can be managed by SAO personnel during weekly visits to NRAO. SAO can also support installation with up to two engineers on site if safety qualification can be arranged and harnesses provided. The PI or SAO staff substitute can also support installation activities. Additional support from Carilli or Perley is not counted here in the interest of conservatism.

Complications in receiver/feed installation on EVLA antennas are not anticipated because the EVLA and VLA barrel cabins are the same, the P-band feed assemblies are the same, and the P-band signal paths prior to sampling are the same. Adjustment for the higher noise diode control signal (28V versus 15V) and higher supply voltage (17V versus 15V) is readily handled in the 1.5m receiver design, which includes regulators. The most likely difference in receiver performance will involve internally generated RFI, where the EVLA environment is quieter, though a test installation on an EVLA antenna during summer 2005 would provide certainty.

RFI

At the VLA, the RFI environment in the commercial broadcast bands is much more aggressive than anticipated, based on site monitoring in mid/late 2004. *Though more difficult than first believed, mitigation still appears to be practical.*

A substantial fraction of observed narrow-line RFI is internal and not phase coherent; the frequencies of lines are often antenna dependent and only a small fraction appear in cross power. (We note that tests on antennas 6 and 17 show that almost all lines enter via the feed rather than the cabling and electronics racks.) Nearly all of the strong lines seen in cross power are related to TV broadcasting (Figure 7-9). The audio carrier is frequency modulated chiefly over ~20 kHz, with additional modulation possible over 200 kHz (e.g., SAP), and reception can cause ringing in Fourier transform spectra. The video carrier is amplitude modulated, causing both ringing and interfering with operation of the VLA auto-level control system (ALC). Additional RFI features in spectra include DTV signals where the carrier is not modulated, but the broadband signal exhibits substantial spectral structure and overall emission for known sources can be well above the sky noise level (by ~ 10 dB).

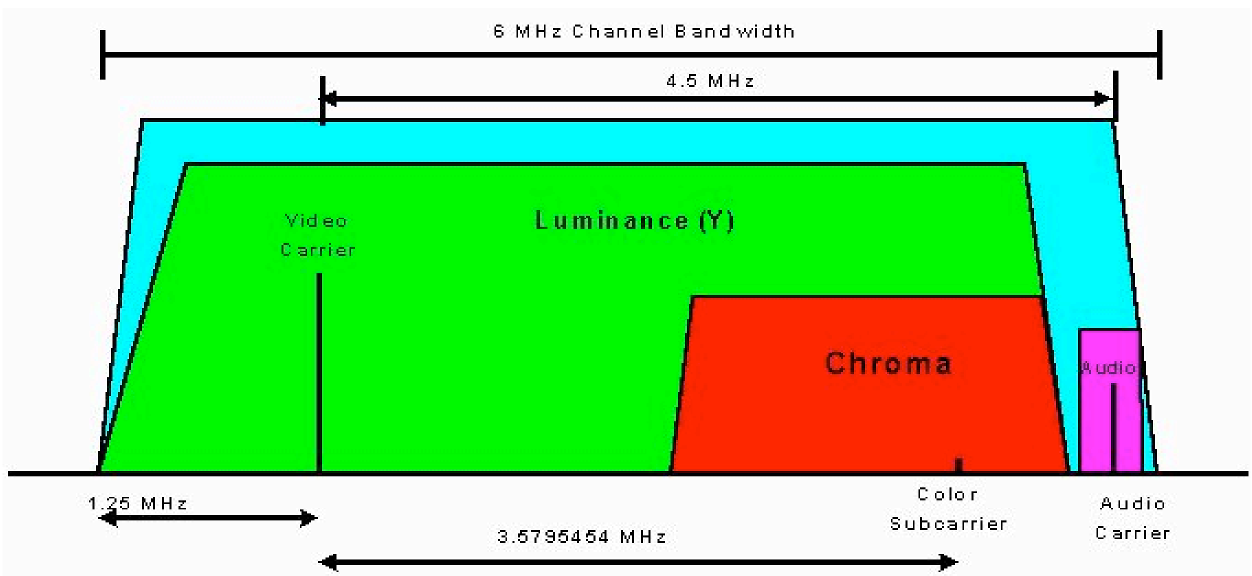

Figure 7—Allocation of analog TV transmission for an individual channel. (Graphic taken from "Understanding and Measuring Video TV-RF Signals," by Glen Kroupuenske.) In the case of VLA spectra, video and audio carriers are readily detected (see following figures), but the color sub-carriers are not observed.

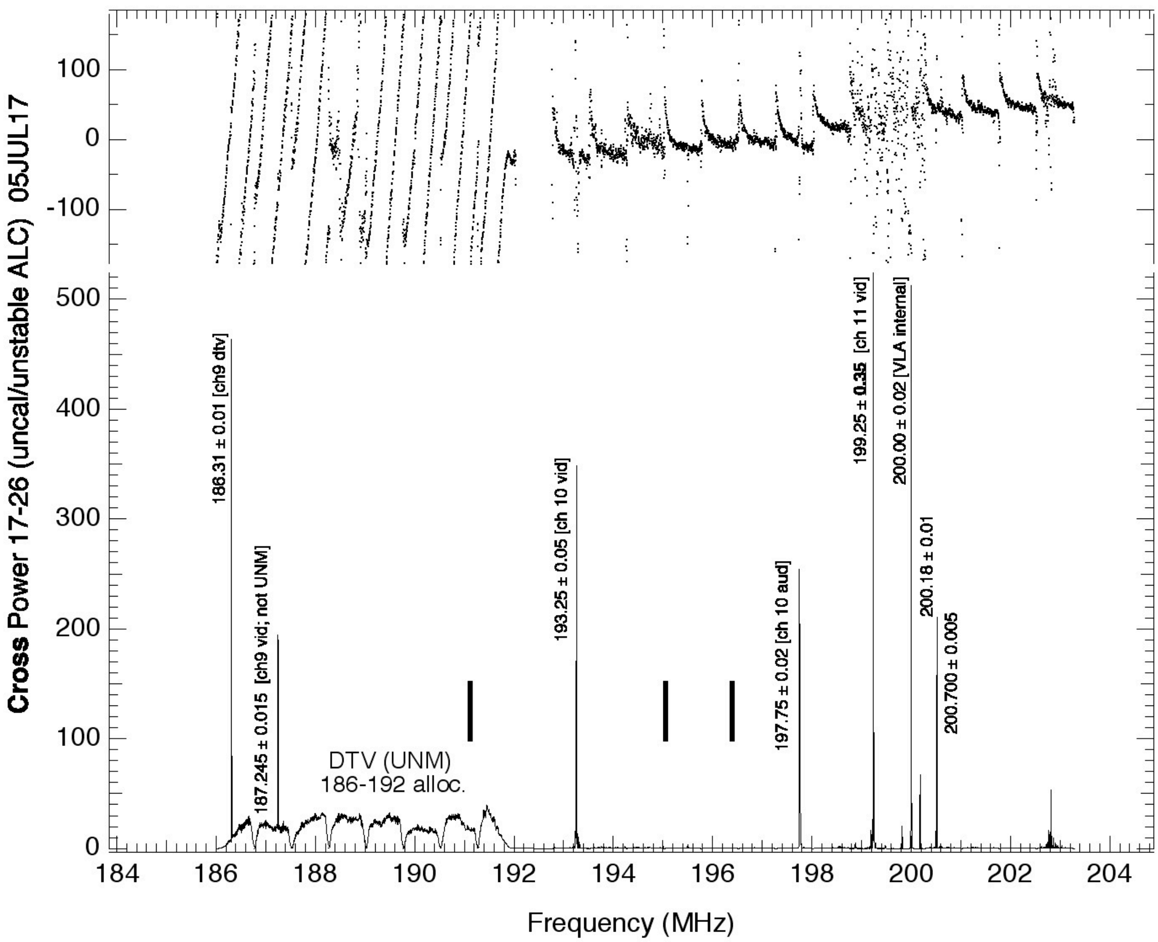

Figure 8—Complex cross-power spectrum of RFI from 186 to 203 MHz (05 July 17, night), dominated by analog TV carriers. Channel allocations are 6 MHz wide (e.g., 186-192 MHz). Line-center frequencies for our proposed astronomical targets are indicated by vertical bars. Visible DTV transmission is known to be KNMD, operated by the University of New Mexico. Weak DTV emission between 192 and 198 MHz has also been detected intermittently, which we believe to be low power operation by KCHF. The spectrum shown comprises separate 0.8 MHz bands. Bandpass responses have not been removed, hence the deviations in phase and amplitude at the (many) band edges. Channel spacing is 1.5 kHz.

A three-layered approach to RFI mitigation appears to be the most promising.

Coordination

DTV: DTV transmissions are the most substantial obstacle to the proposed science, because the signal can be many dB above the sky, it uniformly fills broad (6 MHz) bands, and nearby stations overlap our key science band. Channel 9 (KNMD) covers 186-192 MHz, and channel 10 (KCHF) covers 192-198 MHz. The line-center HI emissions associated with the three target quasars proposed in AG686/706 lie between 191.1 and 196.4 MHz. Necessary offline science bands may extend as low as ~188 MHz and as high as ~198 MHz.

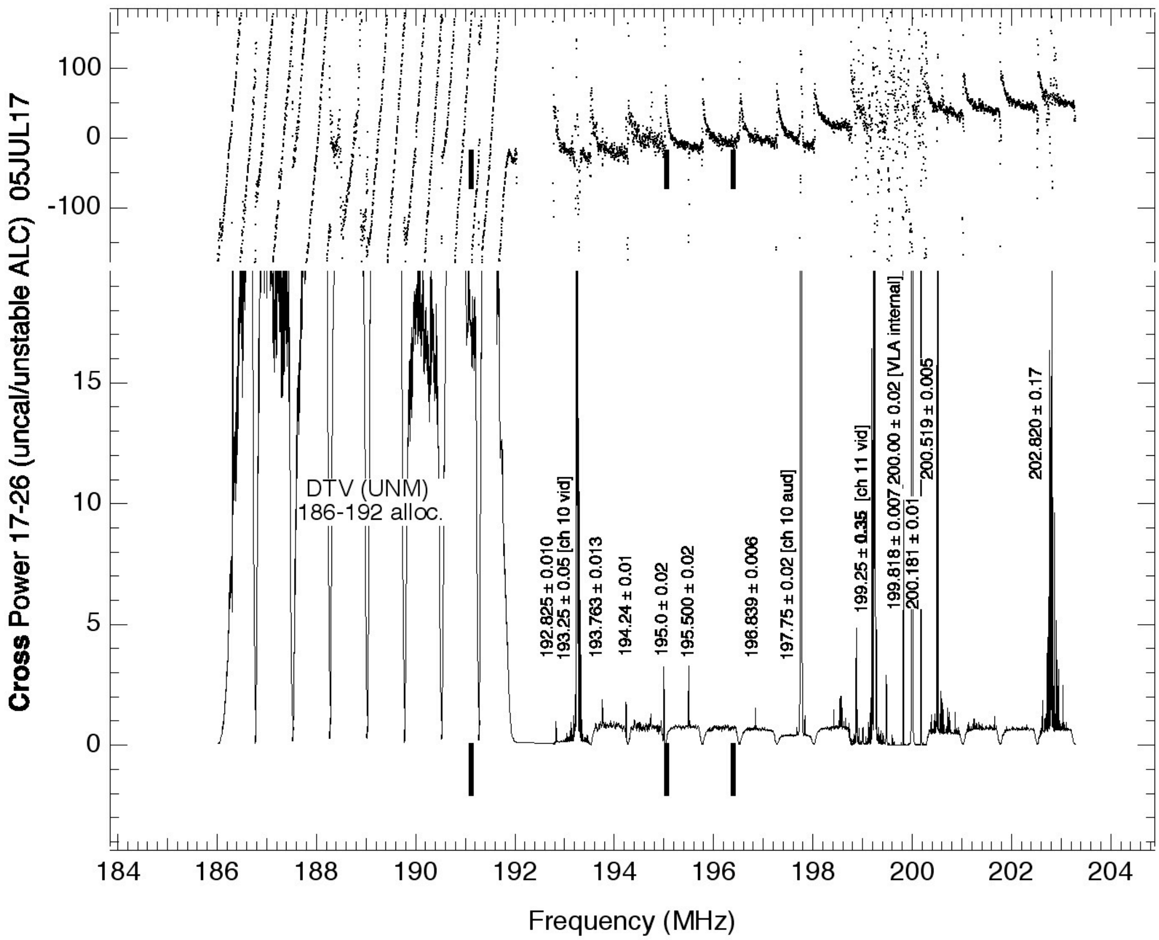

Figure 9—Expanded view of the cross-power spectrum shown in Figure 8. Weak lines that appear in this ~2^m scalar average are probably not related to TV broadcasting and may be internally generated.

KNMD operates a 0.2 kW transmitter on Sandia Mt, and the received power is ~10 dB above the sky. KCHF operates a 1.7 kW directional transmitter west of Santa Fe (serving Santa Fe and Albuquerque) and is building a 30 kW omnidirectional facility at the same site. To date, KCHF transmission has been observed intermittently only somewhat above the sky noise. However, its larger facility will be at least12 dB stronger, if activity to date represents full-power testing, and the detected signal will be substantially stronger than the detected for KNMD.

KNMD is operated by the University of NM and through the efforts of Frank Gilfeather has expressed willingness to coordinate with late night/early morning operation at the VLA. We have already successfully coordinated test time on May 18. (Our key science targets transit at midnight between late February and mid-March, and observing has been requested for Q4 2005 and Q1 2007.)

KCHF is also a noncommercial station. Our contact at KCHF is the RF system engineer. He has more than once expressed willingness to work on coordination for late-night/early morning tracks. Full-power broadcasting (30 kW) is expected in mid-2006. Daily low-power broadcasting may begin in late 2005.

If the panel review approves continued work on the 1.5m receiver system, we will follow up with both stations, to inform them of timelines and to obtain additional commitments in writing if possible.

FM: New FM transmission facilities to be built near Riley, NM will service 95.9 MHz, and the first harmonic lies in our science band. A managing partner for Matinee Radio, LLC has agreed to work with NRAO and SAO when engineering and construction of the station are underway, to assure low out-of-band emissions. However, for the time being, the Riley site is inactive.

FILTERING

An eight pole filter will define the passband of the proposed 1.5m production receivers The 3dB points will be 184 and 198 MHz. VLA front-end filters may also be used (185/25 MHz for EOR science and 187/12.5 MHz for general-user science – see later section). The strongest RFI is broadcast by TV channel 7 (audio) at 179.75 MHz (300 kW at Sandia Mt). This constrains the lower end of our passband. A complex of lines and associated modulation products constrain the upper end.

We have demonstrated routine operation of the VLA through use of 2 MHz engineering-grade front-end filters tuned to exclude carriers (195.4±1 MHz). Based on this success, we have formulated a plan to notch filter eight analog TV carrier and other lines that have been observed in cross power (on a 1 km baseline; Figures 8, 9). The notches will be created at RF using high-Q crystals (Figure 4). Lab tests with a 100 MHz (space qualified) crystal have generated on the order of 15 dB suppression with a –3 dB width of ~7 kHz. Models indicate we may anticipate another ~10 dB of suppression from our intended parts, and broader notches can be created by adjusting the impedances around the crystals with moderate loss in depth. Other weak lines (20 kHz FWZI) have been detected in cross power and excision from correlator data demonstrated for channel spacings of 6 kHz. This should also be practical for the correlator modes we anticipate using (channel spacing 12.2 or 24.4 kHz after Hanning smoothing).

SUBTRACTION

Techniques that employ antenna nodding and subtraction using reference antennas (e.g., VLA antennas pointed > 1 beam off source) are under consideration, but we require a larger array (> 3 antennas) to test dynamic range limitations, assess need, and develop algorithms.

General User (Legacy) Science

Legacy science has been an important consideration in conception of the VHF program and in design of the production receivers.

184-186 MHz

General users are unlikely to be able to observe at 186-198 MHz because coordination with the DTV stations will be impractical if demand is high and projects cannot be block scheduled. To cover this eventuality, we have designed a sufficiently broad receiver bandwidth that useful observations can be made at 184-186 MHz using narrow back end filters (0.4-1.5 MHz). This corresponds to TV channel 8 (analog). Practical operation in this band may be anticipated from success at frequencies in a narrow band close to 195.4 MHz during field testing (analog TV channel 10). Electromagnetic finite element modeling shows the gain of the 1.5m feed at 185 MHz will differ by ~ 2% from the gain at 195 MHz, which is smaller than the uncertainty in the model (see later section).

ABOVE AND BELOW THE TV BROADCAST BANDS

Predicting the RFI environment over the long term is difficult; new DTV stations or other users may be encountered in the current TV broadcast bands. Once the key science proposed for AG686/706 has been completed, a simple refit (by NRAO) of the 1.5m receivers would enable general user science in somewhat more benign parts of the spectrum, specifically the fixed-mobile

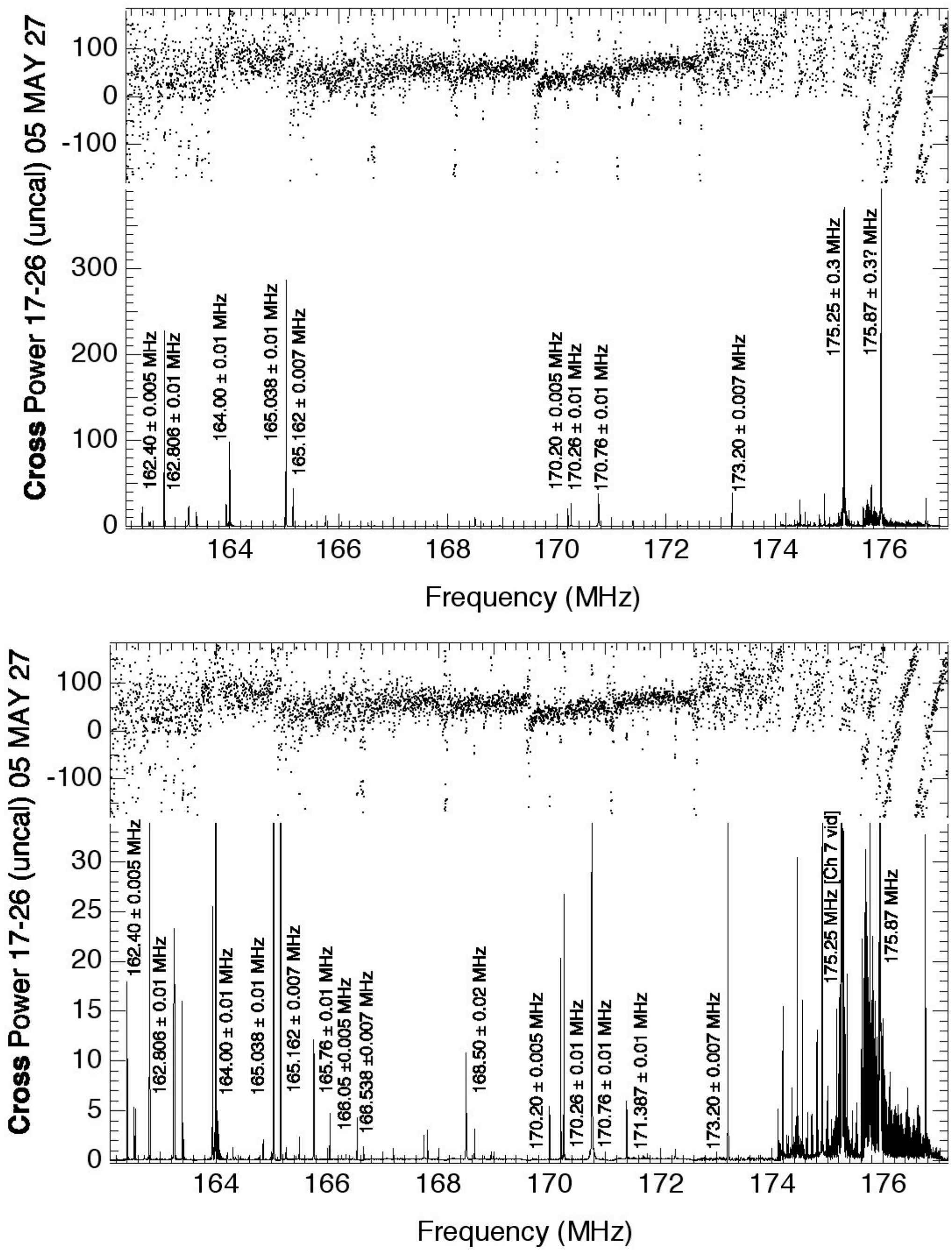

Figure 10—Cross-power spectrum of RFI from 162 to 177 MHz (05 May 27,

allocations at *either* 162-174 (Figure 10) or 216-235 MHz (see also www.ntia.doc.gov/osmhome/allochrt.pdf). The surface mounted 8-pole bandpass filters in each RF module would need to be replaced (~$400 per antenna), and the feed assembly would require adjustment (present arms detached, longer or shorter dipole arms inserted, changing the L/C values used in the balun at little unit cost). Replacement of the notch filters should not be necessary because transmissions in these two bands comprises carriers with narrow-band frequency modulation for which excision should be possible, especially after commissioning of the EVLA correlator.

Proposed Deployment Program

Experience has shown that two receiver systems can be installed in one day. We propose to install four systems each week, using a full maintenance day and two software half days. Testing will comprise fringe checks using short tracks each day and efficiency/holography tests using longer tracks at the end of each week.

The 2005/6 D-configuration, for which 150^h has been approved contingent on performance, ends on 2006 January 17. We have adopted a target date for full deployment of Monday December 5. In order to be ready, deployment must begin no later than the week of October 10, where we have discounted the week of Thanksgiving. The proposed schedule includes ~15% contingency by not counting the "double maintenance day" that occurs once per month.

The proposed deployment schedule is a substantially faster one than the one proposed at the 2005 January review because we had to delay final assessment of results from field testing. Overall, the testing took longer than anticipated because of the unanticipated intensity of RFI (which complicated formulation and interpretation of experiments and measurements) and lead time in procurement of our 2 MHz front-end filters. Production and lab testing will be phased so that shipments can be made to the VLA at a steady rate during October and November. The components with the longest lead times, the 8-pole bandpass filters (Filtro-netics), quadrature hybrids (Anaren), and notch filters (Raltron), have been ordered and arrangements made with manufacturers to speed delivery where possible. We expect to receive initial deliveries of bandpass filters by September 10, Q-hybrids by mid-August, and notch filters by September 30. The notches will be the last components to be mounted. However, we anticipate little impact because it is possible to assemble and test much of the RF modules without the notch filters in place.

Test time request

To assess receiver health and performance, as new units are deployed, we request 1^h (night) at the end of each installation day, using a subarray comprising at least four 1.5m-equipped antennas. We will use this time to measure phase noise and to make beam cuts on two axes (at 1.5m). We also request 7^h (night) at the end of each week for 1.5m and P-band holography and sensitivity measurements (3^h for holography in each band and 1^h for snapshot imaging and study of S/N at different frequencies across the passbands. To establish a baseline, we request 1^h (night) shortly before the start of deployment to measure G/T for each antenna at P and L-bands (see Table 6).

Table 6: Test Time Requested

Activity	Timing†	Track
fringe test; sensitivity; beam cuts	night; end of each installation day	1^h line mode; 1^s dump
holography (1.5/0.92m); sensitivity; passband sweep	night; end of each week	7^h line/cont; 1^s dump
baseline performance (P/L bands)	night; once just before deployment starts	1^h continuum mode; 10^s dump
Short stand-off assessment (1.5/0.92m)	night; end of 2nd day	7^h line/cont; 1^s dump

† Request will depend ultimately on what is practical if coordination with broadcasters is necessary.

TESTING AND IMPLEMENTATION OF SHORT STAND-OFFS BETWEEN DIPOLES

The emission that we hope to detect or constrain is extremely weak (on the order of 10 mK), and 1.5m sensitivity will be critical to the quality of science we obtain at the VLA (i.e., even a little more would be significantly better). Some gains will be achieved through the reduced T_{RX} of the production receivers. However, *we would like to test at or before the start of deployment, a small modification to the feed assembly that we anticipate will enable a meaningful increase in gain* (e.g., Table 3). Electromagnetic finite element modeling of an infinite ground plane, 0.92m dipole, and 1.5m dipole has shown that the gain of the later can be improved (10%) by reducing the length of the stand-offs that separate the dipoles (Figure 11; Table 7). At present the default spacing (both dipoles $\lambda/4$ from the ground plane) is 15.6 cm, dipole arm center-to-center. We would like to test ~10cm stand-offs. The physical limit set by actual feed geometry is 8 cm.

Table 7: Model 1.5m Gain† vs Distance from a 0.92m Dipole

Distance (cm)	185 MHz (dB)	195 MHz (dB)
15.6	7.41	7.33
10.0	7.74	7.78
8.00	7.39	7.90
5.00	7.28	8.02

† Gains are relative. Reflection loss at the balun input is zero at 195 MHz but contributes to loss of gain at 185 MHz.

Tests can be performed once at least two production receivers and feed assemblies are installed at the VLA. (The existing prototype baluns are narrowly tuned for operation with 15.6 cm stand-offs, and the existing prototype receivers are overall too sensitive to changes in dipole impedance to be reliable testbeds). Testing to confirm model predictions may be attempted at one of two times, depending on readiness of hardware. Our preference is to deploy two production receivers without notch filters but augmented by our 2 MHz front-end filters in late September or early October. We estimate the testing will require 2 software intervals and one maintenance day or two maintenance days. Two 4 hour tracks at night for holography will probably be necessary in the event daytime coordination with broadcasters is not possible.

Our contingency is to combine testing and first week deployment activities, though this will be an organizational challenge. This plan is practical only because first-order tests can be completed quickly (measurement of RMS phase noise and four beam cuts at 1.5 m and 0.92m during the nightly 1h test tracks; see Table 6). Full characterization could be completed before the start of activities during the second week and assessment by NRAO completed before the third week. We propose (1) install receivers 1, 2, and 3 with long stand-offs, (2) obtain baseline data at the end of day 2, (3) swap stand-offs and dipole feed assemblies on day 3, while the RF modules for receiver 4 is being installed, and (4) obtain comparison data over the weekend.

If the rudiments of the model are *not* born out, deployment can continue with long stand-offs as originally planned. Only three antennas will need to be refit, which can be accomplished by the end of week two. If measurements are consistent with the model, then we would present informally to NRAO a memo summarizing the tests and results at the start of week two. The volume of data to review will be comparatively small, and if the use of short stand-offs is approved before week three, then only fiveantennas will need to be refitted with short stand-offs over the course of the deployment. Conversely, if use of short stand-offs is not approved, then only three antennas will need to be refitted with long stand-offs.

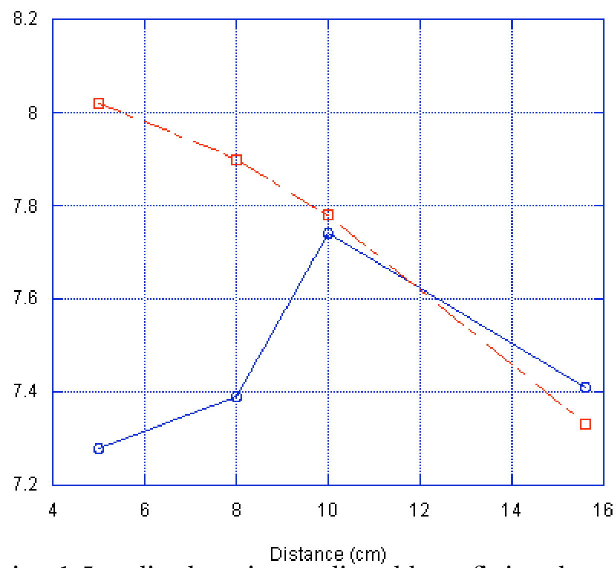

Figure 11— Relative 1.5m dipole gain predicted by a finite element model, as a function of spacing from the 0.92m dipole, including reflection losses at the balun. *(blue)* 185 MHz, *(red)* 195 MHz.

IMPACT OF SHORT STAND-OFFS ON P-BAND PERFORMANCE

Stand-off length affects P-band performance as well as 1.5m performance. Figure 12 shows the result of electromagnetic modeling for five frequencies across the band, and indicates 5% degradation at 305 MHz and no degradation above 315 MHz. These results are encouraging and will be confirmed with field tests during the same tracks used to evaluate 1.5m performance.

Sensitivity and Key Science

The *a priori* 1.5m SEFD adopted for technical discussion in our most recent proposal was 2240 Jy (T_{SYS}=160 K, efficiency=40%). The SEFD observed with the prototype receivers on different days has been 2700-4400 Jy.   Improvement in T_{SYS} anticipated through simple changes to the RF signal path (10%) will reduce the SEFD to 2400-4000 Jy. If model results are accurate, then reduction to 2100-3400 Jy (a ~25% gain total) may be achieved with adjustment to feed placement (see earlier discussion).

For the *a priori* SEFD, we have previously estimated a thermal noise limit of 3.1 mK assuming a 1.6 MHz line, dual polarization, 300^h integration with 85% duty cycle, 26 antennas, 0.2 kλ taper (15′ beam half power full width) and sufficiently broad bandwidth to enable simultaneous observations of one on line band and two off line bands for foreground subtraction. (The 15% overhead is applied to calibration of flux can polarization response.)

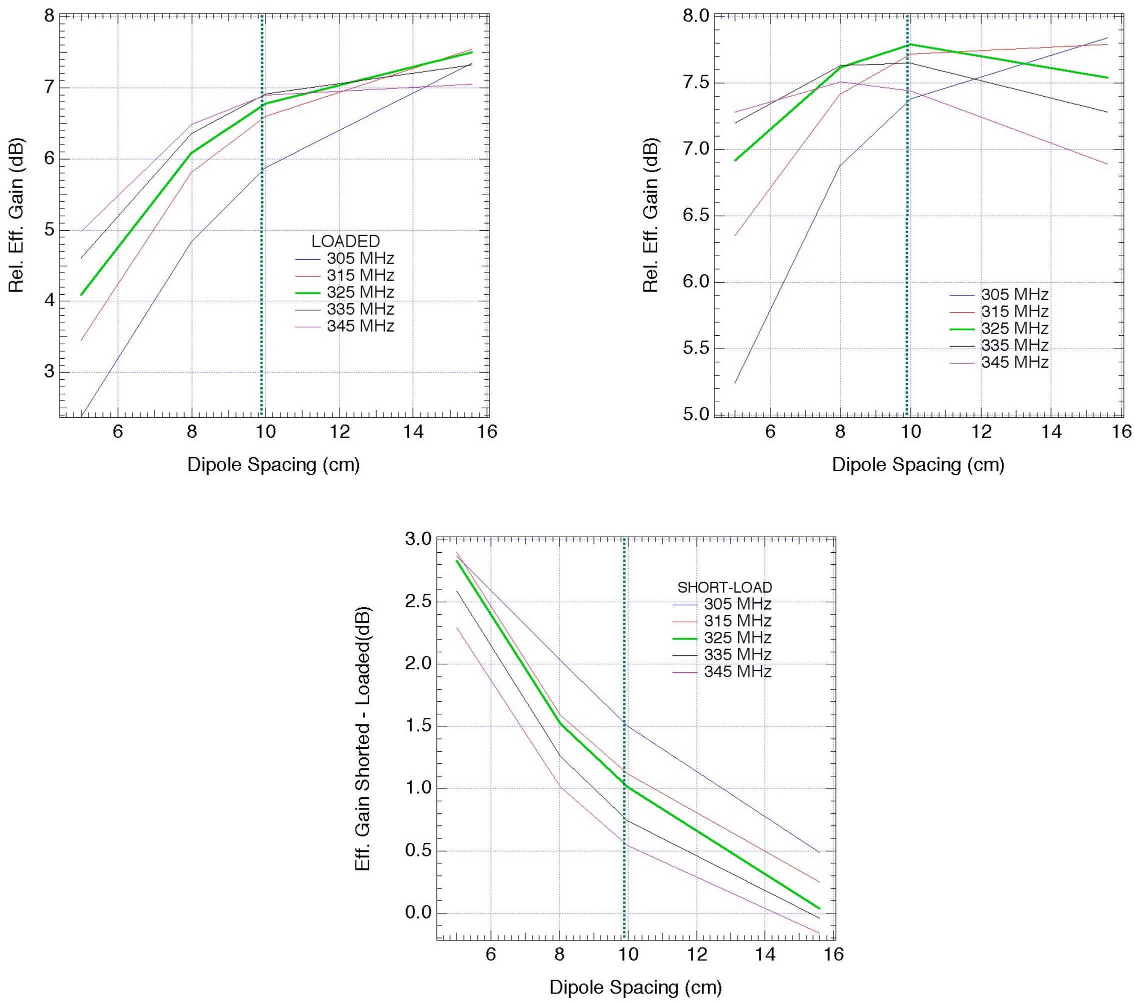

Figure 12 – Finite element model gains calculated for a ground plane and horizontal 0.92m dipole offset by $\lambda/4$, with a 1.5m dipole at different spacings. *(top left)*—Loaded 1.5m dipole. *(top right)*—Shorted 1.5m dipole. *(bottom)*—difference between shorted and loaded dipole. A shorted1.5m dipole slightly improves performance of the 0.92m dipole on average between 305 and 345 MHz. The effect is more pronounced for shorter spacings between dipoles but below 10 cm, the relative gain at 0.92m drops significantly below the value in the absence of a 1.5m dipole (7.55 dB).

The actual sensitivity we will achieve will depend in part on the correlator mode we select, and that will be dictated by how we deal with RFI. The originally proposed plan, 800 kHz channel spacing, is no longer viable. The detection of numerous weak lines in cross power, beyond the TV carriers that will be filtered in hardware, will drive us to use excision to a large extent and requires use of relatively narrow spectral channels, no more than 12.2-24.4 kHz considering the 10-20 kHz full widths (zero intensity) of these weak lines. Two possible correlator modes are 4×0.781 MHz and 4×1.5625 MHz (with online Hanning smoothing). For the latter, reduction in bandwidth on the line will impose a factor of *1.10 penalty in noise* with respect to the original sensitivity calculation, assuming the central 85% of the band is used. Off-line observations will alternate between high and low frequencies to enable interpolation across the line and thereby minimize systematics. Subtraction of interpolated off-line data will impose a factor of *1.41 noise penalty*. These losses may be offset somewhat by (1) reduction in source sample from 3 to 2 (increasing integration time to 450^h each in 2007) with concomitant factor of *0.82 noise reduction* and (2) improvement in SEFD with a *multiplier of 0.90 or 0.75 on the noise level.*

For a 4×1.5625 MHz observation of 450^h, the thermal noise limit is 4.2 mK to 7.0 mK,, with the default 15.6 cm separation between 1.5m and 0.92m dipoles. The noise limit is 3.7 mK to 5.8 mK for a 10 cm separation and predicted decrease in SEFD. For a source perfectly matched to the beam, it would be possible to detect a 100% neutral shell of HI with a signal to noise ratio (S/N) of 3.3-5.5 for a 15.6 cm spacing of dipoles and 3.9-6.2 for a10 cm spacing. (Because the target positions and redshifts are known with high accuracy, a 3σ result would be significant.) Alternatively, an upper limit of ~0.5 could be established with 3σ significance for overall good RFI conditions (obtained via coordination with broadcasters) and a 10 cm offset between dipoles. This would be a substantive advance given that at present there are NO direct constraints on the neutral fraction during the epoch of reionization. However, we note with some caution that reaching the thermal noise will be a challenge (see last section). On the other hand, substantive uncertainties probably exist in prediction of source strength, which depends on indirect inference of quasar luminosity, degree of concentration of intergalactic Hydrogen on length scales of ~5 Mpc, accretion geometry, degree of overlap among quasar HII regions, and quasar age. In this last case, a 20% increase in source size would enable use of a slightly heavier (u,v) taper than 0.2 kλ and modest improvement in surface brightness sensitivity.

Sensitivity and Legacy Science

We anticipate that observing for legacy science (~185 MHz) will be somewhat less sensitive than for key science (~195 MHz). Sky temperatures will be ~ 10-15% hotter depending on proximity to the galactic plane at the lower frequency, and receiver systems will be less well optimized to some degree. On the other hand, larger array configurations will be usable, which reduces the impact of RFI. For a 6^h track on source, 27 antennas, two 1.3 MHz IF (85% of 1.5625 MHz), and conservative SEFD of 5000 Jy, the thermal noise limit will be ~1 mJy or 400-500 K in the A-configuration (9″ synthesized beam).

Miscellaneous Issues

MAINTENANCE AND SPARES

SAO is constructing 28 receiver units for deployment at the VLA. At the request of the earlier review panel, SAO will also provide 2 complete spare feed assemblies and receivers, 3 extra (fully stuffed) receiver circuit boards and balun circuit boards, and two extra sets of cables. These extra parts will be provided after the 28 receiver systems are deployed. All schematics, mechanical drawings, circuit board designs, part descriptions, and lab/field procedure descriptions will be turned over in editable electronic formats agreeable to NRAO and SAO personnel. There are no specialized test fixtures at this time.

There are no special maintenance requirements known above and beyond what may be applied to the P-band receivers. The RF module, including bulkhead connectors, are sealed with rubber gaskets and silicon RTV adhesive. The LMR-300 cables that connect the feed and receiver are rated for 30 years, outdoor use. Power cables are Teflon coated, and connector ends are shrink wrapped. The dipole assembly is also weather tight (RTV), and it contains no active components apart from the dipole shorting switches. The default position will be shorted, to protect P-band. (The default position for the control relay that alternates power between P-band and 1.5m receivers will also select P-band.) Exposed surfaces are either brass (painted) or P.E.T. (Polyethylene Terephthalate), which will not degrade in sunlight or as a result of temperature swings.

MOU

A draft MOU was assembled in 2005 May in consultation with the Jim Ulvestad and Charles Alcock. It has been under consideration by the director of NRAO. In light of progress made since May, some revision may be appropriate.

OBSERVING SUPPORT

The real-time system already routines services observe files for 2-band, and required modifications to JOBSERVE may be small. There are two differences between P-band and 2-band observing cards. First, the band identifier "22." Second, the L6 setting most often used is –839.9 MHz for an IF nominally centered at 185.1 MHz (VLA 25 and 50 MHz front-end filter) or 187.1 (VLA 12.5 MHz front-end filter). L6 settings of -810.1 and -860.1 MHz will also partially overlap the intended pass band of the 2-band receivers (184-198 3dB), if the 50 MHz front-end filter is specified.

SOFTWARE

Field-test data has been reduced using AIPS without modification. In order to make possible polarization beam calibration, foreground subtraction, and active RFI mitigation, it will probably be necessary to switch at least a fraction of the processing to AIPS++ or derivatives. A processing path in AIPS++ has not yet been formulated. Some algorithm development will be necessary. We anticipate employment of two to three post-doctoral fellows or students at SAO and NRAO, who will be responsible for these developments.

Uncertainties

In the context of the perspective discussed on page 3, we note the following uncertainties that are still outstanding. Requested observing time in the 2005/2006 D-configuration will enable us to address most of these. Some relate to extrinsic factors (e.g., the good faith of broadcasters with whom are in discussions regarding coordination) and are unlikely to disappear altogether.

- Is there a limit to how quickly or how far image noise levels will drop with integration time; how much does modulated analog TV transmission away from carriers limit dynamic range; when DTV channels 9 and 10 are will subtraction of compact extragalactic foreground sources truly enable imaging to the thermal noise limit; will polarization calibration be stable and adequate to enable accurate subtraction of diffuse galactic foreground emission?
    - The answer is not yet known because of dynamic range limits and calibration limitations imposed by a three element test array. Proper treatment requires a full or nearly full deployment.

- Will the TV/RFI environment worsen, making key and legacy science impossible?
    - We have anticipated broadcasting on channels 9 and 10, which is critical to proposed key science. Coordination appears possible, though it depends on broadcasters' flexibility and continued neighborliness.
    - Legacy science at 184-186 MHz may be affected by eventual development of DTV broadcasting on channel 8, although terrain shielding is good (Farmington). We have established the contingency of shifting general user science to lower frequencies in the era of the EVLA correlator (162-174 MHz).
    - Continued interest by UNM in low frequency astronomy at the VLA site may strengthen our position in discussions with local broadcasters.

- Will internally generated inteference be a problem for EVLA electronics?
    - The EVLA is expected to be at least as quiet at the VLA.
    - Nearly all internal RFI enters the existing signal path via the feed.
    - The 3 kW power supplies have been identified as a potential source of RFI.
    - We are working to measure the impact of these supplies over the next week. In the worst case, the EVLA is likely to shield the power supplies, driven at least in part by a desire to protect P-band performance.

- Will the EVLA antennas be ready by 2005 December?
    - We hope NRAO will have installed the requisite P-band RF support modules and utility modules for control of the dipole shorting and DPDT receiver power switches (Figure 4). If this proves impractical, we will move ahead because operation with 21 or 22 antennas is better than not operating at all, in light of the need to demonstrate capability in support of our request for time in 2007. The same applied to the EVLA antenna power supply shielding. If it is not available, we will choose to drop the EVLA antennas.

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