Chapter 5

TECHNICAL ISSUES AND BUDGET

5.1 INTRODUCTION

This Chapter discusses tradeoffs between the requirements of different astronomical problems, and some engineering difficulties, that must be resolved to settle the design, cost and (in some cases) the schedule of the project.

5.2 ANTENNAS AND RECEIVERS – TRADEOFFS

5.2.1 Polarization vs. Wide Bandwidths

The design of feeds and receivers which support observations over large bandwidths requires either the use of linearly polarized feeds or of circularly polarized feeds with compromises made on polarization purity. The typical cross-polarization performance of wide bandwidth circular polarizers, shown in Fig.5.1, is two or three times worse than for the current narrow bandwidth polarizers. Linearly polarized feeds would give better sensitivity and lower cross-polarization. Their main disadvantages are: the need to calibrate the relative amplitude and phase of the two polarizations accurately, the difficulty of analyzing the data when parallactic angles differ at the ends of long baselines, and the fact that their performance for total intensity measurements degrades less gracefully than for circularly polarized feeds if one polarization channel malfunctions.

The VLA now uses circularly polarized feeds. The accuracy of polarization measurements is limited not by the absolute value of the cross-polarization, but by its time variability. It would be unwise to increase the cross-polarization significantly until the cause of the time variability in the existing VLA systems is understood. The tradeoffs between using linearly and circularly polarized feeds for the new wide-band systems therefore require careful study.

5.2.2 Spillover

With the completion of the 1.4 GHz band upgrade in 1994, ground pickup at low elevations became a significant problem. The 1.4 GHz feed should be redesigned to eliminate spillover problems. There is also keen interest in observations at lower frequencies in the 1.4 GHz band. The extent to which the 1.4 GHz band may be extended and improved without eliminating or seriously compromising

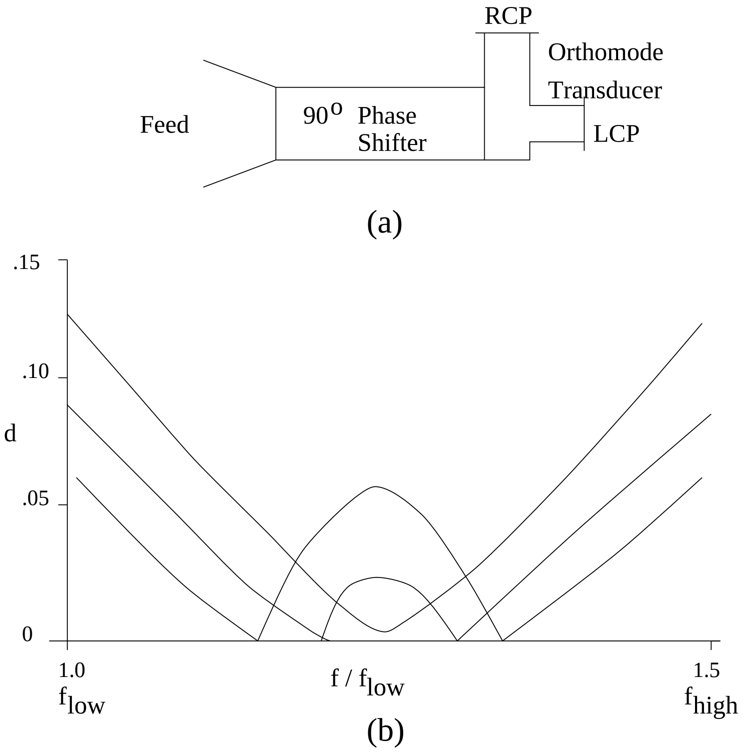

Figure 5.1: (a) Schematic diagram of circular polarizer. (b) Typical variation of the cross-polarization voltage ratio, d, across the band. Typical curves for three different phase shifter designs are shown.

other systems on the feed ring (*e.g.*, the 2.4 GHz band system that is also scientifically attractive) or at the prime focus must be considered carefully.

The best way to improve performance in the 1.4 GHz band alone would be to install a larger subreflector, similar to that used for the VLBA. This could provide good performance at a lower frequency for the same size feed mouth as at present. But this option is expensive and introduces compatibility problems for all feeds, especially at the prime focus (see Sec.5.2.3). In principle, the 1.4 GHz band can be extended down to 1.2 GHz with a new high-performance feed at the Cassegrain focus, illuminating the current subreflector. This approach would however require a long, geometrically awkward feed with an expensive and heavy lens, without which the feed would extend through the vertex room floor. A solid dielectric lens would weigh about a couple of tons; a compound lens such as that on the present feed would not be broad-band, though it is unclear how far such a design could be pushed. It will be important to assess how the performance of any proposed system degrades below 1.2 GHz, as reasonable performance down to about 1050 MHz might reduce the need for the most problematic prime-focus system (800-1200 MHz),

5.2.3 Prime Focus Systems vs. Cassegrain Performance

To observe at frequencies above ≈ 400 MHz requires modifying the quadrupod and focus-rotation mount (FRM) if high performance is desired. The reason for this is illustrated in Fig. 5.2 which shows that the subreflector support structure currently blocks the prime focus. Obtaining access to the prime focus by retracting the subreflector requires lengthening the legs of the quadrupod.

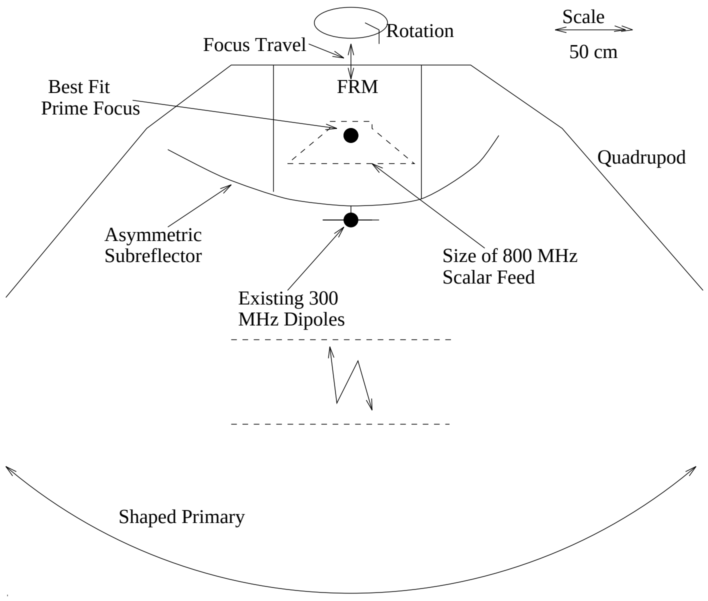

Figure 5.2: A sketch, approximately to scale, of the prime focus region of the VLA antenna.

The FRM must then be modified to position the subreflector to illuminate the Cassegrain feeds optimally. The only way to avoid this with the present subreflector is to accept the poor beam shape and reduced aperture efficiency associated with operating the feed at an out-of-focus position, as we do now.

Other options that might be considered to expose the prime focus include shifting the subreflector laterally, tilting it to one side; or, if the subreflector is rebuilt, having it open like a clam shell. (The last approach may be the only practical way to operate at the prime focus if a larger subreflector is used to extend the 1.4 GHz band down to 1.2 GHz.)

The 800–1200 MHz system may be the most problematic. Because of the size of the feed, it must be located at the prime focus. Design of an *efficient* feed at the prime focus is hampered by the shaping of the primary reflector (which departs from a true paraboloid by about 1 cm, so there is no exact prime focus). To avoid interfering with observations in other bands, the feed must be removable. One idea is to stow a scalar feed against one leg of the quadrupod, swinging it into place when needed. There are concerns, however, about the mechanical complexity and maintenance of such a system.

Another concern is that prime focus systems are somewhat more susceptible than Cassegrain systems to interference from low-elevation sources. This may become more important in the presence of an ever-worsening RFI environment (see §5.6).

At issue is which options offer the best scientific return without seriously compromising the performance at other frequencies. The present 75 MHz and 327 MHZ feeds may raise the system temperature at L Band by about 10% (the magnitude of the effect is not well-determined). This effect may be present for the proposed prime focus systems at all bands, and is likely to depend on frequency in a complex manner.

A related issue is whether to pursue high-efficiency performance at the prime focus at all. Fig. 5.3 compares the proposed enhanced frequency coverage for the VLA with that of other large interferometers and single dishes. The GMRT in India, and the WSRT in the Netherlands, will provide coverage in the frequency bands of interest, albeit with reduced sensitivity or narrower

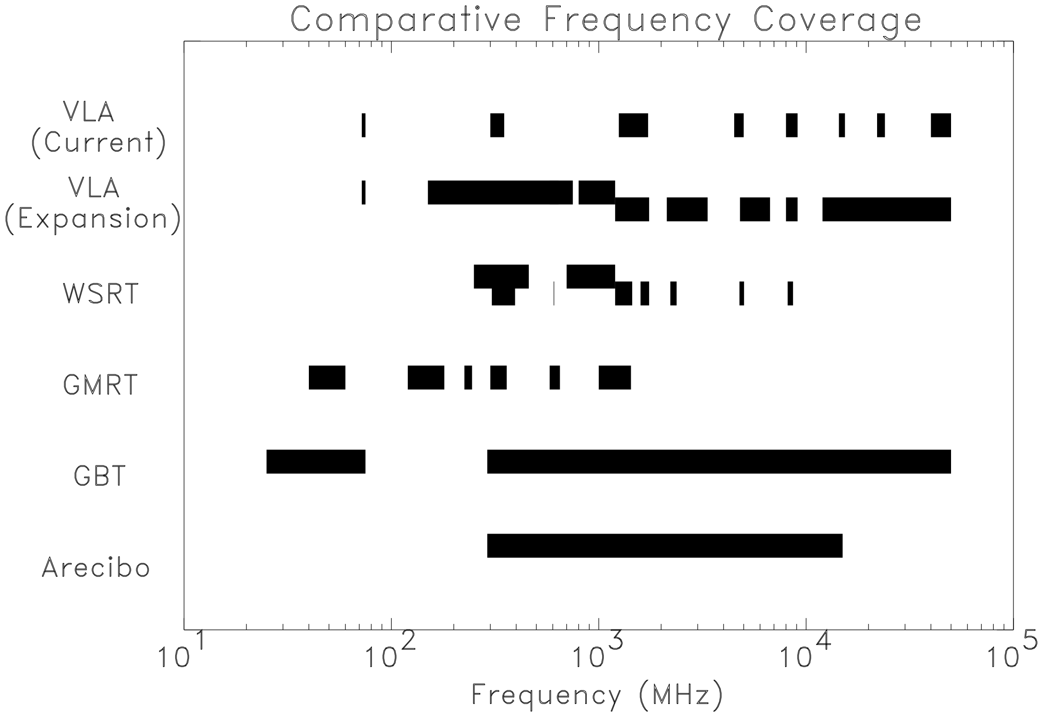

Figure 5.3: The frequency coverage of large interferometer arrays and single dishes compared with the current VLA and with the proposed VLA enhancements.

bandwidths. The GBT and Arecibo will provide a single dish capability over the frequency range of interest with good sensitivity.

An alternative to prime focus operation at the VLA may be to build inexpensive wide-band antennas (*e.g.*, log-periodic arrays) to support some low frequencies separately. Such a stand-alone antenna system, sharing access to the I.F. transmission system and the correlator for simultaneous observations with the VLA paraboloids, has previously been proposed for 74 MHz. It may be appropriate to identify what *range* of observing frequencies could be better served by such an array than by working at the prime focus, and at what cost. For 74 MHz, antenna tolerances can be met cheaply because the wavelength is so long (4 m). At higher frequencies, more costly and more numerous antennas would be needed to sample the shorter *u*-*v* spacings (or the antennas would need to be transportable). The cost and effectiveness of such options (as a function of frequency) should be weighed against that of prime focus operation, but it seems unlikely that that they would help the most difficult (800–1200 MHz) case at reasonable cost.

The difficulties of operating prime focus systems between a few hundred and 1200 MHz without degrading the Cassegrain performance emphasize the need for knowing more about VLA's RFI environment (see §5.6). Improved RFI statistics might help to define the most appropriate band edges.

5.2.4 Antenna Modifications

To add 2.4 and 33 GHz observing bands at the Cassegrain focus we must rearrange the feeds on the VLA feed ring and install a new feed enclosure. A structure more like the VLBA feed cone will likely be used. Support of multi-band performance (§1.2.6) would entail additional modifications.

Modifications to the antenna quadrupod and FRM are needed to support the proposed higher-efficiency prime focus systems: the 600 MHz system, a broadband UHF system, or a cooled 800-1200 MHz receiver. For the first two options, the quadrupod must be lengthened to allow siting these systems at the prime focus (at present, the 330 MHz feed is $\approx 0.5\lambda$ out of focus). For the 800-1200 MHz system, we need to study how to optimize the desire for sensitivity (*e.g.*, to search for redshifted HI in emission or absorption) versus the added weight of a refrigerator. Lightweight (Sterling) refrigerators will alleviate the problems. The effect of modifications to the quadrupod structure and the FRM, together with the weight of a feed and cooled receiver, could conceivably cause excessive gravitational deformation of the primary reflector. This must be checked by structural analysis.

Performance in the 40–50 GHz band requires some effort to improve the surface quality, pointing accuracy, and tracking accuracy of the antennas that are not now outfitted for this band. The methodology for measuring and adjusting the primary reflectors is now well understood.

5.2.5 A Robust Total-Power System

A fast and accurate means of measuring the total power is needed. In recent years, mosaicing has been used often and successfully at the VLA to image fields of view comparable to, or larger than, the primary beam of the antennas. To measure the visibilities for the smallest u-v separations required in mosaiced images, we need total power measurements with single antennas. These could be made with the VLA antennas by scanning rapidly across the region being imaged and adding the "single-dish" information to the interferometer data. This capability requires a stable total power system for each antenna and some on-line and off-line software development.

A second reason for a robust total power system is for observing transient phenomena which can significantly change the system temperature over short timescales. An outstanding example is that of solar flares, which can change the system temperature by an order of magnitude in a few seconds.

5.2.6 Multi-band Performance

For some experiments, multi-band performance is highly desirable. For example, transient phenomena on the Sun and stars would benefit greatly from simultaneous measurements in two or more bands. One possibility is to support dual-frequency measurements in the 2.4 and 8.4 GHz bands and/or dual-frequency measurements in the 4.9 and 15 GHz bands. An additional benefit of dual-frequency observing is that one of the two bands in a given pair could be corrected for the long-standing problem of beam squint, caused by the VLA asymmetric geometry, through the use of a tertiary mirror.

A practical benefit of dual-frequency observing is that the lower frequency of a given pair can be used to track the phase variation of the atmosphere, from which corrections can be derived and transferred to the high frequency. Implementation of such a scheme will be considered for enhanced high-frequency performance at the VLA.

In the case of solar observing, an alternative to multi-band performance is "frequency-agile" performance using a low-performance (helical or log-periodic) feed at the prime focus.

5.3 IF TRANSMISSION SYSTEM

The details of the IF channelization are still to be decided. A possible design has the ∼2 GHz of instantaneous bandwidth broken into 2 pairs of oppositely polarized IF channels, each 500 MHz wide. The two IF channels in each polarization need not be contiguous in frequency. At higher frequencies, where much more than 1 GHz of receiver tuning range is available, four different frequencies could be observed simultaneously. For full flexibility, this scheme will require 4 synthesizers per IF conversion in each antenna, and will return 4 independent IF channels to the correlator. It is possible that the number will be further upgraded, to 8 independent IFs. To avoid serious bandwidth smearing of the maps the widest bandwidth to be correlated will probably be no more than a few ×100 MHz.

Analog transmission is preferred for the simplicity of the equipment at the antennas. Stability of the frequency response may drive us to the use of digital transmission, especially on runs longer than 20 km. Further study, including laboratory testing of a fiber link, is required. As well as increasing the instantaneous bandwidth, this new system will strive to provide better bandpass stability leading to better spectral dynamic range.

The antennas in the Pie Town and Los Alamos "rings" must be connected to the VLA by wide-band data links. Many technical and economic aspects of the long runs of optical fiber being contemplated for this, as described in §1.2.5, require detailed study before the cost and feasibility of the A+ configuration can finally be assessed.

For links that the NRAO might install and use on an exclusive basis, we need to explore the cost of obtaining right-of-way and of installation (estimated as about $5 per foot, considerably more than the cost of the fiber cables themselves). The main technical issue for such links would be the stability of the frequency response of the IF channels; this should be evaluated over a link to the Pie Town VLBA antenna as soon as possible.

The proposed links to Bernardo and to the "Los Alamos ring" antennas are unlikely to be economic to install and operate on an exclusive basis. It may however be practical to lease long wide-band fibers and suitable booster amplifiers from commercial carriers when these links are needed for A+ configuration operation. The NRAO should plan to get early experience in using commercial fiber links for real-time interferometry using the nearer VLBA antennas. The commercial-link environment should be simulated using a fiber to the Pie Town antenna as soon as possible.

It will be important to evaluate the logistical and technical problems of using commercial fiber before the feasibility and operating cost of the full A+ configuration can be determined. If commercial links can be used successfully, however, this approach may be extensible beyond the baselines considered here as part of the A+ configuration, *e.g.*, to Kitt Peak and Fort Davis.

The final locations for the A+ configuration antennas should be chosen by combining the above factors with the need for good imaging properties when the antennas are used with both the VLA and the VLBA. These areas require further study, which should begin as soon as possible.

5.4 CORRELATOR DESIGN

The current VLA correlator is limited to a bandwidth of 4 × 50 MHz. A new correlator is needed to process the ∼ 2 GHz of bandwidth and to achieve the increase in continuum sensitivity and instantaneous spectral coverage. Moreover, the current correlator limits the type of science which can be done due to its limited spectral resolution at wide bandwidths. With a 50 MHz bandwidth now, the VLA can only produce 8 (Hanning smoothed) spectral channels in total. With so few channels, wide-field imaging at low frequencies, and searches for redshifted spectral lines (*e.g.*, H I) are extremely inefficient. Similarly, a 50 MHz bandwidth at high frequencies (*e.g.*, 350 km s^{-1} at

43 GHz) makes observations of radio recombination lines difficult, if not impossible. It also excludes many components of those molecular lines which are split into multiple transitions.

Current specifications for the new correlator are demanding:

- **Bandwidth and IF Channelization**

  Current specifications call for processing 1 GHz of IF bandwidth in two orthogonal senses of polarization. The cost of the digital part of the correlator is minimized if the band is subdivided before digitization, but this increases the cost and complexity of the analog part. There is some number of baseband channels, presently undetermined, that will minimize the cost. It appears that the minimum number of channels is 2 per polarization (making 4 channels of 500 MHz each per antenna), and each of these should be separately tunable within the front end bandwidth. The present state of the art in digitizers allows channels up to about 2 GHz wide (4 GHz sampling rate, several bits per sample), so sampling does not constrain the channelization. Considerations other than cost may be important. In the case of strong in-band interference, a large number of channels is favored so that bad channels can be rejected before digitization.

- **Spectral Resolution**

  If the IF channelization is such that two pairs are employed, a minimum of 512 channels in each of the four 500 MHz IF channels is specified. The bandwidth of each channel would be adjustable by factors of two over a wide range, allowing widely variable spectral resolution. The spectral resolution should, at least, be comparable to that of the Millimeter Array, of order 0.05 km s^{-1} at high frequencies. This represents a factor of three improvement in the spectral resolution on the widest bandwidth now available, and an order of magnitude improvement in the largest spectrometer bandwidth now available.

  For bistatic planetary radar resolutions of ~ 5 Hz are desired over a few kHz of bandwidth. This can be achieved by bandlimiting the input channels with filters and then drastically reducing the correlator clock rate, but might be better done by recording the digitized signals on tape and correlating in software off-line.

- **Output Time Resolution**

  Support of very short dump periods (<0.1 sec) is feasible for the correlator proper, but we know of no way to handle the data flow if all channels and baselines are used. We assume that each spectral channel of each baseline will have two integrating bins (say, noise calibration on/off or pulsar on/off) available to it; perhaps four bins could be provided, but not a large number. Observations requiring high time resolution (tens of msec) will have to make large sacrifices in other parameters, *e.g.*, spectral channels or baselines.

- **Fringe Rotation and Phase Switching**

  We see no reason to change the present VLA design in which fringe rotation is done in an LO at each antenna. (Moving it to after the digitizers implies a large increase in correlator size.) To accommodate the addition of nearby VLBA antennas, which do not have fringe rotation, there is a consensus that this capability should be added in an LO that is part of a "VLBA to VLA interface box." Similarly, the VLA phase switching scheme should be retained and that feature should be added to the VLBA antenna signals as part of the interface. It is noted that observations requiring high output dump rates might not be able to make effective use of the phase switching, thus limiting their dynamic range.

Careful consideration will be given to including hardware internal to the correlator for real-time detection and removal of short-time-scale interference. For example, it might be feasible (in an FX correlator) to examine each FFT for channels with excessive amplitude and delete those channels from the cross-correlation.

If possible, the development of a new VLA correlator should be combined with that of the Millimeter Array correlator. The overall similarity of the needs in terms of the antenna-bandwidth product should be exploited wherever possible. Unless the time scales on which the two correlators are required turn out to be significantly different, they should at least share the same basic architecture and the same ASIC(s).

5.4.1 Ultra-wide Bandwidth Performance

Current thinking regarding a new correlator and IF transmission scheme are based on a 2 GHz total bandwidth capacity (1 GHz in each of two polarizations). Since modern feeds can provide good performance over a bandwidth $\approx$35% of the center frequency in linear polarization, it is clear that a great deal of potential sensitivity is given up at the higher frequencies. An alternative is to consider an ultra-wide bandwidth system, in which accurate polarization, spectral resolution, and field of view are given up for maximizing the instantaneous bandwidth.

An ultra-wide-bandwidth correlator for continuum observations above 18 GHz could be built as a separate instrument from the main 1 GHz correlator. The required spatial field of view is likely to be a cost driver, since it determines the frequency resolution needed to avoid bandwidth smearing. Preliminary thinking indicates that 8 GHz/polarization at 200 MHz resolution might be feasible, but no cost estimates have been made. An analog correlator should be considered, especially if a coarser frequency resolution (>100 MHz) might be acceptable. Economic and performance tradeoffs should be studied for three approaches: a pure analog correlator, with optical fiber delay lines (considerable testing will be needed to see if adequate passband stability can be achieved); digital delay followed by conversion back to analog for correlation; and an expanded pure digital correlator. It is likely that the digital approach would win if frequency resolution <100 MHz is required.

It should be recognized that this is an expensive item that will be useful only at the highest frequencies, and that various compromises will prevent it from achieving very high dynamic range. Assuming a 35% bandwidth, and the improvements mentioned elsewhere in system temperature and antenna surface accuracy, sensitivities of better than 1 μJy in 12 hrs are possible between 18 and 40 GHz.

5.5 THE E CONFIGURATION

Support of an ultra-compact E configuration requires construction of new antenna stations and rail access to them. Careful consideration must be given to the number of new stations needed and their placement.

One possibility (E1) is to move the outer three antennas from each of the three arms of the D configuration to the inner part of the configuration. This option would require only 9 new stations and two new rail spurs (Fig. 5.4). The E1 configuration would have a maximum baseline of 500 m. Simulations have shown that it would achieve a given surface brightness sensitivity in half the time as an optimally tapered observation with the D configuration.

A more optimal configuration (E2) would require essentially 27 new stations and 5 or 6 new rail spurs. It could be designed to provide essentially Nyquist-sampled u-v coverage and a small grating response. Simulations of one such configuration (Fig. 5.5) indicate that it could be 5–10 times faster than the D configuration in reaching a given surface brightness.

A comparison of the relative sensitivities of the D, E1, and E2 configurations (parameterized as the filling factor of antennas in the area covered by the array) is shown in Fig. 5.6. While the E2

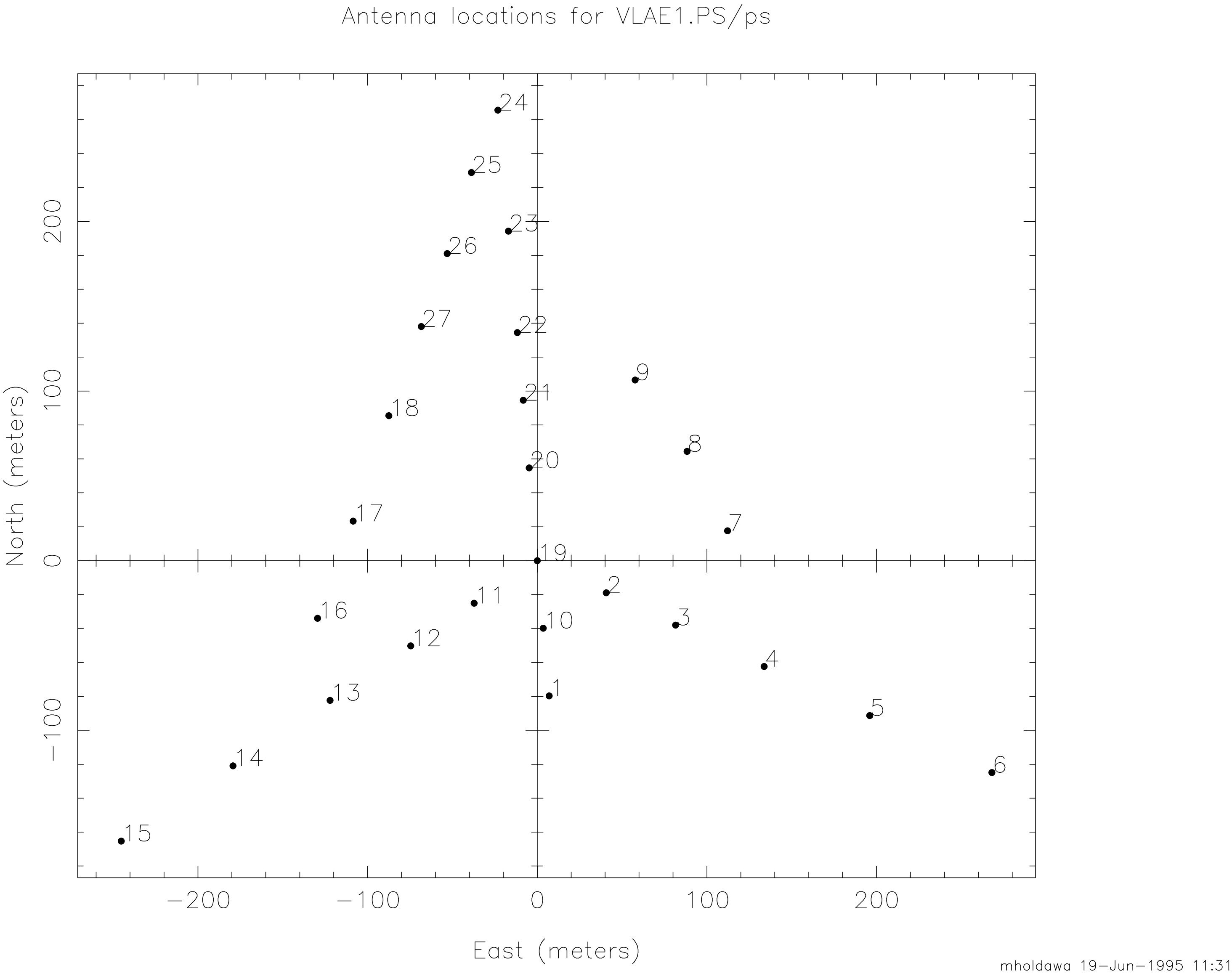

Figure 5.4: Example of a possible E configuration requiring only 9 new antenna stations and two new rail spurs.

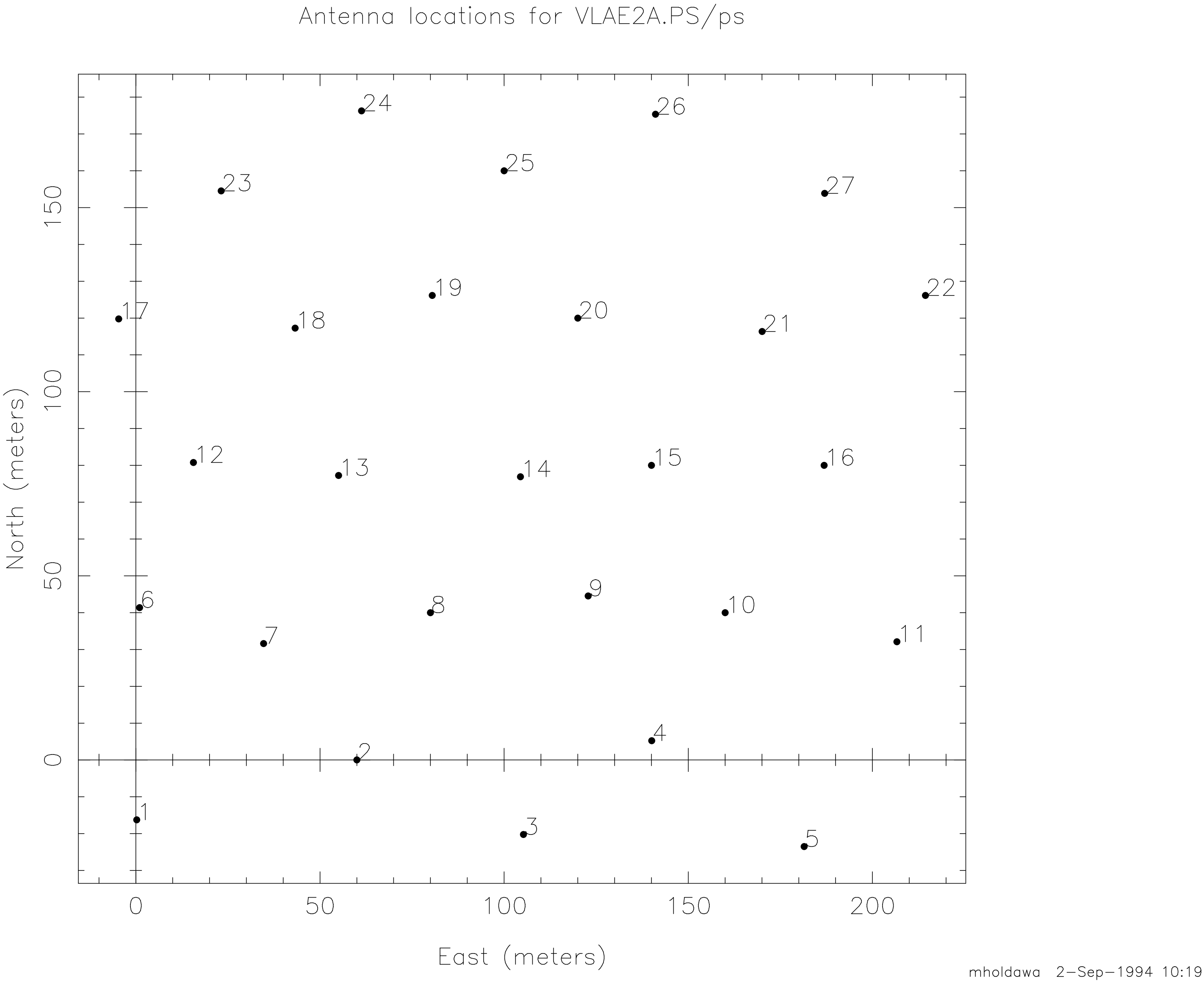

Figure 5.5: Example of a more optimum E configuration, requiring 27 new stations and 5 or six new rail spurs.

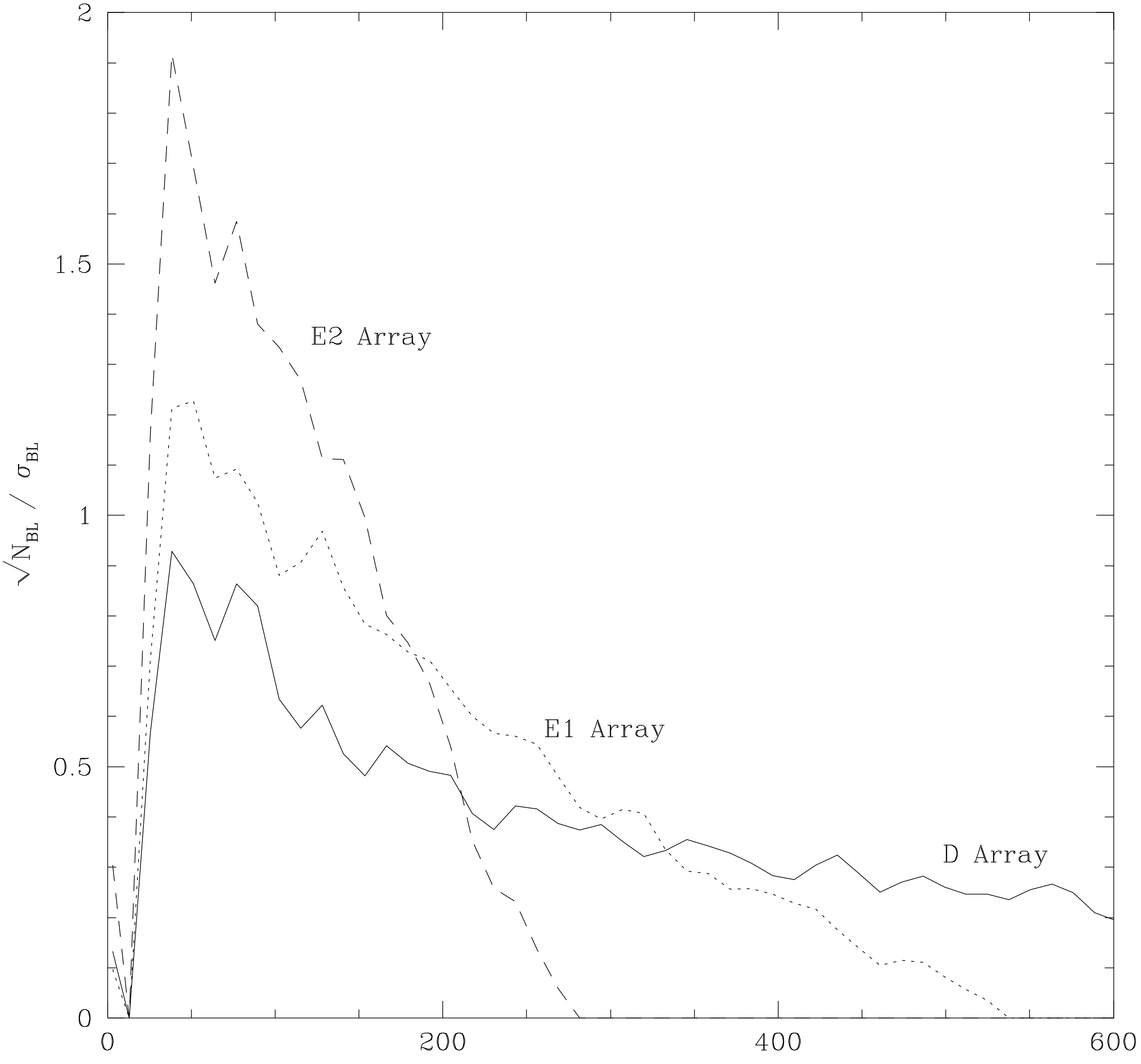

Figure 5.6: Relative sensitivities of the D, E1 and E2 configurations.

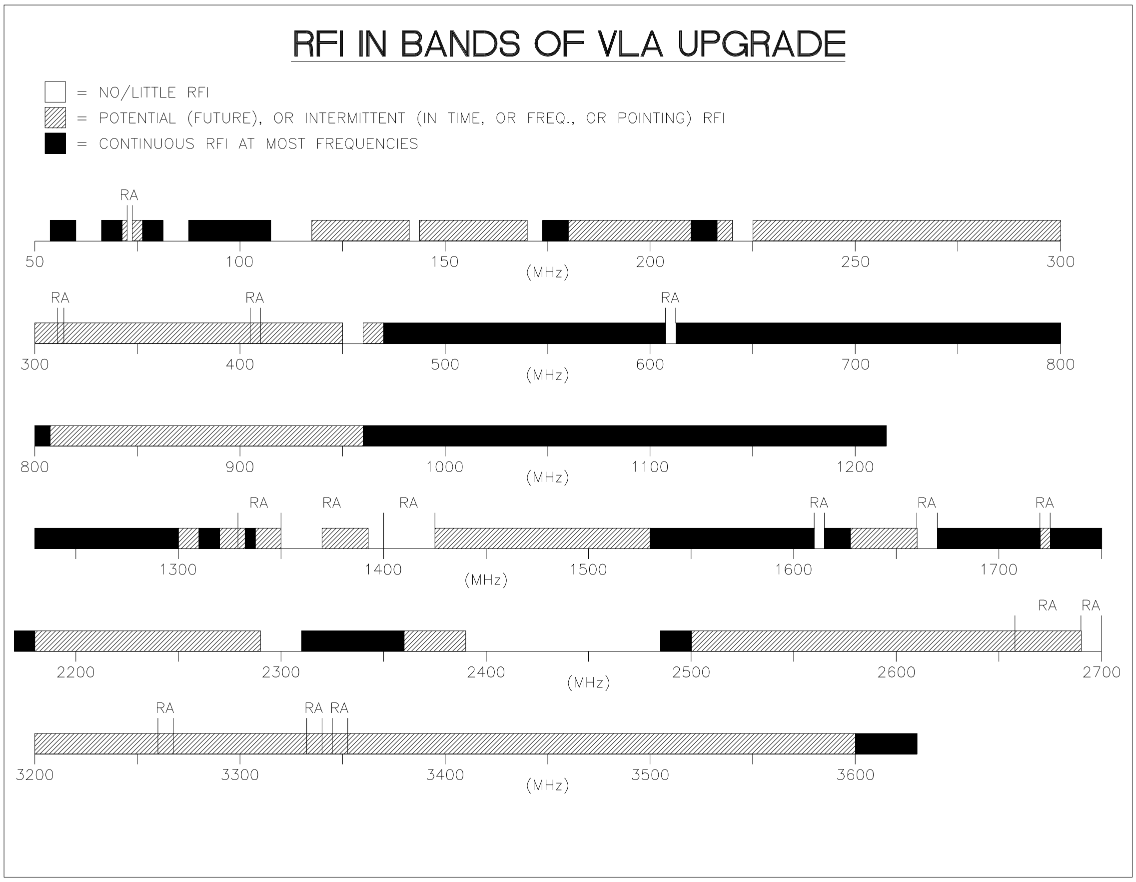

Figure 5.7: Potential for RFI in the Enhanced VLA Bands

configuration is preferable to the E1, preliminary cost estimates show that it comes at four times the cost of the E1. A detailed cost-benefit analysis is clearly needed.

Shadowing is of little concern for either of these possibilities. Simulations have shown that there is little shadowing for hour angles -3h<HA<+3h for source declinations $\delta \geq -10°$. Long tracks will not be needed for good *u*-*v* coverage; snapshots at several hour angles will suffice for many programs. For low declination sources, a hybrid or "E-south" array configuration may be needed.

The E configuration will be, above all, a mosaicing configuration. Successful exploitation of the E configuration will require a total power capability on all antennas, as discussed in §5.2.4.

5.6 RADIO FREQUENCY INTERFERENCE

An important consideration for the VLA Development Plan is the reality of radio frequency interference (RFI). The desire to upgrade the VLA to wide-bandwidth performance (of order 1 GHz per polarization channel) means that the instrument will often operate outside of the protected frequency bands. The array will therefore be susceptible to RFI to a even higher degree than it is now, especially at frequencies below a few GHz. It is unfortunately safe to assume that the RFI environment will be significantly worse when the VLA Development Plan is completed than

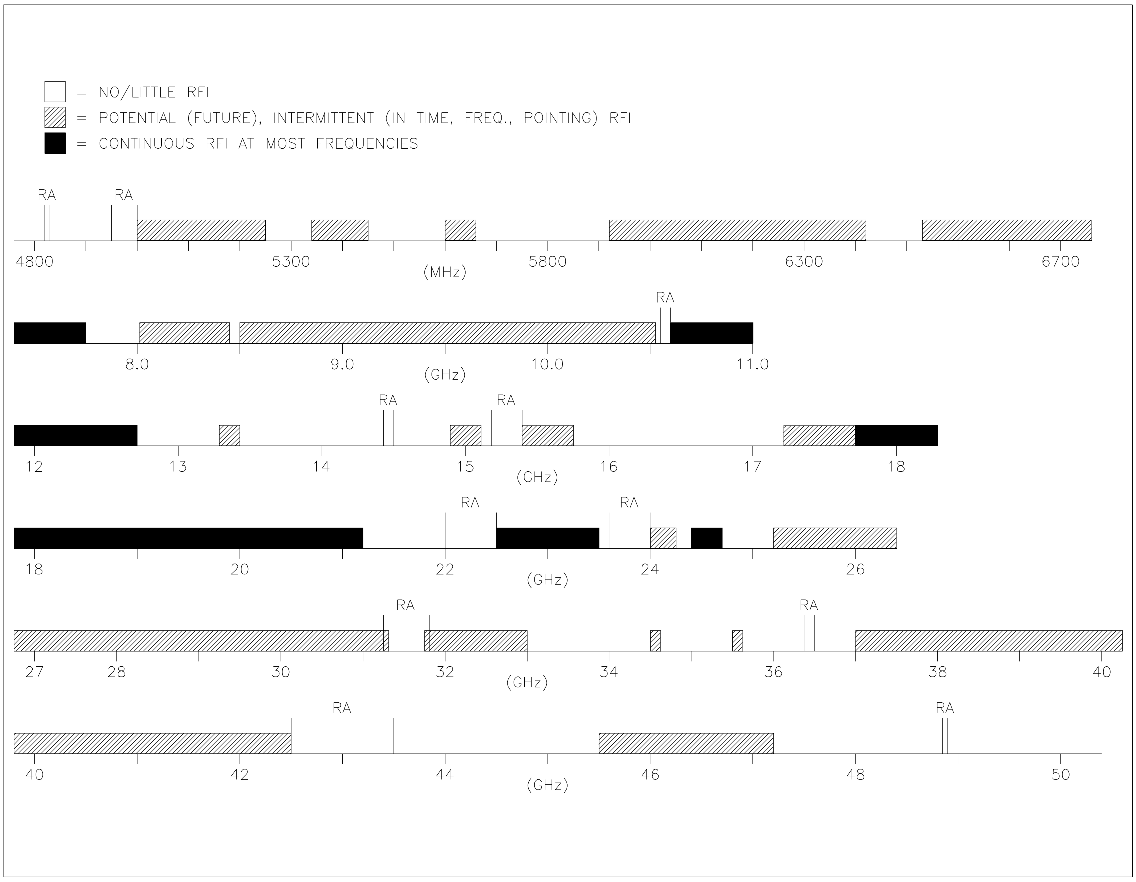

Figure 5.8: Potential for RFI in the Enhanced VLA Bands

it is now.. This results from the accelerating demand for mobile personal communications systems and from the fact that several areas of spectrum, previously lightly used and under the control of the Federal Government, are being transferred to the control of the FCC. It is essential that all equipment be designed with requirements for detection, rejection and excision of RFI in mind.

Some general statements, based on frequency allocation tables and preliminary RFI monitoring at the VLA site, can be made about likely RFI in the proposed enhanced VLA bands. Figs. 5.7 and 5.8 show the expected RFI problems for each band. Between $\sim 100 - 800$ MHz it seems unlikely that the wide-band low-noise amplifiers in a receiver covering this frequency range will be driven into compression by RFI. It will be essential, however, to provide filtering after the first 20-30 dB gain low-noise amplifier to prevent compression further downstream in the receiver electronics chain. This filtering should take the form of either a tunable bandpass filter or a number of switchable bandpass filters which pass only those frequency ranges needed for the observation and known to be relatively free of RFI. The selection of the filters and observing frequency range would be made on the basis of data provided by an RFI monitoring system to be located at the VLA site. Between 800–1200 MHz, the same remarks apply. The frequency range 840–920 MHz may become particularly difficult to use because of the proliferation of cellular telephones (except possibly for a short period late at night). The frequency range 960–1220 MHz will be problematic due to its allocation to aeronautical navigation uses. Between 1200–1750 MHz, it is unclear whether or not the filtering scheme proposed for the lower bands will be needed, but the possibility of installing it in the future should certainly be included in the design. There will almost certainly be unusable frequency ranges such as 1610–1627 MHz which is assigned to the mobile satellite service for which constellations of satellites totaling hundreds of elements in orbit are proposed. For the bands $\gtrsim 2$ GHz there should be fewer cases in which severe filtering will be required to prevent compression of the electronics. A frequency range where it is likely that filtering will be required is the Direct Broadcast TV Satellite Band 12.2–12.7 GHz. Any frequency range in any band assigned to a satellite down link or aeronautical application may become unusable.

While the use of independently tunable IF channels will allow users to "steer around" some of the more damaging sources of interference (*e.g.*, airport radar, GPS signals, etc.), it is impossible to avoid all sources of RFI. It is therefore highly likely that all observing will be done in spectral line mode, at least at low frequencies, to allow the identification and excision of RFI from the data in both the temporal and spectral domains. To do so will require increased spectral resolution and more sophisticated data flagging schemes in the early stages of post-processing. For example, various monitor data will be used, not only to identify system components operating in a non-optimal way, but to identify discrete times and channels corrupted by external RFI. These monitor data could be used by a first-stage offline system to flag and/or excise corrupted data before forming a pseudo-continuum data base for further processing.

In anticipation of a worsening RFI environment, we must actively monitor for RFI at the VLA site in all susceptible bands that are under consideration for the enhanced VLA. We must also begin research and development on the technology needed to solve RFI problems and to assess their seriousness for actual experimental situations. Examples of useful technology include: high dynamic range amplifiers and mixers, high performance continuously tunable bandpass filters and superconducting or cryogenically cooled filters. In parallel, a continuing development program is needed for software designed to assist in the automatic identification and excision of data contaminated by RFI. Finally, the actual impact of non-saturating RFI on observations that can use fringe rate and delay discrimination should be tested in the field. This may require building prototype systems on three antennas that could be used to sample the RFI environment on baselines that would be used in experiments such as the proposed high-redshift H I surveys.

5.7 SOFTWARE AND COMPUTING NEEDS

To make sensitive continuum images over wide fields of view at high resolution we need mosaicing and multi-frequency synthesis software which can handle large numbers of channels and make continuum and polarization maps over the entire primary beam. We must be able to look at the data; some sort of automatic flagging, preferably fairly flexible, is probably also essential. We must be able to find and reasonably analyze point sources in the midst of diffuse backgrounds at many frequencies; we must be able to do multi-resolution CLEANs or the equivalent routinely. We must reach dynamic ranges of 10^5:1 routinely, and several million to one with some effort. The latter target requires a concerted study of the problems which limit us now.

Real-time imaging is important for rapid imaging of variable sources to make good use of the new high-sensitivity systems.

Improvements in computing should accompany the enhancement of the VLA, as projects of all types will benefit. These should include streamlined procedures for combining data from the E configuration with data from the larger VLA configurations, autocorrelations, and single dishes. Techniques going beyond the current robust weighting and multi-resolution CLEAN may be needed to image structures on all available scales. Astrometry software for using VLA images fully in multi-wavelength high-resolution studies will also be important.

With more spectral-line channels, data sets will be larger, requiring files larger than the current

2 Gbyte limit and very large disks, perhaps with the ability to write extra-large files across disks. True joint-deconvolution mosaicing will be in demand. Both will bring about demand for faster processing.

Visualization and display of data sets with many channels will require more sophisticated displays and high-bandwidth transfer from recording media to such displays.

Finally, the on-line computing system must be upgraded to handle the additional antennas in Phase 2 of this plan.

5.8 COST AND SCHEDULE

The time scale for carrying out the VLA Development Plan is uncertain, as many engineering aspects of the plan have yet to be defined. The amount of work that will be contracted out and the amount that will be done by NRAO staff are also not yet decided. A fundamental requirement is that the VLA should continue to function as a user instrument while the enhancements are introduced. The impact of this on cost and schedule is presently uncertain, and requires detailed study. Nonetheless, some estimates can be made.

The time scale for the work on the Plains of San Augustin (Phase 1) will probably be set by the need to move antennas through the Antenna Assembly Building for overhaul. The tasks will include:

- New feed cone and receiver installation
- Normal preventive maintenance and retrofits
- Azimuth bearing replacements (~1 out of every 5 antennas)
- Possible quadrupod and FRM modifications

Allowing 4 antennas to have an 8 week overhaul and one antenna to have a 12 week overhaul (for the azimuth bearing replacement), the work on five antennas can be completed per year. This will be a tight schedule and will probably involve working two shifts per day. With 28 antennas, and adding a few months for startup and cleanup, the upgrade project will take 6 years. During that time there will often be two antennas out of the observing array for retrofits.

Six new cryogenic systems (including finishing 45 GHz) will be added to the array; a total of 170 cryogenic receivers will need to be built. Even if design and prototyping can be done before the main project begins, we still need to fabricate about 30 cryogenic receivers per year. During our normal receiver retrofit program we have built between 9 and 12 receivers per year. About 800 new LO/IF modules will have to be built.

Six years should be adequate time to complete the fiber optics system, the new correlator, and E configuration stations. At least two years of design and prototyping should precede the actual project start. If 1996 and 1997 are devoted to R&D, the parts of the upgrade that will be located on the Plains of San Augustin could be completed in 2003. As the normal VLA and VLBA maintenance and upkeep must be kept going throughout Phase 1, we will need to add about 30 people to the Engineering Services and Electronics Divisions for its six-year duration.

Table 5.1 gives an illustrative budget for all items in the VLA Development Plan.

Computing costs, other than for on-site control of the new antennas and the new correlator, are not explicitly included in this budget. They change more rapidly than other items (fortunately tending to decrease) with time. They will therefore be estimated closer to the time of requesting funds.

Table 5.1: Illustrative Budget

Item	Cost ($M)	Sub-Total ($M)
Phase 1		
Antenna LO/IF	5.5	
Antenna Mechanical	2.3	
LO/IF Transmission	2.5	
Central LO/IF	2.5	
Correlator	7.5	
Test Equipment	0.2	
Cassegrain		
1.20–1.75 GHz	0.8	
2.13–2.70 GHz	1.6	
4.80–6.70 GHz	1.4	
12.0–18.0 GHz	1.5	
18.0–26.5 GHz	1.5	
26.5–40.0 GHz	2.2	
40.0–50.0 GHz	1.5	
NRE	0.5	
Prime Focus		
75—300 MHz	0.8	
300—800 MHz	1.2	
800—1200 MHz	3.5*	
Sub-Total		37
E Configuration		
18 stations	4	4
Sub-Total Phase 1		41
Contingency Phase 1		6
Phase 1 Total		47
Phase 2		
4 new antennas	25	
Fiber to DS, PT	2*	
Fiber to BN,HL,VN,LA	8*	
Sub-Total Phase 2		35
Contingency Phase 2		6
Phase 2 Total		41
Plan Total		88
* cost is very uncertain		

The antenna-based items in Phase 1 are costed only for the 28 antennas now in the VLA. The cost estimates for the receivers and feeds are based on recent NRAO experience with similar systems for the VLA and VLBA, and include the costs of material and labor.

The budget for the correlator includes material and manpower costs, including software. It is based on an estimate using a lag design and the VLBA correlator manpower experience. Note that all aspects of the design need more study, but that designs that would increase the cost above this estimate are likely to be discarded for that reason.

The VLA Expansion is considered as a separate phase of this plan for several reasons. It requires the prior completion of the new correlator. Its scientific effectiveness is dramatically increased by the enhanced bandwidth and improved receivers specified in Phase 1. The NRAO also needs some hands-on experience with long fiber optic links to determine the feasibility and operating costs of Phase 2. Unlike Phase 1, Phase 2 will bring significantly increased operating costs—for the fiber links and for the new remote antennas. It can however be done with minimal disruption to the operation of the existing array. If its technical feasibility could be evaluated in more detail soon, its time-scale once funded could be paced by the antenna construction and outfitting and thus be shorter than that of Phase 1.

The cost estimate for the four new antennas is based on the VLBA experience and includes their control systems, feeds, receivers and associated electronics (including VLBA recorders) as well as site development. The cost estimate for the long fiber links is highly uncertain for the reasons outlined earlier.

As many of the scientific benefits of the VLA Development Plan depend on both Phase 1 and Phase 2, it would be very attractive to complete Phase 2 so