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The VLA Upgrade Project Memo Series

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The Case for Continuous Frequency Coverage Between 1 and 50 GHz for theVLA Upgrade

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Returning the Instrument to the State of the Art

National Radio Astronomy Observatory

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1 Introduction

When the VLA was officially dedicated in October of 1980, there were only four frequency bands – at 21cm, 6cm, 2cm, and 1.3cm. Because the receiver systems were designed with the technology of the 1970s, each had by current standards a rather narrow tuning range – a bandwidth ratio of ~1.1[1] for the higher three frequency bands, and 1.3 at 21cm. Because of the rather limited tuning range, many interesting transitions could not (and still can not) be observed with the VLA.

With a formal design study for an upgraded VLA now beginning, it is useful to review the scientific case and technical feasibility for widening the range of accessible frequencies. Because bandwidth ratios of at least 1.5:1 are now feasible, it is clear that a vastly wider tuning range is possible. Indeed, given the inherent frequency insensitivity of a parabolic antenna, it is useful to approach the question of VLA Upgrade frequency coverage from the point of view of enabling continuous frequency coverage over as wide a range as possible. We thus consider three questions:

- What is the scientific case for continuous frequency coverage?
- Can continuous frequency coverage between 1 and 50 GHz be attained?
- If not, for which frequencies should the design be optimized?

This memo is intended to initiate discussion on each of these items.

2 The Scientific Case for Continuous Frequency Coverage

It is clearly desirable to design a radio astronomical instrument that has complete frequency coverage over the useful range of the antenna. But is there a reasonable scientific case to justify an intensive design with such a goal?

In my opinion, the answer is certainly 'yes,' and can be justified on many grounds. Consider the following:

- Molecular transitions from galactic star-forming regions and circumstellar envelopes. These complex regions are the source of a rich cm-wave (and mm-wave) spectrum from a wide variety of molecules. In Fig. 1, I show the 28-50 GHz spectrum from the late-type carbon star IRC +10216, (Kawaguchi *et al.* PASJ, **47**, 853, 1995). At least 188 spectral lines from 22 molecules

[1]The term 'bandwidth ratio' is defined as the ratio of the highest to lowest frequencies tunable with the receiver system

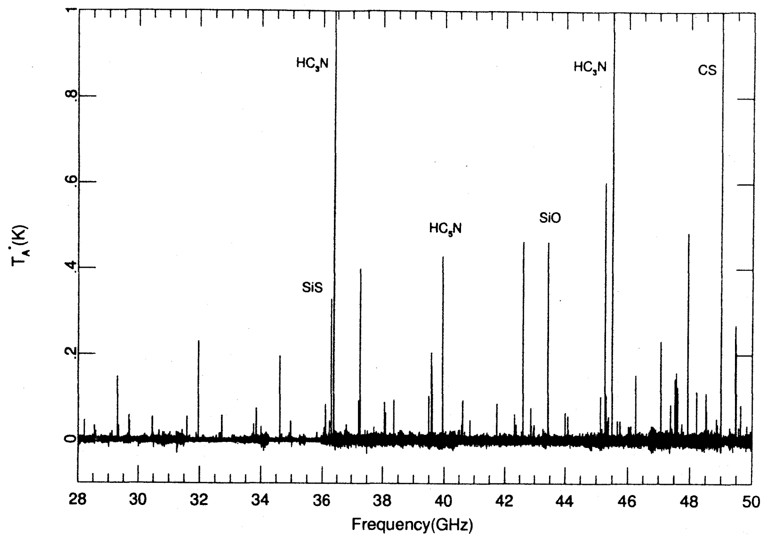

Figure 1: The rich microwave spectrum of the late-type carbon star IRC +10216 from 28 to 50 GHz.

and isotopic variants are seen in this spectrum taken with the Nobeyama telescope. Thirty-eight lines remain unidentified – testimony to our incomplete knowledge of the chemistry and physics of this circumstellar envelope.

Below 28 GHz, there is also a rich spectrum from such regions. Fig. 2 shows a representative spectrum covering the entire range of 1 to 50 GHz, compiled by Al Wootten after consultation with other spectroscopists. Not all known or conceivable molecules or transitions are displayed. The height of the lines represent expected astrophysical importance, not intensity, and are so arranged to convey the essential point that with the exception of the 1.7 to 3.1 GHz range, there are no regions in frequency space devoid of astrophysically important transitions.

Understanding the physics and chemistry of these regions requires observations of many lines, covering a wide range of excitation and molecular species. The VLA is important to these studies because of its sensitivity and imaging capacity. Thus, although many transitions of these molecules can now be observed within the mm-band, and many more will presumably be available after construction of the mmA, and other instruments, it remains important to be able to detect these molecules within the cm-band.

- Molecular transitions from red-shifted objects. The redshifts associated with extragalactic objects will shift spectral transitions down in observed frequency by a factor $1 + z$, so that frequency space relatively empty of spectral transitions for local objects may contain important information from distant objects. A good recent example of the importance of observing redshifted molecular absorption spectra is the determination by Wiklind and Combes (Nature, **379**, 139, 1996) of the redshift of the obsecured lensing galaxy for the well-known gravitational lens source 1830-211. They found $z = 0.88582$, using 12 transitions of 6 different molecules, observing within the 3-mm band. The VLA has already made important observations of this object – Menten, Carilli and Reid have just detected absorption by 8 different molecular species with the VLA's Q-band receivers.

  Molecular absorption is expected out to redshifts of about 4, so to cover all the possible

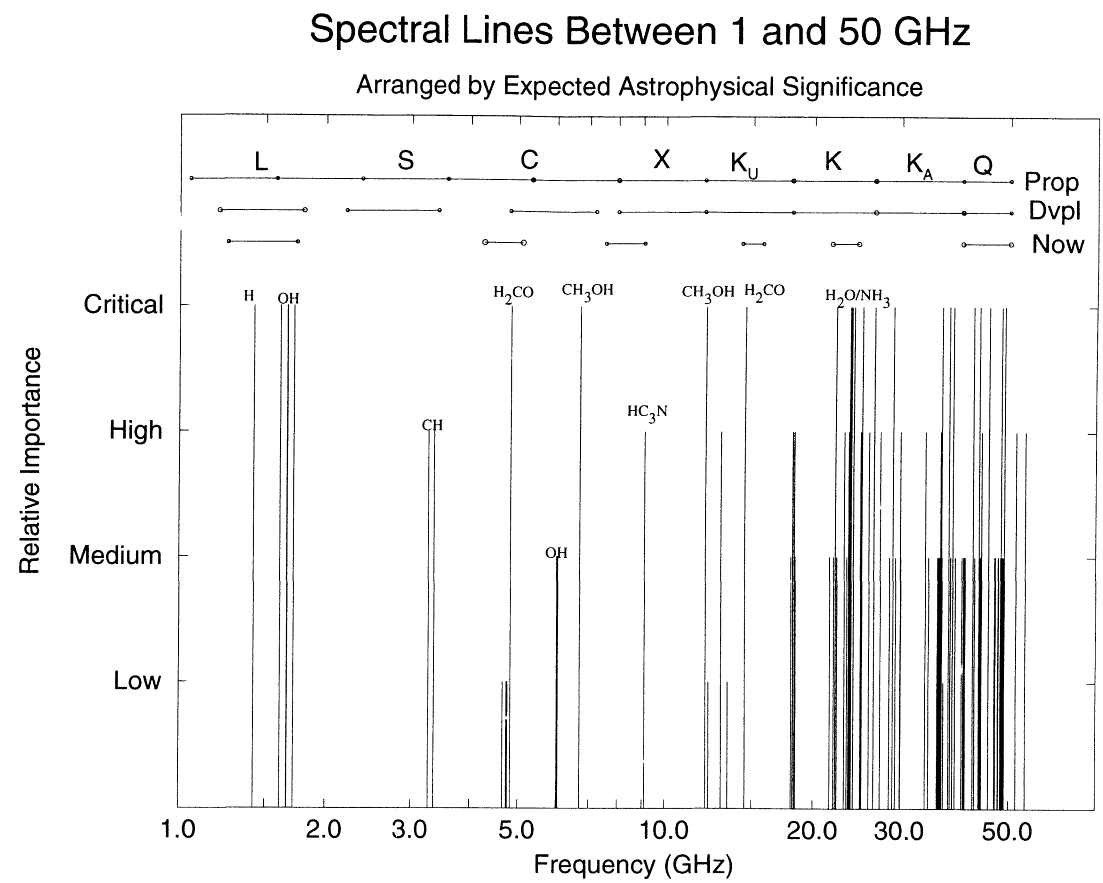

Figure 2: A representation of expected molecular transitions between 1 and 50 GHz. The height of the lines conveys expected importance of the particular transition. Across the top are displayed the frequency coverage of the current VLA, a modified version of the proposal in the 'VLA Development Plan,' and that proposed in this Memo.

combinations of rest frequency and redshift, continuous frequency coverage above 1 GHz is desirable. As with galactic molecular sources, observations of a wide range of species and energies is needed for any good understanding of the physics and chemistry of these regions. Hence, even though the number of transitions below 10 GHz may be small, it should not be deduced that observations of these transitions in the 2 - 4 GHz frequency range will not be important.

- HI emission from distant galaxies. This potentially rich field of research makes a strong case to extend continuous frequency coverage from the current lower limit of about 1.25 GHz to 1.0 GHz (or lower). Examples of anticipated new research include all-sky HI surveys to a redshift of 0.1, deep synthesis surveys of cluster of galaxies to a redshift range of 0 to 0.2, and the evolution of the neutral gaseous content of galaxies at redshifts higher than 0.2.

- Various continuum studies will benefit with continuous frequency coverage. Examples include rotation measure studies, solar observing, and high sensitivity observations of extragalactic objects. Although none of these *require* continuous coverage, *all* would benefit from having this capability.

3 Is Continuous Frequency Coverage Feasible?

To answer this question, it is useful to review some key factors which strongly influence the design of the receiver systems.

The first is the width of each band. The useable bandwidth of a frequency band in the centimeter range has traditionally been limited by the polarizer. Modern cooled polarizer design now permits bandwidth ratios as great, or greater than 1.5:1 with good polarization characteristics. The CDL has nearly completed design on such a polarizer for the proposed 18-26.5 GHz receiver on the VLA. It is expected that the polarizers for frequency bands above 12 GHz will be essentially scaled replicas of the 1.3cm design. Because of this, I assume in this memo that each frequency band on the VLA above 1.0 GHz would have a bandwidth ratio of about 1.5:1. An elementary calculation then shows that ten bands would be required to continuously cover the range from 1.0 to 50 GHz.

The choice of the center frequencies of the upper bands is dictated by available standard waveguide. The choices listed in the VLA Development Plan proceedings (center frequencies near 15, 22.25, 33.25 and 45 GHz) are dicated by these standard bands and should not be changed. This consideration is not a concern below 10 GHz.

A third factor is the impact of the subreflector on band selections. The VLA antennas are an offset Cassegrain design of 9m focal length, with the secondary focus located 168 cm above the bottom of the dish, and offset from the axis by 97 cm. The subreflector diameter is 236 cm, and subtends an angle of 9.0 degrees as viewed from the secondary focus. This requires the feed diameter to be about 8 wavelengths to provide high efficiency and high gain.

It is this required size of the feed at the secondary focus which sets the lower frequency bound for cassegrain operation – at 1.2 GHz, a feed diameter of two meters is required, and at 1.0 GHz, the required diameter grows to 2.4 meters – considerably larger than the diameter of the feed ring. Installation of such a large feed would prevent continuous frequency coverage. Indeed, a 2.4 meter horn would likely prevent any S-band system at all.

Jack Campbell is currently designing an eight-horn feed arrangement for which the lowest frequency is 1.2 GHz. A preliminary design is shown in Figure 3, and clearly shows that the presence of both L and S bands permits only six other feeds, resulting in large gaps in the frequency coverage. The resulting frequency coverage from this arrangment is shown in Figure 2, labelled as 'Dvpl.'

A prime-focus option for covering the frequency range from 1 to 1.5 GHz (which might then permit continuous coverage from the secondary focus from 1.5 to 50 GHz) is not desirable, since optimum performance cannot be obtained from the prime focus for reasons which are summarized in Rich Bradley's VLA Upgrade memo #3. In short, such an arrangement will suffer low efficiency due to the non-parabolic shaped reflector, and high system temperature because of the likely inability to provide full cryogenic cooling combined with a significant feed spillover to the ground. Decreasing the spillover by enlarging the feed will reduce the forward gain.

Thus, it is clear that if continuous frequency coverage with optimum performance from $\sim$ 1.0 GHz to 50 GHz is desired, the subreflector must be enlarged.

In the next section, I sketch a straw-man design for a ten band receiver set, utilizing a larger subreflector, which provides continuous high-performance secondary-focus operation from 1.0 to 50 GHz.

4 A Ten Band System with Continuous Frequency Coverage

I have argued above that continuous frequency coverage with optimum performance above 1.0 GHz is not possible with the existing subreflector, due to the required size for the low frequency feed

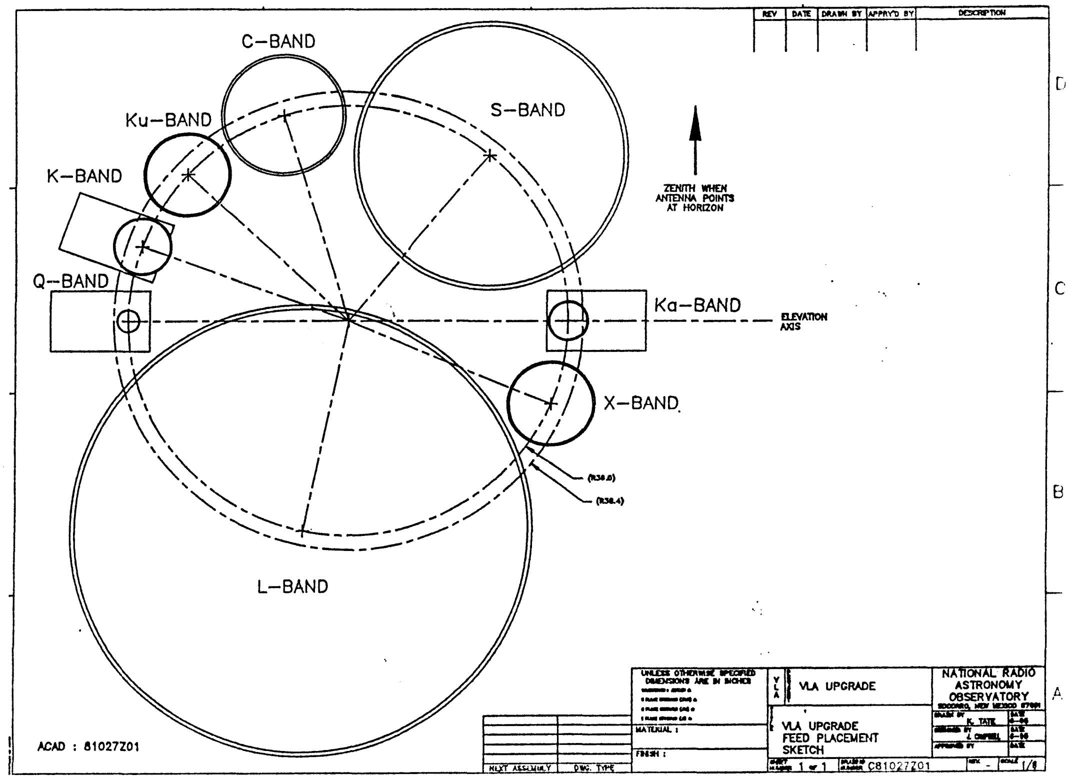

Figure 3: A preliminary design of an eight-band VLA Upgrade feed arrangement. The large L-band horn prevents continuous frequency coverage. Enlarging the horn to provide coverage below 1.2 GHz would probably eliminate the S-band system.

horn. Clearly, a larger subreflector will permit more bands to be supported, since the feed horn size will be reduced in inverse proportion to the subreflector size increase.

A simple calculation shows that a subreflector with 20% larger diameter should suffice to permit fitting ten feed horns around the secondary focus ring. However, some crowding will likely occur, so a working number for the purposes of discussion of 25% will be adopted. It should be noted that this increased size would cause no additional central blockage of the main reflector – the proposed subreflector would have a diameter of ~3.0m, still significantly less than the unpaneled central 'hole' whose diameter is 3.8m.

Of crucial concern for this suggestion is whether a 25% larger subreflector will require modification of the quadruped. Simple estimates indicate that there probably is sufficient space available to accomodate such a subreflector without quadruped modification. This question requires much more careful consideration, and is addressed in greater detail in Peter Napier's Upgrade Memo #5.

Even if there is room to accomodate an enlarged subreflector, there will be two clear negative ramifications: (1) The spherical wave blockage will be increased, due to the inevitable closer proximity of the subreflector edge to the quadruped, and (2) The larger, lower subreflector will considerably complicate any means of exposing the prime focus for low-frequency operation. Both of these aspects will be more fully explored in future memos.

5 Comparison to an Eight Band Ugraded System

The VLA Development Plan proposed an eight-band cassegrain system. This is a 'minimal' upgrade, as it suggests no change to the current X-band receiver, and is fairly modest in its specification of the S- and C-bands. An extension to this proposal would be to maintain the eight bands, but utilize the full BW ratios now available, and adjust the S-band frequency coverage to include both the geodetic bands at 2.2 GHz, and the CH transition at 3.35 GHz. The resulting 8-band system is listed as 'Plan A." The ten-band system proposed in the preceding section is listed as 'Plan B." The following table shows the proposed frequency ranges.

Plan 'A'				**Plan 'B'**			
Band	ν_l	ν_u	BWR	Band	ν_l	ν_u	BWR
L	1.20	1.80	1.46	L1	1.05	1.58	1.50
				L2	1.58	2.37	1.50
S	2.20	3.40	1.55	S	2.37	3.56	1.50
				C1	3.56	5.33	1.50
C	4.80	7.20	1.50	C2	5.33	8.00	1.50
X	8.00	12.0	1.50	X	8.00	12.0	1.50
Ku	12.0	18.0	1.50	Ku	12.0	18.0	1.50
K	18.0	26.5	1.47	K	18.0	26.5	1.47
Ka	26.5	40.0	1.50	Ka	26.5	40.0	1.50
Q	40.0	50.0	1.25	Q	40.0	50.0	1.25

An enumeration of the advantages and disadvantages of these plans is presented below:

1. Plan A – From 'The VLA Development Plan,' but expanded to full available bandwidth.
   (a) Advantages
   - Simpler and cheaper than Plan 'B.'
   - Most major spectral transitions are covered.
   - Continuous frequency coverage between 12 and 50 GHz is attained.
   - The existing subreflector is retained.

   (b) Disadvantages
   - Large frequency gaps exist on each side of S-band and around X-band.
   - Attaining both the geodetic frequency of 2.2 GHz and the CH transition at 3.35 GHz requires a very wide bandwidth ratio of 1.55. Degraded polarization performace at the band edges may result.
   - The low frequency limit for high performance is 1.2 GHz.

2. Plan B – Complete Frequency Coverage with a 10-band System.
   (a) Advantages
   - Provides complete frequency coverage from 1 to 50 GHz.
   - Extends L-band down to 1.0 GHz with optimum performance.

   (b) Disadvantages
   - A considerably more expensive plan than either of the above.
   - Requires a new, larger subreflector.

- Blockage loss due to the quadruped legs will increase.
- Increased mass around primary focus may degrade pointing performance and efficiency.

6 Coverage Below 1 GHz – Having our cake and eating it too

The VLA Development Plan, and VLA Upgrade Memo #2 discuss the feasibility and desirability of obtaining low-frequency observations by a prime-focus system. In VLA Upgrade Memo #3, Rich Bradley argues against any prime focus system, due to the necessary (but unknown) performance loss from the machinery needed to remove the subreflector from in front of the prime focus. Rich proposes a stand-alone array to handle low frequency observations, similar to what Bill Erickson and I proposed in 1984 for a 73 MHz facility.

The subject of a stand-alone array must be discussed separately, as it is a rather complicated subject on its own. In this section, I wish to make a few observations about the interaction of prime-focus systems with an enlarged subreflector.

- A new subreflector which is 25% larger than the current may not, on it own, require changes to the quadruped or F/R systems.
- Implementation of low-frequency, prime focus systems in the frequency range between the current P-band (300 - 340 MHz) and the low end of the Cassegrain system (whether it is 1.2 or 1.0 GHz) will require uncovering of the prime focus, with room to spare for the prime-focus feed package. As discussed in VLA Upgrade Memo #2, at least 90cm of subreflector travel will be needed, which will require modification or redesign of the quadruped legs.
- This situation is not greatly changed for a larger subreflector. The travel will increase by perhaps another 20cm, and the 'clear area' between the quadruped support legs for the subreflector will have to be larger.
- If the large travel of the subreflector (perhaps as much as 1.5 meters) becomes a problem, one could consider a Gregorian subreflector. This has the advantage of always lying behind (above) the focus, so that very little travel is required – only that which is needed to adjust the focus to the secondary feeds, perhaps 15 cm. The disadvantages are that the Gregorian is larger than the Cassegrain for the same secondary feeds, so that the mass loading problem becomes worse, and that the moment arm of the Gregorian is significantly higher than the Cassegrain. How serious these are, and the extent to which they can be minimized by new designs or materials, needs to be analyzed.

However, suppose it is shown that a 25% larger subreflector requires modification of the feed legs. In this case, I would advocate another approach, which really would permit us 'to have our cake and eat it too.' The unpaneled area of the VLA antenna has a diameter of 357 cm, a factor of 1.51 greater than the current subreflector. The unpaneled area represents the largest subreflector which can be accommodated without increased direct blockage. Such a subreflector would permit eleven bands, and extend the cassegrain system down to perhaps 700 MHz. We could then, in principle, enjoy optimum performance for redshifted Hydrogen studies out to $\sim z = 1$.

7 And if we can't ...?

If an enlarged subreflector cannot be accommodated, then what is the best arrangement available with the current subreflector? In my view, the modified 8-band system described above as 'Plan A' is a good compromise, since it covers all important spectral transitions, and provides good L-band performance down to 1.2 GHz.

8 Summary

It is highly desirable on scientific grounds to provide both as continuous a frequency coverage as possible, and to extend L-band down to 1.0 GHz with optimum performance in an upgraded VLA. Both of these goals can be achieved by designing a system utilizing a new subreflector some $\sim$25% larger than the current one. If access to the prime focus is not important, it is probable that a new subreflector would not require modifications to the feed leg structure. If prime focus operation is considered necessary, major changes to the quadruped will be required, whether a new subreflector is used or not. Studies of the effect such changes have on the performance of the antennas must begin soon.