EVLA MEMO 50

VLBA/EVLA INTEGRATION IN THE EVLA PHASE 2 PROPOSAL

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ABSTRACT

The Phase 2 (Completion Phase) proposal for the EVLA will be written soon. It is still unclear what will be included in that proposal to facilitate the use of the NMA and EVLA with VLBI observations. With this note, I suggest what I believe is a reasonable option. This is meant to get the discussion going, not to present a final, well developed, well costed, and carefully justified scenario.

1. Introduction

The NMA is being sold partly on the connection with the VLBA. Half of the new logarithmic frequency/resolution space provided by the NMA, as shown on the plot that is widely used in NMA documentation, is provided by the connection to the VLBA. The NMA will work with the VLA mainly when the VLA is in the A configuration. It can work with the VLBA at any time. When the NMA and VLBA are working separately, one or the other will be degraded by missing antennas. Thus operationally there must be a tight connection no matter what is done to facilitate joint use. All this makes it likely that the VLBA and NMA will be used together for a fraction of the time that is comparable to the time NMA works with the VLA. We should do what it takes to make this joint use as scientifically productive as possible.

I presume that the Phase 2 budget will fund the design for conversion of a VLBA antenna to a NMA antenna. This is needed for the conversion of Los Alamos (which will probably be moved) and Pie Town. This note does not address the conversion.

Below are the major items that I suggest might be included in the Phase 2 proposal to facilitate use of the NMA with the VLBA. My philosophy is to include those items needed at the NMA antennas and at the correlator, but not those items needed at the 8 non-NMA VLBA sites (although see EVLA Memo 48 on the possibility of including FD and KP in NMA). I mention the items that would be needed at the VLBA sites to show what we would need to try to get from RE or other funding sources.

This document was distributed by email on 2002 Nov. 21. I am releasing a slightly modified version as a memo on the advice of Rick Perley.

2. Science Case

The NMA and VLBA used together provide resolutions intermediate between those of either instrument alone. There is a factor of about 10 in resolution between the NMA and the VLBA that is not covered well by either instrument alone but that is reasonably well covered if both can be used together. That is the equivalent of 2 VLA configurations. Observations in that range are required to distinguish between thermal and non-thermal sources at the sensitivity limits of the arrays. The continuity of available resolutions will make possible broad band, matched resolution observations that are often needed to understand the physics of sources. Three examples of important types of observation that require the combined instrument are:

1. Transient microquasars can become so large that they can only be studied on the shorter VLBA baselines. The VLBA alone has inadequate UV coverage and sensitivity on the required baselines for decent imaging. The NMA alone has inadequate resolution. Sensitive movies spanning the transient's full life cycle, from hours to days, are essential to constrain simulations of microquasar evolution and explore their application to quasar populations. These movies can be made only if the VLBA and NMA are able to observe simultaneously, and provide unique structural information that complements photometric monitoring across the EM spectrum.

2. Multispectral observations, such as those needed to study free-free absorption by accretion regions, require matched resolution observations over a wide range of frequencies. Without the NMA/VLBA connection, the capability to do this is limited by the VLBA UV coverage to frequency ranges of a factor of 3 or so, which is significantly less than one would like. This argument makes provision of the highest frequencies on the NMA important because those are the frequencies for which the shorter baselines are needed for matched resolution work. These observations make it possible to study the accretion regions around AGN, not just the jets themselves.

3. Continuum observations with the NMA and VLBA will have the brightness temperature sensitivity to enable two key studies involving the distant starbursts that dominate the microjansky sky. For both studies, the brightness temperature sensitivity of the NMA alone or the VLBA alone is inadequate.

- The NMA+VLBA will be able to follow the afterglows of gamma-ray bursts as they age beyond 100 days and fade below the emission from their starburst hosts. Analysis of aging afterglows provides unique information on burst calorimetry. The resolution of the NMA+VLBA will be required in many cases to distinguish between GRB and host galaxy emission.
- The NMA+VLBA will be able to filter distant obscured starbursts for embedded AGN, ensuring a complete census of massive black holes in the early universe and also leading to improved photometric redhifts by removing the radio emission from the AGN. The NMA alone has inadequate resolution to distinguish thermal from non-thermal sources below about a milliJansky. The VLBA alone, on the other hand, has inadequate sensitivity to detect the lowest brightness non-thermal sources.

The science case should be fleshed out with examples that take advantage of the combined array's ability to observe thermal sources at the highest resolution, to image the maser flux density that is missing in many VLBA images, to image sources subject to scattering, to match the HST resolution at L band, and so on.

3. Data transmission

For the NMA and VLBA to work together, the data from both systems needs to make it to the same correlator. That will require recording systems on the NMA, or real time links to the VLBA antennas. We would prefer the latter, but probably can only afford the former in the foreseeable future.

Assuming that recording systems are the only viable option, each NMA antenna should be outfitted with a VLBI recording unit. That will most likely be a Mark5 system, although by the time the NMA is built, it might be a second generation system with wider bandwidth, but about the same cost. A rough estimate of the cost is \$150k for the 8 record units plus a spare, \$500k for a supplement to the disk supply, and \$250k for the interfaces from the LO/IF systems to the recorders for a total of \$900k. See the appendix below for more details.

In the last 10 years, the cost of disk capacity has dropped by over 3 orders of magnitude. We are almost to the point that it is affordable to have a disk based system that can handle 1 Gbps sustained. By the time the EVLA is done, we should reach the point where a disk system can affordably record 4 Gbps sustained and probably even 16 Gbps. Those are the data rates needed for 1 and 4 GHz bandwidths with 2 bit samples. But the cost of the required disk supply will depend strongly on technology trends that are hard to predict and on exactly when we purchase the disks.

I am pessimistic enough to think that the step from 16 Gbps to 64 or 96 Gbps for full EVLA bandwidth could not be made affordable on the 5 to 10 year time scale relevant for this project.

4. Correlation

The most minimal situation is to continue to use the VLBA correlator for all long baselines. But that restricts the bandwidth to 128 MHz (2 bit samples) without multiple pass processing when there are more than 10 antennas or 256 MHz for 10 antennas. The 128 MHz bandwidth is over 128 times smaller than the maximum EVLA bandwidth! The baseline sensitivity would be more than 10 times worse.

As described in NRC-EVLA Memo 6, the EVLA correlator could be used as a VLBI correlator. In fact, it appears (and this needs to be checked carefully) that the 40 station correlator that would be built for the EVLA/NMA could replace the current VLBA correlator with no loss of current capabilities, and with a considerable increase in bandwidth. This is made possible by the fact that one EVLA station input, that can handle 16 GHz, can be used to process 2 stations at 4 GHz bandwidth or 4 stations at 1 GHz bandwidth. To take advantage of this capability, playback systems would be needed for the correlator. These could either be new, potentially upgraded systems, or could be the ones from the VLBA correlator if that correlator is shut down.

Table 1: Subarray options

Subarray 1 (real time)	Subarray 2 (from disk or real time)
1. 27 EVLA + 10 NMA at 16 GHz	8 VLBA + 4 VLBI at 1 GHz
2. 27 EVLA + 10 NMA at 16 GHz	6 VLBA at 4 GHz
3. 27 EVLA + 8 NMA at 16 GHz	10 VLBA at 4 GHz
4. 27 EVLA at 16 GHz	8 NMA + 10 VLBA + 8 VLBI at 4 GHz

To imagine how this correlator might be used for the VLBA in addition to the NMA and EVLA, consider the possible distributions of input signals shown in Table 1. Note that any particular bandwidth can mean really that bandwidth, or narrower bandwidths at higher spectral resolution. Any subarray can also be split into smaller subarrays. "VLBI" means non-VLBA antennas such as phased VLA, GBT, EVN antennas etc.

The table shows that the VLBA could always be correlated with 1 GHz bandwidth, and often with 4 GHz. These are very significant increases over the current correlator. There also will be an increase in the number of spectral channels available. I have not reviewed this carefully yet, but suspect that there would be 4096 spectral channels at 4 GHz and 1024 at 1 GHz. Recirculation would allow more channels for narrower bandwidths.

One operational complication with both positive and negative implications is that, unless a real time system is possible, the VLBI parts of the above table are for what is being played back. That would need to be compatible with what is actually happening on the array at the time of correlation.

Given all of the interactions between the instruments, having one correlator and one control center for the VLA, NMA and VLBA will make the most efficient use of this unified telescope.

The cost of the required Mark 5 playback systems would be between $34k and $440k depending on the total number needed and whether the systems from the current VLBA correlator can be transferred. A wild guess for the interfaces to the correlator is about $250k. A rough estimate for software effort is about 2 man years above what the correlator would otherwise require.

Note that, if the NMA is not built, the 32 station Phase 1 correlator will always have enough capacity to correlate the 10 station VLBA at 4 GHz bandwidth, if the interfaces are provided.

Adding the NMA recording systems, disk supply, and playback systems, with interfaces where needed, the wild guess total cost is in the $1200k - $1600k range. A critical need is for a conceptual design to be made to provide a better cost estimate and to confirm the technical feasibility. I suggest that the cost derived from such a conceptual design be added to the EVLA Phase 2 proposal.

5. Antenna electronics

I do not propose that the EVLA Phase 2 proposal fund the changes needed at the VLBA stations to utilize the correlator capabilities. It would make sense for these costs to be covered, but I don't see a realistic chance that they will be. If RE budgets were reasonable, they could be financed that way, but... In any case, for completeness I outline the station costs and concerns here. There are some details in the appendix below and a lot of questions in a second appendix.

For 1 GHz bandwidth, it should be possible to obtain the required signals at the VLBA antennas by sampling the current 500 MHz IFs. Nothing new would be needed in the electronics on the antennas. But it would probably be necessary to provide a flexible frequency conversion to allow fine tuning. The samplers and recording system interfaces would also be needed. It is difficult to estimate the cost without a conceptual design, but I'm guessing it might be as high as $550k.

For the 4 GHz bandwidth, and to do the 1 GHz bandwidth "right", a new LO/IF system would be needed. The 2 cm and above receivers have adequate bandwidths to feed a 2 GHz/polarization (4 GHz total) system. A subset of the EVLA LO/IF system would probably do the job, but a design is needed. Based on the WBS, I estimate in the appendix that the cost of the required EVLA LO/IF subset to be about $2M for 8 stations plus spares. Using the EVLA system would be the logical first step toward full conversion to EVLA standards.

It would be desirable to enhance some of the receivers to cover some old wish list items and to utilize the wider bandwidths. Hopefully we can get Ka band with DSN help. Perhaps the top priority for our own funding would be the 4-8 GHz receiver. That receiver would cover several maser spectral lines in the 6 GHz range. It is probably the optimum frequency range for high sensitivity, phase referencing observations. It is also a good range for using basebands at opposite ends of the receiver band to remove the ionosphere. Based on the WBS, the 4-8 GHz receiver for 8 antennas and a spare would be $255k.

The desire to spread frequencies for ionospheric removal, multi frequency synthesis, and Faraday rotation measurements suggests that there should be at least 2 well separated polarization pairs of IF channels. For 4 GHz maximum bandwidth, each could be 1 GHz wide possibly allowing the use of only the narrower band samplers. It will not be possible to obtain well separated pairs for the 1 GHz system if the current IF system is used.

Two of the VLBA antennas will be upgraded to full EVLA standards because they are part of the NMA. The ultimate goal would be to upgrade the other VLBA antennas to the same standard but much could wait until it becomes possible to consider returning 64 Gbps (16 GHz, 2 bit) to the correlator. That is probably a long time in the future, although upgrading and attaching Kitt Peak and Fort Davis on a shorter time scale could be worthwhile (see EVLA Memo 48).

6. Short Summary

I suggest that the EVLA Phase 2 proposal include approximately $1.6M for VLBI recording systems for the NMA and for playback interfaces to the EVLA correlator. A pressing need is for a conceptual design for these items, and for the VLBA station items needed to use them, so more defendable cost estimates can be made.

A. Appendix: EVLA/VLBA Connection Concepts and Costs

This appendix gives more details for my concepts for connecting the VLBA and NMA and for the costs. Warning: I have not discussed these estimates much with the engineers who will need to do the designs so all of this should be treated with considerable caution.

Below, "VLBI" as a set of stations means anything except NMA and VLBA. This includes GBT, phased VLA, Arecibo, EVN antennas etc.

An "IF pair" means the two polarizations at one frequency.

A.1. The items for EVLA Phase 2 proposal

These are the items that I think it is reasonable to fund within the EVLA Phase 2 proposal. They are the items needed to use the NMA for VLBI and to use to EVLA correlator to correlate recorded VLBI data.

- Mark 5 recording systems.
  - Need 8 new for NMA
  - Assume that VLBA has 10, correlator has 20, and VLA and GBT each have 1.
  - Commercial price \$17k. \$153k for 9 (includes spare). Round to \$150.
- Mark 5 playback systems. Options:
  - There are 18 antennas in the NMA+VLBA so that is a minimum number of playback systems. The 13 station inputs not used by the 27 VLA antennas could be fed by up to 26 playback systems at 4 GHz bandwidth. This seems like a reasonable number to handle global observations.
  - 26 at \$17k = 442k (EVLA+NMA+8VLBI)
  - 18 at \$17k = 306k (EVLA+NMA)
  - 2 at \$17k = 34k (EVLA+NMA+8VLBI with 24 units transferred from current correlator)

  I have not explicitly included spares, but the \$17k per unit may be more than we need. Also it will be uncommon that 26 are needed on the correlator.
- Mark 5 disks. This is a very uncertain and potentially large cost.

  For a low estimate, assume 2-TB disc drives can be bought at \$125, or \$0.06/GB. This is 5% of today's price, implying a cost decline of 0.55 annually. Including the housing, an 8-disc module would cost \$1225. At the 1-GHz bandwidth (4 Gbps), we would fill 2.7 such modules per station per day. Assume further 8 stations, and a 20-day supply as an increment to the VLBA pool, less than 40 days because we won't always be recording. For these 160 station-days, we would need 430 disc modules, for a total cost of \$530k.

  It is not clear now what the state-of-the-art will be when we buy the disks. For 4 Gbps recordings, and especially for 16 Gbps recordings potentially allowed by the rest of the system, the disk costs might be several times the above number. We need to think through what to put in the proposal.

Note that we're expecting to need $2M - $4M for the initial Mark 5 deployment on the VLBA. These disks will be considerably smaller than what we would like to be using by the time the NMA is available.

Some of the following interface numbers are guesses made after discussing the issue with Mike Revnell. They are very rough because we don't yet have a serious conceptual design.

- Interfaces to recording systems for NMA antennas.

  Filter to desired bandwidths (digital) and deliver to recorders. 2 IF pair. Total cost maybe $250k.

- Interfaces to the correlator.

  Extract data from VSI unit (Mark 5), configure it for the correlator, and feed it to the station units.

  Roughly $4k per IF pair, 4 IF pair, 13 station $250k.

- Software

  Off the cuff estimate by Barry - 2 man years.

A.2. For RE or other funding source separate from EVLA

These are the items that will be needed to take full advantage of the EVLA/VLBA connection, but that I don't forsee being able to fund with the EVLA Phase 2 proposal because they are "pure" VLBA items.

- LO/IF at the VLBA.
  - We want the ability to send low bit rates if the observations allow.
    Saves disk and shipping costs.
    May allow some real time work sooner.
  - I (and Greg) think we want two independently tunable IF pairs.
    They could be within a single downconverter bandwidth (5 GHz)
  - Recall that the current system sends 2 IF's, each of 500 MHz width, to building.
    They are actually 550 MHz filters.
  - LO/IF parts for 4 GHz option (can also be used for less bandwidth)
    - I think we need everything from the EVLA antenna LO/IF system except:
      - First LO system. I think we can use our current synthesizers.
      - 2 Downconverters. Also the 2 that are needed might be partially populated.
      - Part of the Ku to X band converter - only populate half of device signal paths.

            · Part of the low frequency converters - only populate half?
        * I will assume we need to fund 9 systems (8 plus spare)
        * For some items, we only need half in order to do 2 IF pairs rather than 4.
        * I have not attempted to remove the NRE costs so these should be overestimates.
        * Cost estimate details based on the WBS:

From WBS for:	30 systems	VLBA(9)	VLBA(9 - 2 IF pair)
First LO System	870k	261k	--
Second LO System	1730k	519k	300k
Antenna Reference System	751k	225k	225k
Switches	321k	96k	50k
4/P & L/S/C Converters	300k	90k	50k
UX Converter Module	544k	163k	100k
IF Down Converter	1394k	418k	209k
Samplers and MC bus	1351k	405k	850k
Half samplers/all MC			

        * Wild guess for filtering and interface to recordings $250k
        * Total for VLBA (9 stations, 2 IF pairs) 2034. Call it $2M. Not cheap!
        * Could we save significant amounts in the IF Down converter and samplers if we did 2 IF pairs at 1 GHz bandwidth (1-2 GHz) and used only the 2 GHz samplers - or even 2 GHz 2 bit samplers (commercial product?).
    – LO/IF parts for 1 GHz option
        * The 500 MHz IFs can only be tuned in 200 or 300 MHz steps.
          We probably need a fine tuning capability. Otherwise the required bandwidth is already sent to the building.
        * Need to filter again. The 500 is really a nominal 550 and may be wider.
        * A possible design would have:
          (Prices are wild guesses by me after looking at 4 GHz case)
          Tunable LO near 2400 MHz. Continuous tuning over 128 MHz. $150k
          Upconverter for IF to 1024-2048 range. $100k
          2048 GHz sampler. $200k (EVLA high resolution sampler, or something with fewer bits).
          FIR filter $100k
          Interface to recorders and posible real time
          Total $550k with error of a factor of a few.

- Receiver for 4-8 GHz.

  About 850k parts and labor for 30 so $255k for 9.

- Receiver for Ka band. Get from NASA?

- Long term - full EVLA receiver set and LO/IF system, hopefully with real time data transmission. They would want 48 station correlator.

B. Questions

This appendix lists questions related to VLBI in the EVLA era, especially if using the WIDAR correlator as the VLBI correlator. We will need to address these at some point.

1. What should be the total design bandwidth for the VLBI system used with the EVLA?
   (a) 1 Gbps - VLBA correlator capacity in Mark 5 era.
   Too small to gain benefit of the new correlator.
   (b) 1 GHz total, 4 Gbps for 2 bit samples. 2 IF channels (1 pol pair)
   Minimal but useful increase in sensitivity over current correlator.
   Limited MFS, faraday rotation, and ionospheric removal ability.
   Relatively easy at stations. Limited new LO/IF - in building only.
   (c) 1 GHz total, 4 Gbps for 2 bit samples. 4 IF channels (2 pol pairs) that are independently tunable.
   Minimal but useful increase in sensitivity over current correlator.
   Better MFS, faraday rotation, and ionospheric removal ability.
   Need more LO/IF capability on the antennas.
   (d) 4 GHz total, 16 Gbps for 2 bit samples. 2 IF channels (1 pol pairs)
   Limited MFS, faraday rotation, and ionospheric removal ability.
   Requires the 4 GHz samplers.
   Probably best to use partial conversion to EVLA LO/IF.
   (e) 4 GHz total, 16 Gbps for 2 bit samples. 4 IF channels (2 pol pairs)
   Better MFS, faraday rotation, and ionospheric removal ability.
   Could be done with 2 GHz samplers.
   Probably best to use partial conversion to EVLA LO/IF.
   (f) 16 GHz full EVLA bandwidth. 64 Gbps for 2 bit samples, 96 for 3 bit.
   We probably cannot get this kind of bandwidth back affordably on time scales reasonable for this project, except maybe from KP and FD. Needs full conversion to EVLA LO/IF and best if receivers upgraded.

   I recommend that we plan toward one of the 4 GHz options, even if we can't record that much at first. There are more detailed issues below.

2. What should be the bandwidths of the individual signals recorded on the VLBI systems when using the EVLA correlator?
   (a) Current VLBI baseband bandwidths, up to 16 MHz.
   Too narrow. Correlator limited to 16 subbands or 256 MHz total/pol.
   (b) WIDAR subband channels, up to 128 GHz.
   Fractional bit delay corrections an issue. It's done like the current XF correlators, which causes band edge losses.

Might mitigate by doing delay correction before filtering at station (Station board at station?) to slow down any corrections later, allowing after-the-fact spectral slope application.

Matches the phasing system output from VLA.

(c) Full sampler output, up to either 1 or 2 GHz, depending on design. Sometimes will be more than needed and data volume affects number of disks needed and shipping costs. How do we handle VLA phasing output? May be easiest interface to correlator

3. Where should the signals be inserted into the correlator?

   (a) For full sampler output, use normal IF input. But what do we do if we want 4 stations at 1 GHz per normal station input, but with 2 independently tuned IF pairs per station? Need to combine 2 signals into 1 "IF".

   (b) For recorded subband signals, is there an obvious insertion point? This deals with the independently tunable IF pairs in a natural way.

4. How much tuning capability is needed at the stations (eg before sampling)?

   (a) Are the twiddle frequencies needed or are the natural fringe rates sufficient for the WIDAR? Note that, with the VLBA correlator we sometimes need to edit a few minutes when the fringe rate gets too low.

   (b) Do we need to position bands on spectral lines? I suspect yes.

5. If we opt for using the current 500 MHz IFs, how should it be done?

   (a) The fact that the IFs are really at least 550 MHz, centered on 750 MHz, I think means that they either have to be shifted, filtered, or sampled at something well over 2 GHz to avoid aliasing problems. Is this right?

   (b) The only tuning available before the 500 MHz IFs are made comes from the 1st LOs, which tune in steps of 200 and 300 MHz. Fine tuning is not possible there without new synthesizers. The EVLA synthesizers cannot be used because they don't have low enough frequencies.

   (c) Any comments on the scheme outlined in the following steps? Is there a more clever way?

      1. Provide an LO that can be finely tuned for about 128 MHz near 2.4 GHz.
      2. Mix the IFs into the 1-2 GHz range.
      3. Sample, perhaps with the EVLA high resolution, 2 GHz sampler.
      4. Make the main delay corrections. (optional)
      5. FIR filter to correlator subbands.
      6. Record the desired subbands.

      This scheme is probably cheaper than using the EVLA LO/IF system, but does not upgrade easily.

6. If we opt to provide up to 4 GHz from each station:

(a) The correlator can handle 4 GHz from 2 stations in one 16 GHz station input. Can those 4 GHz be spread across 2 IF polarization pairs if not all available bandwidth is used from each pair (use 1 GHz on each incoming IF, not the 2 that is the design maximum)? If not, can 2 1 GHz signals be combined into a single 2 GHz signal?

(b) Would it be reasonable to opt to never use more than 1 GHz per IF/pol while we are limited to 4 GHz total? This might mean we don't need the fast samplers at the stations.

(c) For an implementation of the EVLA LO/IF system, I think we need:
- LO reference receiver and Reference Generator and Distribution.
- 4/P to L-Band Converter (2 IFs?)
- L/S/C to X band Converter (2 IFs?)
- Ku to X band converter (2 IFs?)
- No EVLA first LO synthesizers - I think we can use the VLBA units.
- 2 Second LO Synthesizers
- 2 Downconverters
  Modified for 2 outputs for 2 GHz samplers and none for 4 GHz samplers?
  Design might not work for this because of sideband problems.
  Might have to use the 4 GHz samplers - maybe only them
- 4 samplers running at 2 GHz.
- Filter to desired recording channels.

(d) A partial implementation of the EVLA LO/IF can be expanded naturally to a full implementation when the data transmission capability is available.

7. The current correlator design can phase 8 subbands for 1 GHz output.

   (a) Should we press to expand this to 4 GHz?

8. The number of spectral channels needs to be reviewed.

   (a) My first take on it is that the spectral channel bandwidth is the same with 1X16 GHz station, 2X4 GHz stations, or 4X1 GHz stations inserted into each "station" unit.

   (b) Does the 1 MHz/channel of the widest bandwidths restrict the field of view uncomfortably? For full VLBA baselines, the field of view from delay smearing would be a couple of arc seconds. Recall that this can be improved with recirculation with narrower bandwidths.

9. Physically where does everything associated with the correlator go? An operation sort of like the VLBA correlator will be needed, although it is likely to be possible to do all the disk mounting during 1 shift each day. Space will be needed for:

   (a) 10 record systems for the NMA antennas.

   (b) Up to 26 playback systems for the correlator.

   (c) A largish supply of disks.

   (d) Shipping operation
   Someone suggested the old VLA correlator room.
   With wideband communication to Socorro, all this could be put in the AOC.

The bandwidth required is, say, 26 stations X 16 Gbps/station or 416 Gbps, less than that used for 5 full EVLA stations. The data transmission hardware costs might be significant.

That's all for now. But more is needed soon to firm up the costs for the proposal.