VLBA Sensitivity Upgrade Memo #15

A PROPOSAL TO INCREASE THE SENSITIVITY OF THE VLBA

April 16, 2007

Craig Walker, Jon Romney, Walter Brisken, & Steve Durand

MEMO NOTE: This memo is a copy of a proposal submitted to NRAO to use funds from the GBT azimuth track remediation settlement for VLBA projects. It differs from the original proposal only in that detailed budget information has been removed because the memo series is public. Memo prepared May 1, 2007.

ABSTRACT: We propose to use funds from the GBT azimuth track remediation settlement for two projects to increase the sensitivity of the VLBA. The larger project will take the next major steps toward achieving a bit rate of 4 Gbps by 2011, thereby increasing the sensitivity for most projects by a factor of 5.6 compared to what was available with the traditional sustainable rate of 128 Mbps or a factor of 2.8 times the best available, but not sustainable, rate with the current system. Elements of this project are a wide band digital backend for the antennas, a 4 Gbps recording system, and a 1 Gbps correlator that is a start toward a 4 Gbps system. The second project will replace the low noise amplifiers in the 43 GHz receivers to increase the sensitivity of the highest frequency, highest resolution band at which high quality imaging, phase referencing, and astrometry can be done. The costs are $812k for the bandwidth increase project and $182k for the 43 GHz receiver upgrade. Portions of the bandwidth increase project will involve collaboration with the Haystack Observatory

A PROPOSAL TO INCREASE THE SENSITIVITY OF THE VLBA

1: Summary:

The NRAO and Haystack Observatory convened a committee, led by Greg Taylor and Colin Lonsdale, of members of their staffs and representatives of the US astronomical community to consider the future of astronomical VLBI in the US. That committee reviewed past accomplishments of VLBI and the VLBA and considered the future scientific prospects. In their 2004 report[1], *Mapping the Future of VLBI Science in the U.S.,* (hereafter TLR) they reviewed the science and recommended three phases of technical development. Of the Phase I recommendations, the transition to Mark5 disk based recording systems on the VLBA, VLA, GBT, and Arecibo has been accomplished. The 22 GHz receiver enhancement is in progress. But the 43 GHz receiver enhancement, antenna and receiver upgrades at 86 GHz, and investigation of WVR and dual frequency observations have not happened. The latter three projects require manpower that is not now available. This proposal requests $184k to allow the 43 GHz receiver enhancement to follow the on-going and successful 22 GHz enhancement.

The TLR recommended a Phase II in which the bandwidths of VLBI are increased to 4-16 Gbps. Phase II also includes aggressive pursuit of mm VLBI, a project currently outside the scope of the NRAO effort but being pursued elsewhere. There is a VLBA effort in progress, in cooperation with the Haystack Observatory, to reach 4 Gbps (1GHz with 2 bit samples) by 2011. This is considered critical to the future effectiveness of the VLBA. Indeed, the NSF Senior Review[2] stated that "the VLBA is poised to produce its strongest scientific contributions", a statement based in part on having been told about the effort to increase the sensitivity by implementing wider bandwidths. Reaching 4 Gbps will require a replacement for the baseband converters, samplers, and formatter at the stations, a new recording system, and a new correlator, along with acquisition of an adequate disk supply. Initial development efforts for a digital backend (DBE) are under way, as is initial deployment within the VLBA environment of a very promising software correlator originally developed at Swinburne University in Australia. And development of a Mark5C recording system capable of 4 Gbps has begun at Haystack and Conduant. These efforts, along with the ongoing acquisition of disks, are being funded from operations or, in the case of Mark5C, by the geodetic community. This proposal requests funding for the initial deployment of these new systems with the goal of obtaining a sustained 1 Gbps capability and test capability at 4 Gbps during 2008. The final deployment of recording systems and acquisition of adequate disk supplies to reach sustained 4 Gbps operation will require funding from operations or other sources in the future. The cost to deploy the DBEs is $362k ($234 for a limited capacity option). The estimated cost for NRAO participation in the development and prototyping of the 4 Gbps recording system is $200k. The cost for the computers for a 1 Gbps software correlator is $250k.

The requests to fund the 43 GHz upgrade and the progress toward 4 Gbps are combined in one proposal as they share much of their scientific justification and are both part of the effort to implement the recommendations of the TLR. But they are separate projects technically and either could be funded, and be scientifically productive, without the other. Because of both its larger impact on sensitivity, and its impact across all frequencies, the bandwidth upgrade is clearly the higher priority component.

2: Introduction:

Since the end of construction until the last couple of years, the VLBA saw very few scientific enhancements. About the only major hardware addition was the 86 GHz system, which was made possible by significant funding from the Max-Planck-Institut fuer Radioastronomie (MPIfR). The formation of the HSA, and the development of new calibration algorithms, have also helped significantly, but were not hardware upgrades. This stagnant situation has started to change. Over the last 4 years, the tape recording system has been replaced with the Mark5 disk-based system that is more reliable, easier to operate, and offers the promise of much increased bandwidth in the future. Design work has begun on the systems needed for that increased bandwidth. Work has also begun on upgrading the 22 GHz receivers with new low noise amplifiers from the CDL. The expectation was that the overall Tsys would be reduced to about 70% of current values, but results from the first 2 receivers deployed suggest that the sensitivity will be increased by nearly a factor of 2.

Of the many enhancements desired for the VLBA, two have been singled out for this proposal based on their technical readiness and on their potential impact on VLBA science. The most important continues the effort to deploy a much wider bandwidth system to increase the sensitivity of all continuum and band-limited line observations. The other follows up the LNA improvements to the 22 GHz system by providing a similar improvement at 43 GHz, the highest frequency, and hence highest resolution band at which high quality imaging and astrometry can be done on the VLBA.

3: Science Case:

The TLR contains the results of a community-wide effort to identify the future scientific directions of VLBI in the U.S. That effort was far greater in scope than what could be generated separately for this proposal and need not be repeated. The items requested with this proposal are a major part of the NRAO effort to implement the recommendations of that report. In this section, the future directions expected for US VLBI, as given in the report, are outlined quickly, with some attention to progress that has been made in the last few years. The impact on each of the directions of the proposed enhancements is noted. The key future prospects for VLBI identified in the TLR, with their numbering scheme, are:

3.1: Imaging a massive black hole – Is General Relativity the true theory of strong field gravity? Addressing this subject requires imaging the emission close to a black hole, probably in SgrA*, using mm VLBI. It is not directly a VLBA project, but the technical developments required to increase the bandwidth of the VLBA will also be required to conduct such observations.

3.2: Gravitational Lenses – where is the dark matter? Modeling of the images of gravitationally lensed systems is used to determine the distribution of dark matter in lensing systems. High sensitivity is required to detect the effects of small satellite clumps in galactic halos and to detect central images. Increasing the bandwidth is one of the enabling technologies.

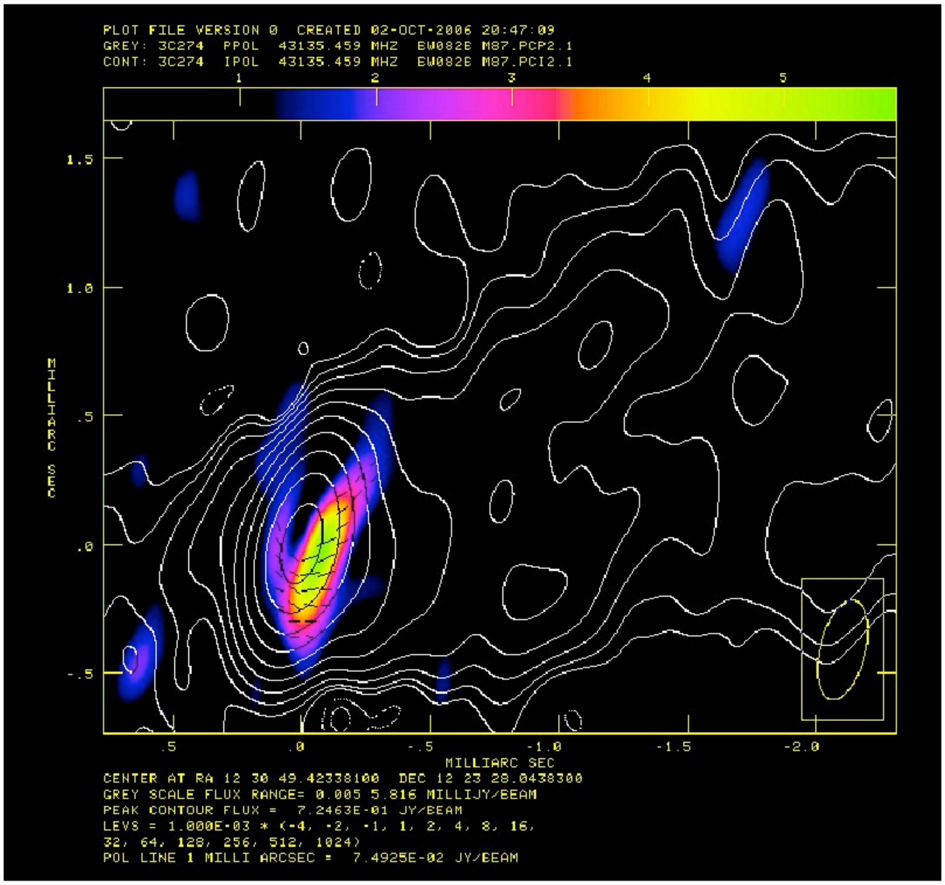

Figure 1. An unpublished image from the 43 GHz M87 movie pilot project showing the total emission in contours (factor of 2 starting at 1 mJy/beam), the polarized emission in the color scale, and the electric vector as short line segments. Note that the polarized emission is just barely not detected beyond about 0.5 mas where the total intensity flattens out. As a result, the polarization information is of limited usefulness. This observation was made with a recorded bit rate of 128 Mbps, a bit less than the current sustainable bandwidth. With the changes proposed here, the system temperature would be better by a conservative 30% and the bandwidth would be 32 times higher, giving a sensitivity that would be 8 times better. It is likely that the polarization structure would be observed to beyond 2mas in the above image providing a wealth of information on the magnetic field structure in the edge brightened jet on scales closer to the black hole, in gravitational units, than is possible in other sources.

3.3: Supernova factories and nascent AGNs – what happens when galaxies collide? High-resolution observations in ultraluminous infrared galaxies of both radio supernovae and buried AGN provide information on the star formation processes and AGN formation in regions that are heavily obscured at other wavelengths. But the radio sources involved are very weak and only the brightest can be observed today. Example results for the brightest starbursts, Arp 220 and Arp 299, are given by Parra et al, 2007[3] and Neff et al, 2004[4]. Even these very sensitive images reach no fainter than 10-100 times the power of CasA. Increased bandwidth will significantly increase the sample of such sources that can be observed.

3.4: Launching AGN jets – How are relativistic, collimated flows generated? VLBI observations at the highest frequencies available provide the highest resolution imaging studies of the inner portions of jets. A prime example is M87 where an edge brightened structure with a wide opening angle at the base is seen in 43 GHz VLBI images. Because of the high mass of its black hole, the strength of the jet, and the relative proximity to Earth, M87 offers the best opportunity to study jet structure close in gravitational units to its base. The 0.18 mas resolution of the VLBA at 43 GHz corresponds to about 2500 au or about 50 Schwarzschild radii. A project to make a movie of that source is in progress, but initial indications are that the VLBA is not quite sensitive enough to detect the polarization structure along the jet in individual epochs (Figure 1). The receiver enhancements and bandwidth increases proposed here would provide the extra sensitivity needed to obtain this very important information. The enhancements would also allow similar studies of jets in other large-angular-size black hole sources, such as M84, where the jet is known to exist, but the current sensitivity does not allow the structure to be determined well enough to study the dynamics. Note that even higher frequencies have the potential for higher resolution studies, but the system performance is so much worse that obtaining images of the required quality is problematic.

Along with the strong jets in objects such as M84 and M87, jets are inferred from the flux density measurements of low-radiative efficiency AGNs such as SgrA* and various NGC galaxies, (e.g. Bower et al 2006[5], Anderson, J. et al., 2004[6]; Ulvestad & Ho 2001[7]; Wrobel and Ho 2006[8]). However more sensitivity is required to actually image these jets.

3.5: What are the kinematics of the Galaxy and the Local Group? The understanding of the kinematics of the Local Group would be greatly enhanced if the proper motions of member galaxies could be determined. Projects to measure such motions using masers are under way. Similarly, work is progressing on using astrometric observations of pulsars and masers to determine the parallax distances and proper motions of structures in the Milky Way. Enhanced sensitivity from wider bandwidth would allow the use of weaker target sources and phase reference calibrators, providing more measurements and improved measurements with lower source-calibrator separations. Enhanced sensitivity at 43 GHz would aid any such projects that use SiO masers or that depend in having the highest resolution at which high quality observations can be made.

3.6: What is the role and effect of magnetism in stars? While most stars are not detected in the radio, at several stages of their evolution, they can be bright with gyrosynchrotron emission. This indicates the presence of dynamically important magnetic fields during star formation, binary interactions, and brown dwarf flares. The very brightest such systems can be studied now but the number of accessible systems will increase significantly with the 43 GHz upgrade and the wide bandwidths.

3.7: Super Massive Binary Black Holes – How common are they? Of particular interest are close binaries that will eventually coalesce, giving off copious gravitational radiation. If such black holes are accreting matter, they are likely to be readily identifiable in the radio as AGN and the properties of the system can be measured with VLBI. As large surveys, such as the VLBI Imaging and Polarization Survey, are being done, multiple candidate binary black holes are being found. As with any project requiring searches through large numbers of objects, improved sensitivity from wide bandwidths greatly shortens the time needed to do the science and may, as a result, make such work possible.

Since the 2004 report was written, the importance of astrometric observations has increased. Parallaxes are being measured to a variety of galactic sources whose distances were rather uncertain before. The distance is a very fundamental parameter require for physical interpretation. The parallax distances are becoming sufficiently accurate that the 3-dimensional structure of the nearest star forming clouds in Taurus and Rho-Ophiuchus are being measured (Loinard 2006). Enhancement of the VLBA to 4 Gbps would enable parallax measurements of hundreds of young stars in Taurus, instead of only a few.

A project that is providing significant motivation for the 22 GHz upgrade is to measure accurate distances to a number of H_20 megamaser galaxies in a manner similar to that used for NGC 4258. That should allow a significant improvement in the accuracy with which H_0 is known which, in turn, would help constrain the equation of state of dark energy. That project would benefit significantly from wider bandwidths, at least up to 1 Gbps, to cover all the line features in both polarizations with 2 bit samples to get full sensitivity.

A significant observation that might be possible would be to detect material orbiting SgrA* at 43 GHz (Reid, private communication). Based on the model of Loeb & Waxman (2007[10]) , the 43 GHz emission must come from a radius of about 20 R_s (~1 AU) from the material that circles SgrA* with a 7 hour period. This might be detected by observing a ~1AU (~0.1 mas) position shift in the centroid of the emission in astrometric observations relative to quasars. An increase in sensitivity from upgraded 43 GHz receivers and/or more bandwidth would allow the longer baselines, on which the SgrA* signal is weak because of resolution, to be utilized more effectively.

Essentially all projects on the VLBA would benefit from the bandwidth upgrade by allowing detection of weaker sources, imaging of more extended structures, and use of closer, but weaker, calibrators. Some significant topics that have not been mentioned include GRBs, geodesy, astrometric reference frame maintenance, IDVs, scattering, and high time resolution monitoring. Also it is expected that most sources found with GLAST, to be launched soon, can be studied with VLBI to learn more about activities in the innermost regions. Any projects that require the highest possible resolution with either high quality imaging or phase referencing, not to mention access to SiO masers, will also benefit from the 43 GHz LNA upgrade. Finally, the EVLA, with its 27 antennas and 16 GHz bandwidth, will find many weak sources of interest for high-resolution studies. It is important to that the sensitivity difference between the instruments be as small possible.

4: Technical details

With this proposal, we request funding for two upgrade projects to improve the sensitivity of the VLBA and implement recommendations of the TLR. Each project stands on its own. The most important project is to begin to deploy the hardware necessary to increase the VLBA data rate to 4 Gbps, a factor of 32 more than the sustainable bit rate of 128 Mbps that the VLBA has had for most of its life (up to 512 Mbps is possible for a few observations, but only with a reduced duty cycle). That factor of 32 represents a factor of 5.6 in sensitivity, which will have a significant impact on most VLBA projects. The other project is to upgrade the low noise amplifiers in the existing 43 GHz receivers to improve the sensitivity at that important band by 40% or more. Most of the work to be funded from this proposal on both projects would be done during 2008, with some extending into the next year.

The data rate project has three separable parts. The first is to deploy the digital backend now under development. The second is to fund development and initial test deployment of a recording system capable of at least 4 Gbps. The third is to purchase a cluster computer that, with the software correlator currently under development, has the capacity to support the sustained recording rates expected in the next couple of years and provide a start toward a 4 Gbps correlator.

The full project to increase the data rate to 4 Gbps is larger, and longer in time scale, than what is being requested here. Initial deployment of a disk based recording system and acquisition of recording media adequate for sustained operations at an average of about 170 Mbps has already been done with operations funds and support from the Huygens project. Future enhancements of the disk supply will be done from operations or other funding and are not being requested with this proposal. The design and prototyping of the digital backend is in progress and is being funded from operations, as is the initial deployment of the software correlator on a cluster made up of the control computers on the Mark5 playback units on the existing correlator. That deployment will involve integrating the software correlator into the VLBA operational system. After that, increases in sustainable bit rate will be mainly a matter of acquiring more and faster CPU's. Initial development of a 4 Gbps recording system has begun at Haystack Observatory with support from the geodetic community. The items for which funding is requested here build on these activities to take the next major steps towards deployment of a 4 Gbps system, steps that can accomplished over the next approximately 2 years and that should result in a system able to support sustained 1 Gbps operations, assuming enough disks are purchased with other funds. Beyond that, to reach 4 Gbps, funds not requested here will still be required to increase the disk supply, actually deploy the faster recording system, and enhance the computer cluster used by the correlator sufficiently to keep up with the faster bit rate.

4.1: The digital backend to support ≥ 1 GHz. To reach 4 Gbps without using bits inefficiently, at least 1 GHz of analog bandwidth must be sampled (2 bits/4 levels per sample). That is the total bandwidth that is available from each receiver in the analog IF signals sent to the control building from the vertex room at the VLBA stations. Any increase from there would require expensive LO/IF upgrades. The 1 GHz is in the form of 2 IFs of 500 MHz each, one for each polarization. But the rest of the electronics in the control building, including baseband converters, samplers, and formatter, are limited to less bandwidth, so they must be replaced. Following the style of the EVLA and ALMA, all of those devices can be replaced with a single board, containing a large FPGA, on which two 500 MHz IFs are sampled, digitally filtered, and formatted for recording or real time transmission to the correlator. Power and pulse cal detection are also done in the FPGA. A board, called simply the DBE (for Digital Back End), that can accomplish this for 2 IFs is currently well along in development in a joint project between NRAO and Haystack Observatory. The design takes advantage of the expertise acquired in the development of the EVLA. A side benefit of the digital design will be much increased consistency of bandpass shapes and relative phases between basebands, both of which should improve calibration. While both Haystack and NRAO will use the same board, it is likely the FPGA code will be developed independently to meet individual requirements.

A block diagram for a dual-board version of the DBE design under consideration is shown in Figure 2. To support the specifications of the geodetic VLBI2010 project (a world-wide effort to upgrade the geodetic observing systems to a new, far more capable and common design) and to provide room for future bandwidth expansion, each board can process two signals of up to 1 GHz each (in any of the first

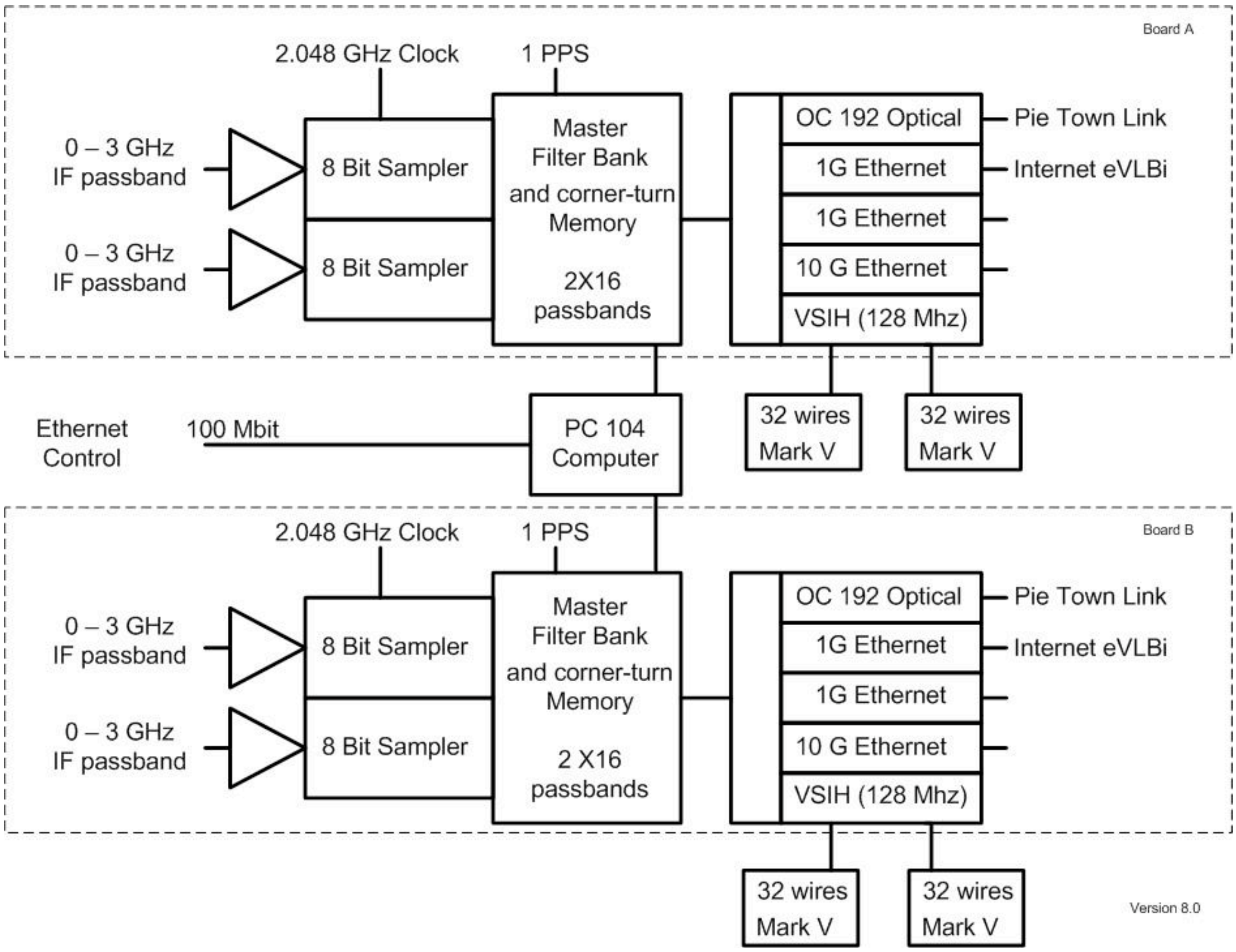

Figure 2: Block diagram of a 2-board DBE system capable of sampling, filtering, and formatting signals from 4 IFs of up to 1 GHz each.

3 Nyquist zones), which is more than the immediate VLBA need in terms of bandwidth. Two boards are required for dual band/dual polarization observations and for VLBI2010 compatibility, but a single board version would meet most VLBA needs. In the VLBA application, without any LO/IF upgrades, the sampler would be clocked at 1024 MHz and the IF would be in the range 512-1024 MHz, which is currently available.

The design of the DBE and the construction of a prototype are being supported with operations funds and should be done by the end of fiscal 2007. It will then be ready to deploy on the VLBA. The costs for the deployment on all 12 antennas (including VLA and GBT), plus spares, were given on the spreadsheets attached to the proposal for 2 options. The costs of the NRE, which are already being spent, are shown but not included in the sums. The preferred option is for the full 2-board, 4 IF system, which costs $362k. The fallback single board system, which covers most immediate VLBA needs, is $234k. These costs include all aspects of the project, including manpower.

Only days before this proposal's due date, Haystack and NRAO learned of a new "iBOB2" board being developed by the CASPER group at UC Berkeley. This board extends the capabilities of the original iBOB, which was used by Haystack for their DBE prototype, and has capabilities similar to the DBE concept described above. It is being developed as a collaboration among a number of radio astronomy organizations, in part to support SKA prototypes, and it may be advantageous to NRAO to join this collaboration. If the iBOB2 design can be completed quickly enough, and for a cost not significantly greater, we may want to use it as the base for the DBE instead of the originally planned EVLA-like board, in the interest of global uniformity.

4.2: The 4 Gbps recording system. The desired recording rate of 4 Gbps is beyond the capacity of any current system. That rate can be recorded using dual Mark5B+ systems, each recording 2 Gbps, although playback is slower in some circumstances. Previous disk-based, wide-band VLBI recording systems have been developed at the Haystack Observatory in collaboration with Conduant Corporation (who make the hardware) and with funding from interested parties globally. Conduant has 4 Gbps systems available already, but they are not configured appropriately for VLBI. Development of a 4 Gbps VLBI system has started at Haystack and Conduant, with support from NASA and USNO, to support the needs of the VLBI2010 project. This system is dubbed "Mark5C". A financial contribution to this project from NRAO would help speed the project and ensure that the VLBA's needs are met. A letter from Alan Whitney, director of Haystack, about the current developments and in support of this proposal is attached.

Since the development of Mark5C is just starting, its cost can only be estimated approximately. Funds will be needed to support the design and testing and for prototype units. The design money will likely support the efforts at Haystack and Conduant. From previous experience with Mark5 development, $100k would be a reasonable amount to support NRAO's share of that development. To interface the system to the VLBA and enable test observations, 4 prototype units would be appropriate, 2 at stations and 2 at the correlator. Without a design, the cost of a prototype can best be estimated by using the cost of a Mark5B+ system, which is $24k. So the total funding requested in this proposal for the recording system is $200k. The plan for the existing Haystack project is to have a prototype operating by the end of 2007 or early 2008. The development will occur at our partner institutions and have little impact on NRAO manpower.

There is much interest and development effort around the world in using real time data transmission over fiber for VLBI (called eVLBI). We will keep an eye on these efforts as an alternative to the recording system. But at this time we do not see a realistic prospect of obtaining access to the required bandwidths at an affordable cost, unlike the situation in Europe where the research networks subsidized by national governments are supporting this work.

4.3: A start on the 4 Gbps correlator. The current 20-station VLBA correlator is limited to 256 Mbps per station without modifications and 512 Mbps per station if the playback interface geared for tape is replaced. A new correlator is required for sustained data rates of 1 Gbps or more. Two options are under consideration. One is to either use extra capacity in the EVLA WIDAR correlator or use separate mini-WIDAR, depending on the final EVLA correlator design. The original EVLA WIDAR design has 32 station inputs but the VLA only has 27 antennas. The extra 5 station inputs could be used as a 20 station, 1 GHz, or 10 station, 4 GHz VLBI correlator. While this proposal was being prepared, the WIDAR designers in Canada suggested a wiring change that would allow the EVLA correlator to have 28 stations. They offered to build, as part of their EVLA contribution, a mini-WIDAR for VLBI that can process 16 stations at 4 GHz. While the hardware, and software common to the EVLA use, would be provided by Canada and the EVLA project, there would still be significant software effort and interface hardware required to use the systems for VLBI.

The second option is to use a software correlator. It is becoming clear that a major paradigm shift for correlators for instruments with limited numbers of stations and/or bandwidth is happening. General purpose computers are becoming fast and cheap enough that software correlators are becoming cost effective. And software correlators are far easier to develop and upgrade and provide far greater flexibility than hardware correlators. The bandwidth and number of stations of the VLBA put it at a size where the choice between a software and a hardware correlator, or even a combination of the two to provide both the desired capacity and range of modes, must be considered very carefully. The rest of this proposal is based on the software correlator option, which appears to be the more attractive. But the requested funding could be used for the VLBI enhancements needed to a WIDAR option if that is chosen after there has been time to consider the mini-WIDAR carefully.

During 2006, the DiFX software correlator[11], developed by Adam Deller at Swinburne University, was comparison tested against a number of other VLBI correlators worldwide, including the VLBA correlator. The results were basically identical, confirming that the software correlator functions properly. That correlator, running on a cluster computer, is now used for production correlation for the Long Baseline Array in Australia. Also the MPIfR is purchasing a cluster computer to allow them to use it for geodetic VLBI and other groups, including Haystack, are considering using it for production and/or for testing correlation methods. In Socorro, DiFX is currently being interfaced to our local operational system. First fringes without Deller's immediate involvement were obtained on April 15, 2007, just before submission of this proposal.

As part of the process of implementing DiFX in Socorro, the CPUs of the computers on the older Mark5 playback units on the current correlator will be upgraded and a switch has been purchased, all with operations funds. The Mark5 units will then provide a low cost “cluster” on which to gain experience with the software correlator and work on streamlining integration with the rest of VLBA operations. But that “cluster” will not be sufficiently powerful to become the production VLBA correlator. One advantage of a software correlator is that the main hardware can be purchased late, when the software is done, and can be brought on-line very quickly. It can also be upgraded easily later. This proposal requests funding for a cluster adequate to allow use of sustained bandwidths of up to 1 Gbps, to be purchased after the software development is done on the Mark5 cluster. By the nature of a software correlator, this machine will allow observations at much wider bandwidths, like 4 Gbps, to be processed, but at slower than real time. For eventual full time 4 Gbps operation, the requested cluster would need to be enhanced significantly, but that is best done later when adequate disks are available and the required computers are even less expensive. Note that, a rough estimate suggests that the cluster required to keep up with observing will cost on the order of a quarter to a half as much as the disk supply required for the same sustained data rate and a reasonable, 1 month cycle time, almost regardless of the data rate. Thus the cluster is never the dominant cost.

Based on benchmarks done by Adam Deller, the DiFX correlator could keep up with sustained 1 Gbps observations if run on a cluster with about 400 typical modern processor cores. With dual and quad cores per CPU and dual CPUs per machine common, this involves a cluster of 50-100 server class PCs, probably configured in 1U racks or blades for use in a cluster. A rough cost estimate for such a machine in April 2007 is around ~$400k plus on the order of $50k for networking etc. The whole cluster would fit in one or two racks and the cooling now available for the VLBA correlator should be more than adequate. Due to the rapid increase in performance per dollar of commodity computers, it would not make sense to purchase the hardware for a production correlator until the software development is done and the other equipment needed for 1 Gbps operation, including disks, are in place or on order. That will likely be 18 or more months from the time of this estimate, about one Moore's law doubling time. Therefore we request $250k for the correlator cluster computer. The consequences of an error in this estimate are low as the number of units purchased can be adjusted easily to match available funds. The only effect is on the sustainable bit rate at an intermediate stage of the overall project to reach 4 Gbps. And once this machine is in production, it will be possible to provide a much more accurate estimate of the cost to reach 4 Gbps. The manpower required to deploy the software correlator will be provided from VLBA operations and scientific staff. If a WIDAR option is chosen, some of the $250k will likely be used for software.

4.4: The 43 GHz LNA upgrade. The low noise amplifiers in use on the VLBA are sufficiently good at most bands that significant improvements would not be available from LNA upgrades. But that is not true at high frequencies. The project in progress to upgrade the 22 GHz receivers is proving highly successful. As of this writing, 2 upgraded receivers have been installed and provide system sensitivities of about 460 Jy (weather dependent – below 400 Jy has been seen), on the order of half of what they were before. It is expected that an LNA upgrade for the 43 GHz receivers would have a similar impact on sensitivity as what has been seen at 22 GHz. Of the science goals mentioned earlier, a 43 GHz upgrade would significantly impact studies of AGN jet launch regions, the kinematics of the Galaxy and the Local Group, the effect of magnetism in stars, and the possibility of observing material orbiting SgrA*.

The 22 GHz project has a budget of about $300k, about evenly split between parts, wages, and new test equipment and is being done in a manner intended to minimize impact on EVLA receiver construction. A project to provide a similar upgrade to the 43 GHz receiver would be very similar in nature and so could follow naturally behind the 22 GHz upgrade, which is expected to finish late in 2007. The cost would be less because the test equipment would still be available. And the timing would be good because the person hired for the 22 GHz project would still be available.

New LNAs using Cryo 3 devices from the Central Development Lab, should be able to improve the receiver temperatures by about 25K. If the 22 GHz project is a guide, other clean-up efforts will provide additional improvements of an unknown amount. Thus we estimate that the new systems will provide an overall improvement, from the current about 100K system temperatures on the sky, of about 30K. It could be considerably more.

As with the 22 GHz project, the upgrade could be done in roughly a year, starting after the 22 GHz project is done. For much of that time, the VLBA would not have 43 GHz receivers on all antennas, but every few weeks there would be an opportunity for 10 station observations. With dynamic scheduling, this should be adequate to support ongoing projects.

A detailed cost estimate for the 43 GHz upgrade, including parts and labor, was attached to the proposal, but is not included in this public memo. It totals $182k.

5: Conclusion.

With this proposal, we request funding for the next major steps in efforts to increase the sensitivity of the VLBA and comply with the recommendations of the Taylor/Lonsdale Committee. There are two separable projects in the proposal, one to take the next major steps toward increasing the bandwidth of the VLBA to 1 GHz (4 Gbps). The other is to upgrade the LNAs in the 43 GHz receivers to significantly increase the sensitivity of the VLBA at the highest frequency, with the highest resolution, at which high quality imaging, phase referencing, and astrometry can be done. The bandwidth increase portion of the project has three parts that can be separated, but all of which are required eventually for a wide band system. They are deployment of a new digital backend, development of a recording system capable of 4 Gbps, and acquisition of a computer cluster for a software correlator. The costs are summarized in Table 1. As an indication of the priority within the VLBA project of the bandwidth upgrade, nearly all funds from the VLBA operations budget that are available for new hardware for the last several years, and until at least 2011, are being used for related equipment including the Mark5 system, disks, DBE and software correlator development, and eventually more disks, new recording system deployment, and the correlator. The GBT settlement money will be a major contributor to the project, but still well under half of the total.

We thank Jim Ulvestad, Claire Chandler, Vivek Dhawan, and Alan Whitney for support and comments on the proposal. The 43 GHz cost spreadsheet was prepared by Charles Kutz, and Bob Hayward and we thank them for the considerable effort involved.

Table 1: Cost summary

Subproject	Cost (Thousand $)
4.1: Deploy DBE – two board option (Up to 4 GHz from 4 IFs)	362
4.1 alt: Deploy DBE – one board option (Up to 2 GHz from 2 IFs)	(234)
4.2: Develop 4 Gbps recording system	200
4.3: Purchase computer cluster for 1 Gbps software correlator	250
4.4: Upgrade 43 GHz low noise amplifiers	182
TOTAL:	994 (866)

REFERENCES:

1: Taylor, G. B. and Lonsdale, C. J. 2004 Aug. 16, *Mapping the Future of VLBI Science in the U.S.* http://www.nrao.edu/VLBIfuture/future.pdf (TLR).

2: Report on the National Science Foundation Division of Astronomical Science Senior Review Committee 2006 Oct. 22. *"FROM THE GROUND UP: BALANCING THE NSF ASTRONOMY PROGRAM"* Can be found at: http://www.nsf.gov/mps/ast/ast_senior_review.jsp.

3: Parra, R. et al. 2007, Ap. J., 659, 314 “The Radio Spectra of the Compact Sources in Arp 220: A Mixed Population of Supernovae and Supernova Remnants”.

4: Neff, S. et al. 2004, Ap. J. 611, 186 “A Supernova Factory in the Merger System Arp 299”.

5: Bower, G. et al. 2006, ApJ., 648, L127 “The Intrinsic Size of Sagittarius A* from 0.35 to 6 cm”.

6: Anderson, J. et al. 2004, ApJ. 603, 42 “Low-Luminosity Active Galactic Nuclei at the Highest Resolution: Jets or Accretion Flows?”.

7: Ulvestad, J. S. and Ho, L. C. 2001, ApJ, 562, L133 “The Origin of Radio Emission in Low-Luminosity Active Galactic Nuclei: Jets, Accretion Flows, or Both?”.

8: Wrobel, J. M. & Ho, L. C. 2006, ApJ, 646, L95 “Radio Emission on Subparsec Scales from the Intermediate-Mass Black Hole in NGC 4395”.

9: Loinard, L. 2006, BAAS, 209, 133.03 “VLBA Determination of the Distance to Taurus and Ophiuchus with 1% Precision”

10: Loeb, A. & Waxman, E. 2007, JCAP03(2007)011 “Properties of the radio-emitting gas around SgrA*”

11: Deller, A. T., Tingay, S. J., Bailes, M. & West, C. 2007, PASP, 119, 318 “DiFX: A Software Correlator for Very Long Baseline Interferometry Using Multiprocessor Computing Environments”.

COST SPREADSHEETS – removed for memo.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

HAYSTACK OBSERVATORY

WESTFORD, MASSACHUSETTS 01886

Telephone: 978-692-4764
Fax: 781-981-0590

15 April 2007

Professor K.Y. Lo
Director, National Radio Astronomy Observatory
520 Edgemont Rd.
Charlottesville, VA 22903
Dear Prof. Lo,

This letter is written at the request of Dr. Craig Walker to explain the role of MIT Haystack Observatory and other institutions in the continuing cooperative development of very-high-data-rate Mark 5 VLBI data systems, and how the proposed contribution to that work by NRAO will aid in achieving the goals outlined in the document "A Proposal to Increase the Sensitivity of the VLBA".

The Mark 5A and Mark 5B disk-based 1Gbps VLBI data systems were developed by Haystack Observatory in collaboration with Conduant Corp. of Longmont, CO with funding support from a broad consortium of international institutions including NRAO. In the four years since Mark 5 was first introduced, more than 150 Mark 5 systems have been deployed globally, replacing nearly all of the world's tape-based systems. A follow-on Mark 5B+ system, capable of recording data at 2Gbps, has been introduced by Haystack Observatory and is now also in routine use.

In October 2006, representatives of the VLBA and Haystack met at Haystack Observatory to discuss possible collaboration on the development of high-performance VLBI back-end and data systems. The result of this meeting was agreement to work together to leverage combined expertise to meet the needs of both organizations at the least cost and on the shortest schedule.

Development work on Mark 5 systems is continuing at both Haystack Observatory and Conduant Corporation. Current work includes modernization and extension of the capabilities of existing Mark 5 systems supported by NASA, USNO and JIVE, as well as modest NRAO support for NRAO-specific support and maintenance work. Extension of the Mark 5 system to 4Gbps (dubbed Mark 5C') has been started with funding from NASA and USNO in support of the geodetic 'VLBI2010' program. Collaborative funding support to Haystack Observatory from NRAO to aid in this effort would help to both speed this development effort as well as ensure that the VLBA's needs are met.

Sincerely,

Alan Whitney
Interim Director
MIT Haystack Observatory

P.S. I apologize that, due to the very short notice regarding the submission of this letter, that it was impossible to solicit letters of support for this VLBA upgrade proposal from NASA, USNO or JIVE. I am confident such letters would be forthcoming if solicited.