Proposal for a Cost-Effective Doubling of Existing VLBI Sensitivity

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Abstract: Continued sustained progress in both astronomical and geodetic VLBI efforts demands ever-increasing sensitivity. Recent demonstrations of the feasibility of a fourfold increase in VLBA/Mark IIIA data recording rates to the order of 1-Gbit/sec demonstrate the cost effectiveness of this approach to doubling existing VLBI sensitivity. Such a sensitivity increase could be crucially important for some proposed geodetic programs using small transportable antennas over long baselines. A proposal is presented to upgrade existing Mark IIIA data-acquisition systems to this quadrupled bit rate at an estimated cost of $60K/system. A similar upgrade is also possible for the VLBA recorders. A phased approach starting with prototype development and testing is outlined here. The consequences of this upgrade on necessary correlator capability are also examined. A coordinated multi-agency effort could prove very effective in fully implementing the proposed program at a modest cost and maintain preeminence in critical VLBI technology.

1 Introduction

The progress of VLBI over the last decade has been truly dramatic. Following is a partial list of a few of the many advances that have been made:

- In astronomy-related research, the list of VLBI researchers and their accomplishments continue to grow:
  - VLBI observing frequencies have been pushed ever higher – observations at 100 GHZ ($\lambda = 3mm$) are now fairly commonplace, resulting in angular resolutions of better than 100 microarcseconds. This is the highest resolution ever achieved by any technique in astronomy or any other science.
  - High-precision VLBI phase information has allowed multi-hour phase-coherent integrations using a strong nearby source as a reference. Such observations have been used to probe at the very limits of sensitivity for the existence of extremely faint objects, such as the multiple images of gravitational lenses and faint signals from multiple-body objects.
  - Phase-referenced astrometry observations have allowed differential positions of closely-spaced objects to be measured to microarcseconds, allowing the dissection of the absolute motions of components of complex superluminal objects.

- In geodetic VLBI, the advances have been equally dramatic:
  - Distances between radio telescopes spread widely over the world are routinely measured to the order of 1 cm, meeting and exceeding the stated goals of the NASA Crustal Dynamics Project. As a result, the motion of tectonic plates, typically a few cm/year, has been measured directly for the first time, and a new goal of mm-level measurements has been set.
  - Specially-instrumented and conducted R&D experiments in the fall of 1989 showed measurement precision and repeatability of ~3 mm on baselines thousands of kilometers in length.
  - VLBI routinely provides the primary information for measurement of the earth's rotation rate and spin-axis orientation.
- The first demonstrations of space-based VLBI, which has spurred the planning of dedicated VLBI observatories in space to be launched in the 90's.
- Funding and construction of the world's first large-scale dedicated VLBI array, the VLBA, to be completed in the mid-90's

These advances have been largely fueled by a broad spectrum of technological advances. Among these are:

- Routine use of the Mark III system beginning in the early eighties increased the recording bandwidth of VLBI data from 4 Mbits/sec of the Mark II system to more than 200 MBits/sec, improving the basic sensitivity of continuum observations by more than a factor of 7.
- Development of the Mark III and Mark IIIA correlators have allowed unprecedented volumes of VLBI to be routinely processed. In the ten years from 1980, an estimated 3 million observations have been processed.
- Improved receiver systems with lower noise and wider-bandwidths
- Improved phase-calibration systems and cable-calibration systems to remove small instrumental effects
- Improved data-analysis techniques and software

Though the advances both scientifically and technologically have been impressive, there is still much room for growth. In this paper, we will attempt to lay a sound plan for cost-effective continued growth in VLBI technology in the 90's based on the clear demands of the scientific users.

2 The Need for Greater Sensitivity

As scientists continue to pursue VLBI science, whether astronomy or geodesy, there is one common clear demand from virtually all quarters - **more sensitivity**. Virtually all of the major advances in VLBI noted above have depended on improved sensitivity, and several couldn't have been even contemplated without it. The demands for more even more sensitivity are clear:

- In astronomy:
  - With longer baselines and higher observing frequencies, scientists are able to probe ever deeper into the central engines of energetic radio sources. However, at the same time, the strength of the radio signals decrease radically, often below current levels of detectability.
  - Phase-referenced observations are often hampered by the lack of suitable strong nearby reference sources. Improved system sensitivity vastly increases the number of potential reference sources.
  - Because the size of VLBI antennas on orbiting spacecraft is severely constrained, sensitivity is of paramount importance.
  - Due to budget constraints, the VLBA has been constrained to an antenna diameter of 25 meters and has been criticized in some quarters for its relative lack of senstivity. A major sensitivity boost for this instrument would substantially increase its scientific usefulness.
- In geodesy:
  - The push to mm-level baseline accuracy demanded by the scientific community requires observing strategies which currently are marginally acceptable, specifically that many radio sources spread over large angles in the sky be observed in quick succession. With more sensitivity, the choices for observing strategy significantly broaden:
    - schedules can be utilized which use smaller antennas moving more quickly around the sky
    - 'on-source' time can be reduced significantly to achieve the same signal-to-noise ratios, also achieving the ability to cover more sky in a given time
    - weaker sources may be utilized for better distribution across the sky

3 The Means To Greater Sensitivity

VLBI sensitivity may, in general, be increased in only three ways:

- Increase antenna size. For any given observation, the signal-to-noise ratio increases directly as the geometic mean of the effective collecting area.
- Lower receiver noise. For any given weak-signal observation, the signal-to-noise ratio improves inversely to the geometric mean of the receiver temperatures.
- Increase bit-rate on tape. The signal-to-noise ratio improves essentially as the square root of the bit rate. Actual recorded bandwidth may be traded off against #bits/sample, but the SNR remains basically the same for a given bit rate on tape for either the cases of 1 or 2 bits/sample.

In the case of geodesy, the measurement precision of group delay is also related to the total *spanned* bandwidth as well as the signal-to-noise ratio. Recent experiments have pushed the spanned-bandwidth of geodetic measurements to 10% of the observing frequency, which is approaching the practical limit.

4 The Case for Increasing Recorded Bit Rate

Of the three possible options to increase sensitivity, it is our contention that increasing recorded bit rate is the most cost effective in the current climate of VLBI technology. The reasons are as follows:

- A recent demonstration has been made at Haystack of a 1 Gbit/sec recording capability. This was done by simply adding headstacks to existing unused positions on the tape transport and then driving all heads simultaneously. The maximum bit rate was increased a factor of fourfold from 256 Mbits/sec to 1024 Mbits/sec, increasing the overall fundamental sensitivity by a factor of 2. No new technology is involved.

- General consensus is that antenna costs increase roughly as the cube of the diameter. Even for small antennas, the cost of increasing the diameter by a factor of $\sqrt{2}$ is likely to be in excess of $100K, and often impossible for transportable systems; for large antennas, it is completely uneconomical. For an SNR improvement of 2, the diameter of *both* antennas of a baseline must be increased by $\sqrt{2}$ in diameter, or a single antenna by a factor of 2. Also, additional costs must normally be incurred to make larger antennas slew with sufficient rate to support geodetic/astrometic schedules.

- Although receiver technology continues to improve, practical limits are being reached, particularly in wavelengths in the cm range. In any case, all VLBI receivers at *every* frequency would have to be improved by a large margin to gain the same benefit that increased bit-rate-to-tape will gain automatically for *all* frequencies.

Of course, increasing bit rate on tape also imposes additional loads on correlators, which must also be taken into account. As a rule of thumb, correlators have been designed for a given total bit-rate throughput, so that increasing that data rate by a factor of 4 will in general cause the data throughput rate of a given correlator to drop by the same factor. Nevertheless, although it will be necessary to increase correlator capacity in order to keep up with an increased data rate, such correlator costs are virtually guaranteed to be smaller than the alternatives to gain the same basic sensitivity.

5 The 1-Gbit/sec Feasibility Demonstration

The VLBA recorder normally operates with a single headstack with a maximum formatted data rate of 256 Mbits/sec. However, the transport has positions for up to four headstacks, three of which are vacant for a standard VLBA recorder. For a special feasibility demonstration of very-high-data-rate recording, a standard VLBA tape recorder was outfitted with four standard headstacks to occupy all headstack-positions available on the Honeywell 96 tape transport. A standard VLBA formatter was used to drive the 36 tracks on each headstack at a bit rate of 9 Mbits/sec/track for a total of 1.296 Gbits/sec total data rate. With the normal formatting overhead of $\frac{9}{8}$, this corresponds to a 1.152 Gbits/sec data rate for formatted VLBI data. Data were recorded for several adjacent passes on the tape to simulate a portion of an actual experiment. For compatibility with the Mark IIIA correlator, data was recorded in Mark IIIA format at 33,000 bits/inch along each track.

Following recording of the data, the Mark IIIA correlator at Haystack was used to auto-correlate the recorded tape (in several passes) to verify the quality and validity of the data. All data were read properly and the processing through the correlator produced nominal results.

6 A Specific Proposal

Over the past dozen or so years, over 35 Mark III and Mark IIIA data-recording systems have been installed around the world, becoming the true worldwide work-horse VLBI data-acquisition system. Most of the original Mark III systems have now been upgraded to the high-density Mark IIIA system, which provides for much higher-density recording but does not increase the maximum (formatted) recording-rate capability of 224 Mbits/sec. Due to this large installed base of Mark IIIA equipment, we feel it is worthwhile to consider significantly upgrading its capability in data-recording rate. Such a proposal must also explore the resulting impact on correlator systems and examine compatibility with other existing systems. In the following sections, we propose a specific upgrade path for the Mark IIIA recording system, correlator development work, and examine the compatibility issues. A similar path exists for the VLBA recorder, 12 of which have already been constructed by Haystack, and an additional 8 are in process this year.

6.1 Mark IIIA Upgrade to 896 Mbits/sec Data Rate

The Mark IIIA and VLBA recording systems use exactly the same Honeywell tape transport and headstack assembly; therefore, the Mark IIIA data recording system may be upgraded in a similar fashion to that demonstrated in the 1-Gbit/sec demonstration, provided the necessary formatter and write electronics are provided.

The standard Mark IIIA data-acquisition-system configuration provides 14 video converters, each with independent upper and lower-sideband channels of 4 MHz bandwidth maximum each, for a total maximum bandwidth of 112 MHz. The existing formatter provides 28 channels of data at 1-bit/sample, at a maximum sample rate of 8 Mbits/sec/channel, for a total maximum date rate of 224 Mbits/sec. Two identical standard high-density headstacks are mounted in the Mark IIIA recorder, one headstack dedicated to writing and the other to reading. Of the 36 tracks available in each headstack, only 28 are used by the Mark IIIA system, each track independently carrying data from a single video-converter sideband.

The following actions will be necessary to increase the maximum data rate of the Mark IIIA to 896 Mbits/sec (factor of 4 increase):

- Increase the maximum bandwidth of a video-converter sideband to 8 MHz by replacing one of the existing unused (or seldom-used) internal filters with an 8 MHz filter and changing the gain-compensation resistors.
- Design a new formatter with the following characteristics -
  - Plug-in replacement for existing formatter
  - 28 channels @ 16 Msamples/sec (and lower rates)
  - 1 or 2 bits/sample
  - channel-to-head cross-point matrix switch

- Replace existing write interfaces with VLBA read/write interface which uses same head for read and write
- Use both existing headstacks for both reading and writing, for a total of 56 available tracks
- Add necessary write electronics to support 56 heads

The **Mark IIIB** system will have the following characteristics:

- 56 tracks at 16 Mbits/sec/track for a total of **896 Mbits/sec formatted data**
- Will use the same 16 micron-thick tape chosen by the VLBA:
  - 18000' of tape on standard 14" reel
  - longitudinal density: 56,000 bits/inch/track
  - tape speed: 320 ips (16 Mbits/sec/track)
  - record time per pass: 11.25 minutes
  - record time per tape (6 passes): 67.5 minutes
- **~95% SNR improvement** over present maximum-data-rate Mark IIIA
- Full backward compatibility to all standard Mark IIIA operating modes, as well as compatibility with as many VLBA modes as possible

Based on current projections, the estimated **upgrade cost per Mark IIIA system is ~$60K**, broken down as follows:

- New formatter – $10K
- 8 MHz filters (28 per system) – $2K
- New read/write interfaces – $2K
- Extra write electronics – $1K
- Labor and overhead (based on 3 x M&S) – $45K

The only major new design work necessary for the upgrade to Mark IIIB is the new formatter, which is estimated to require ~2 man-years of engineering time. In the new formatter design we expect to also support many of the VLBA data-multiplexing modes currently unsupported by the Mark IIIA system, although we do not propose to support the 'non-data-replacement' tape format which is supported by the VLBA formatter.

6.2 Correlator Impacts

The Mark IIIB system proposed above will basically create data in the same Mark IIIA tape format that has been supported by correlators for some years. In fact, the existing Haystack correlator (designated 'Mark IIIA', but not to be confused with the Mark IIIA recording system) or the VLBA correlator could process the data from the Mark IIIB recording system, but would require several times as long. This is clearly impractical given the established observation rates of both astronomers and geodesists. Therefore, we consider here a correlator design that can properly complement the Mark IIIB recording system. Similar capabilities could be adapted to the VLBA correlator.

Based on the requirements for processing data from the Mark IIIB recording system, a correlator with the following major characteristics is being constructed for USNO applications, through NASA:

- Utilize the same basic 'baseline' architecture of the existing highly-successful Haystack VLBI correlators

- Adopt the same basic playback machine design developed by Haystack for the VLBA. This playback machine will support tape-playback speeds to 320 ips, compared with the existing 135 ips of the current playback machines.

- New 'correlator modules' are being designed based on the highly-successful 'Bos' correlator chip designed by Albert Bos of the Netherlands Foundation for Radio Astronomy. Module cost is expected to be significantly lower than current module by incorporating modern gate arrays, semi-custom IC's, and microprocessors.

- Improved modelling capabilities to reduce possibilities of systematic errors

- Operation at data rates up to 32 Mbits/sec

- Compatibility with Mark IIIA, Mark IIIB, and some VLBA-format modes

- Significantly-improved computer support utilizing the Unix operating system on a modern platform

- Full real-time capability integrated into the design in anticipation of real-time VLBI processing in the future

- Improved hardware reliability and ease of maintenance

This correlator has been dubbed '**Mark IV**', following the tradition of imaginative designations bestowed upon its predecessors.

A new correlator module of advanced design will form the heart of the Mark IV correlator. The overall processing capability of the Mark IV module is expected to exceed the present Haystack correlator module by roughly a factor of 8, where processing capability is defined as (max-bit-rate)x(number lags)/unit-cost. The module will be mated to a standard VME-based backplane, which provides a standardized I/O system with high-speed data capability, and the ability to use standardized low-cost in-crate processors for real-time control. An on-board microprocessor, probably of the Motorola 68000 series, will provide the power for intelligent decision-making and real-time computational tasks. The decoder portion of the module will make use of a Xilinx programmable-gate-array chip, performing the same function of approximately 30 MSI chips on the Mark IIIA corrlelator module.

The Mark IV correlator control computer will be significantly upgraded to a modern Unix-based system, which will connect through a high-speed interface to the VME single-board computers, which will in turn communicate with the Mark IV modules.

As a first step in this direction, we propose to use the existing Haystack correlator as a software development platform for the Mark IV system. This will allow us to replace and upgrade the aging

Hewlett-Packard 1000 machines that control the current correlator and allow the development of software to support the Mark IV at the same time.

Some VLBA-compatible modes will be supported by the Mark IV correlator; further cost analysis remains to be carried out to identify which modes can be economically supported. In any case, the VLBA data-acquisition system is capable of writing data which can be processed by the Mark IV correlator system. Some of these compatibility issues will be addressed in the next section.

6.3 Compatibility Issues

The subject of compatibility between various VLBI data-acquisition system and correlators is a very complex one. In this section we will only attempt to summarize the salient similarities and differences of the various systems; a complete discussion is beyond the scope of this document.

6.3.1 Data-Acquisition Systems

The major differences between the Mark IIIA, proposed Mark IIIB, and VLBA system can be summarized as follows:

- the Mark IIIA has 14 video converters, each with a maximum bandwidth of 4 MHz/sideband, supports only 1 bit/sample, data-replacement format only, and maps data from one VC sideband to one tape-track (i.e. no data-multiplexing or 'barrel-rolling'), with a maximum data rate of 224 Mbits/sec on 28 tracks

- the Mark IIIB has 14 video converters, each with a maximum bandwidth of 8 MHz/sideband, supports 1 or 2 bits/sample, data-replacement format only, support several modes of multiplexing, with a maximum data rate of 896 Mbits/sec on 56 tracks

- a single standard VLBA data-acquisition system has 8 video converters, each with a maximum bandwidth of 16 MHz/sideband, supports 1 or 2 bits/sample, data-replacement or non-data-replacement format, many mode of multiplexing and barrel-rolling, with a maximum data rate of 256 Mbits/sec on 32 tracks; each VLBA station will (eventually) be equipped with 2 standard VLBA DAS's; on special order, a VLBA DAS may be equipped with 14 VC's

Table I shows a simple comparison of the data-recording capabilities of the Mark IIIA, the Mark IIIB, and VLBA data-acquisition systems. The major differences to note are numbers of channels and channel bandwidths. As you can see from an examination of Table I, there are many compatible modes between Mark IIIB and VLBA, though the reader is referred to official VLBA documentation for a complete discussion of the capabilities of the VLBA DAS.

6.3.2 Correlators

The issue of correlator compatibility with various recording systems and modes is no less complex and we cannot address all the issues here. The correlators at Haystack and their twins at USNO in Washington and Bonn, W. Germany, were designed to be a good match to the Mark III and Mark IIIA data-acquisition systems, while the VLBA correlator is being designed to be a good match to the VLBA DAS. The primary differences between the Mark IIIA, the proposed Mark IV correlator, and the VLBA correlator can be summarized as follows:

- the Mark IIIA and Mark IV correlators use a so-called 'XF' algorithm (cross-correlation followed by Fourier transform) while the VLBA correlator has adopted an 'FX' algorithm
- the Mark IIIA correlator, in its present form, supports 5-stations of 14-channel data, expandable to a maximum of 8 stations; the Mark IV correlator will support a maximum of 16 stations with 14 channels/station; the VLBA correlator will support a maximum of 20 stations with 8 channels/station
- the Mark IIIA correlator is compatible only with a 'data-replacement' tape format; the Mark IV and VLBA correlators will support either 'data-replacement' or 'non-data-replacement' modes
- the Mark IIIA correlator supports only non-multiplexed tape modes; the Mark IV correlator will support non-multiplexed and some multiplexed tape modes; the VLBA correlator will accept many multiplexed modes
- the VLBA correlator will support some special 'Mark III compatibility modes' where the number of Mark IIIA channels is greater than the number of VLBA channels, provided the Mark IIIA channels are adjacent in RF frequency; see official VLBA documentation for further explanations

Again, the issue is a complex one, and observations which use mixed systems must be carefully thought through ahead of time to insure compatibility with the target correlator.

7 Longer-term Possibilities

We would like to bring to your attention several possibilities for longer-term investigations:

- The proposed Mark IIIB system uses only two of the available four headstack positions on the Honeywell tape transport. Filling those two positions along with the necessary support electronics would raise the data rate another factor of two to 1.792 Gbits/sec. This would be a more major upgrade than from the Mark IIIA to Mark IIIB, but is perfectly feasible.
- Investigate the feasibility of metal-in-gap heads in place of the existing ferrite heads. The following potential benefits are offered:
  - will allow use of modern metal-evaporated-tape (MET) with 7-8 db SNR improvement using current linear bit densities and track widths
  - should allow linear density on tape to be extended to ~100,000 bits/inch/track (current consumer 8-mm video high-band system using MET operates at an analog equivalent of ~100,000 bits/inch with a 10μm track width at 150 ips); the VLBA and proposed Mark IIIB DAS's operate at 56,000 bits/inch with a 40μm track width.
  - at a bit density of ~100,000 bits/inch/track, the data rate on a single track can be increased another factor of 2 to 32 Mbits/sec/track. With four 36-track headstacks operating at 32 Mbit/sec/head, the potential data-recording rate rises to more than than 4 Gbits/sec.

- tape thickness may be reduced to a little as 4μm to increase tape volume density by a factor of 4 over VLBA and Mark IIIB recording systems
- recording time per tape for the proposed Mark IIIB system operating at 896 Mbits/sec would increase to ~8 hours

- The VLBA data-acquisition system has been designed to be modularly expandable in the future to a maximum data rate of 1.024 Gbits/sec on a single recorder by adding additional headstacks, write modules, and formatter modules. With a new formatter capable of generating 16 Mbits/sec/head formatted data, the maximum data rate for a single VLBA recorder could be extended to more than 2 Gbits/sec.

8 Proposed Plan of Action

A straightforward, two-step plan is suggested for implementation of the Mark IIIB recording system:

1. **Build a prototype system and test in a real VLBI experiment.** A new formatter will be designed, and two existing Mark IIIA systems will be fully upgraded to Mark IIIB capability. A 'full-up' test experiment then will be conducted between two sites and the data processed on the correlator at Haystack Observatory. Estimated cost for this development and test effort is ~\$500K over two years. Multi-agency support is proposed to make this development cost effective for all applications.

2. **Develop a kit for upgrade from Mark IIIA to Mark IIIB.** As in the past, Haystack will transfer the Mark IIIB design to other interested colleagues in the U.S. and around the world, as well as to industry. Replication of the upgrade kit can be made by all interested parties.

This strategy has proven effective in the past for several major VLBI sub-systems, and should prove equally effective in this case.

9 Summary

The path to a doubling of VLBI sensitivity is clear, surprisingly straightforward, and modest in cost. No new technology is required for the proposed upgrade of existing Mark IIIA recording rates from 224 Mbits/sec to 896 Mbits/sec, at an estimated cost of ~\$60K per system.

A correlator of straightforward design, based on an existing well-proven architecture, can handle the vastly-increased data rates, although existing correlator systems could process this data at slow rates.

Since the usage of many VLBI systems is already shared between several agencies, a coordinated multi-agency program of support for the proposed upgrades would mutually benefit all, at a modest cost to each. Furthermore, such a technology development would assure continued preeminence in an increasingly-competitive VLBI world.

DAS CAPABILITY COMPARISON

		Mark IIIA		Mark IIIB		VLBA*	
		# chans	Mb/s	# chans	Mb/s	# chans	Mb/s
4 Msamples/sec	1 bit	14x2	112	14x2	112	14x2	112
	2 bit	-	-	14x2	224	14x2	224
8 Msamples/sec	1 bit	14x2	224	14x2	224	14x2	224
	2 bit	-	-	14x2	448	14x1	224
16 Msamples/sec	1 bit	-	-	14x2	448	14x1	224
	2 bit	-	-	14x2	896	8x1	256
32 Msamples/sec	1 bit	-	-	-	-	8x1	256
	2 bit	-	-	-	-	4x1	256

*Augmented to 14 video converters; standard VLBA system has only 8.

TABLE I