VLBA Sensitivity Upgrade Memo 46

VLBA at 4 Gbps Using Dual Mark5C Recorders

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5 July 2016

Abstract This memo describes the first test observations made at VLBA antennas at 4 Gbps (1 GHz of single-polarization bandwidth at 2-bit quantization) recorded data rate. This was performd through use of two Mark5C units each running at 2 Gbps. Execution of these tests required intervention as some required capabilities are not yet available in the production environment. An assessment of the effort required to fully operationalize this 4 Gbps capability is made. Alternatives to the dual Mark5C that would allow 4 Gbps or greater recording capacity are briefly noted. This document is in support of NRAO Program Management Project 430.

1 Motivation

Very Long Baseline Interferometry (VLBI) has always been sensitivity starved making increased bandwidth a very attractive option for upgrades to existing VLBI infrastructure. In addition to reducing required time on source, an increased bandwidth can enable crucial calibrations that may not be otherwise possible. The room for and benefits from bandwidth expansion are arguably greatest at the highest observing frequencies where many factors conspire to challenge the observer. At the time of writing, high frequency VLBI, specifically at 3mm and 1.3mm wavelengths, is being revitalized by the expansion of the Global VLBI Millimeter Array (GMVA) and the creation of the Event Horizon Telescope (EHT). Recent enhancements to these networks include phased-ALMA, the Large Millimeter Telescope (LMT), the NOrthern Extended Millimeter Array (NOEMA), and introduction of 3mm observing capability at the Green Bank Telescope (GBT).

2 Test observations

Two test observations were executed as described below.

2.1 Mauna Kea and Pie Town

A first test, T4G01B, made use of the dual-recorders already situated at Mauna Kea (MK) and Pie Town (PT) on 2016 Apr. 21. Normally the second recorders at these two sites are only used for USNO daily observations, however, they are installed in a manner that allows for flexibility in their use. Calibrator source 3C345 was observed at C-band. A schedule file was prepared using the existing version 11.4 `sched` program. The schedule was generated for a regular PFB-style observation with sixteen 32 MHz channels with signed-sum of local oscillators (SSLOs) at −4192, −4256, −4320, −4384, −4448, −4512, −4576, −4608, 7392, 7424, 7488, 7552, 7616, 7680, 7744, 7776 MHz with negative values indicating lower sideband. These channels represent a somewhat random sampling of two right circular polarization IFs with frequency ranges of 4112-4624 MHz and 7376-7888 MHz respectively. A `.vex` file was produced by running `sched`. In the current operational environment, observations using the PFB personality configure a single RDBE and a single Mark5C. The `vex2script` program, which is responsible for translating the `.vex` file into python language (`.py`) control files that the `Executor` processes was modified to generate instructions for two RDBEs and two Mark5C recorders. The first RDBE and Mark5C are configured as per standard operation. In this configuration 16 of the 32 internally generated PFB channels are selected for recording. The second RDBE and Mark5C are configured in exactly the same way, except the channel selection is inverted; that is, the second RDBE is programmed to produce channels with the following SSLOs: −4640, −4544, −4480, −4416, −4480, −4416, −4352, −4288, −4224, −4160, 7360, 7456, 7520, 7584, 7648, 7712, 7080, and 7840 MHz. The T450 matrix switch was commanded to deliver duplicates of the same IF inputs to the second RDBE.

Finally the "X-cube" software-defined Ethernet switch was manually reconfigured. Normally this device receives packets from both RDBEs and sends copies of both to each of two outputs which are connected to the Mark5C recorders. A non-standard configuration where no packet duplication is performed and each Mark5C receives packets from a unique RDBE was commanded by hand (and reversed after the observation). Figures 1 and 2 illustrate the configuration of the back-end electronics as configured by the standard 2 Gbps configuration and the 4 Gbps configuration.

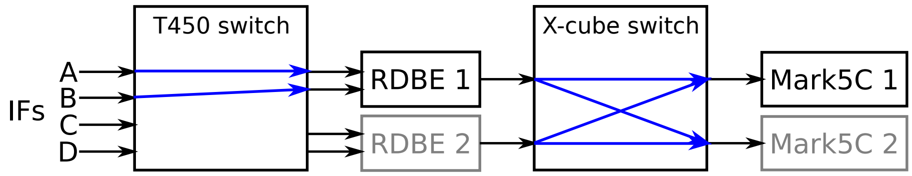

Figure 1: *The backend equipment (switches, RDBEs and recorders) as would be configured for 2 Gbps operation as defined by* `t4g01b.vex`. The greyed-out hardware is not configured. By default all data is routed from both RDBEs to both Mark5C recorders.

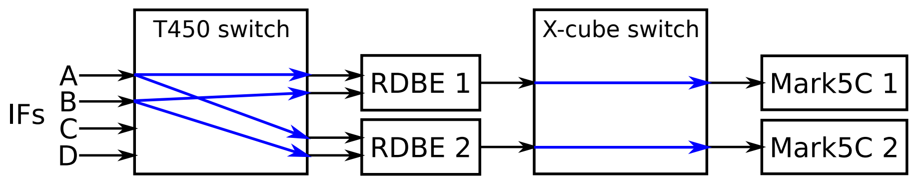

Figure 2: *The backend equipment as configured for the 4 Gbps operation.* A non-standard routing of the X-cube switch is used.

Correlation of the recorded data did not require any changes to the current development version of DiFX. The most recent stable release, 2.4.2, does not yet support multiple datastreams per antenna, but that support is fairly mature in the development version which is slated to become stable version 2.5 in the next couple months. The `.vex` file used as the primary configuration input to the correlator needed to be hand edited to reflect the actual channels that were observed. This involved adding sixteen channel entries to the `FREQ` and `BBC` blocks. The `vex2difx` configuration file (the `.v2d` file) used is shown in Code sample 1. 10 seconds of data was electronically transferred from the stations to the VLBA correlator immediately after the experiment finished observing. Figure 3 shows the visibility spectra for all 32 recorded channels.

One unexpected discovery from this test is that one of the stations' cable pairs from the X-cube switch to the recorders was crossed. For regular observing this cross makes no difference but for 4 Gbps recording it swaps the contents of the two modules. No action will be taken to correct this at this time.

2.2 Four station test

A special test observation followed the May GMVA session. `T161C` observed on 23 May 2016 using a setup very similar to T4G01B. This observation observed 3C345 at 86 GHz. 4 stations, Fort Davis (FD), Los Alamos (LA), MK and PT were outfitted with dual Mark5C recorders. Other VLBA antennas observed with a 2 Gbps subset of this. Most GMVA antennas observed as well using a variety of frequency setups. As of this memo this test has not been correlated so results are not fully known. Two of the VLBA antennas (MK and PT) only recorded on the first Mark5C, but the other two (FD and LA) appeared to have recorded properly. The reason for the recording failure is not known.

Code sample 1 *Listing of the* `.v2d` *file used to correlate* `T4G01B`. Please visit `http://www.atnf.csiro.au/vlbi/dokuwiki/doku.php/difx/vex2difx` for an explanation.

```
vex=t4g01b.vex.obs
antennas=MK,PT                        singleScan=true
machines=swc000,swc001,swc002,swc003  nCore=3  nThread=4

SOURCE 3C345 { calCode=V }

DATASTREAM MK1 { filelist=mk1.filelist  machine=swc000 }
DATASTREAM MK2 { filelist=mk2.filelist  machine=swc000 }

DATASTREAM PT1 { filelist=pt1.filelist  machine=swc000 }
DATASTREAM PT2 { filelist=pt2.filelist  machine=swc000 }

ANTENNA MK { toneSelection=smart  datastreams=MK1,MK2 }
ANTENNA PT { toneSelection=smart  datastreams=PT1,PT2 }

SETUP default
{
  tInt=1.0        fftSpecRes=0.125  specRes=0.125
  doPolar=False   maxNSBetweenACAvg=2000000
}
```

3 Changes required for operations

The two tests proved useful in identifying the full scope of work to realize an operational 4 Gbps observing system based on a pair of Mark5C recorders at each station. In the sections that follow descriptions of infrastructure improvements and tasks are described. The changes would result in a fully operational system that supports 4 Gbps observing using either the PFB or DDC personalities. Cost estimates will be maintained in a separate document with limited distribution[1].

3.1 Infrastructure improvements

Figure 4 shows a layout of the rack hosting the back-end electronics. See the caption for some deviations from the drawing which predates the completion of the Sensitivity Upgrade.

3.1.1 Recorders

Each of the ten VLBA antennas require a second recorder for a complete deployment. Two stations (MK and PT) already have a second recorder (installed for USNO observing). Two additional stations were outfitted with a second recorder for the second test. In these cases, old VLBA Mark5A units were augmented with Amazon cards contributed by the Max Planck Institute for Radioastronomy (MPIfR). Six additional complete recorders will need to be acquired. Each recorder will require a CX4 cable to carry 10 GbE into the Amazon card, a twisted pair cable for control interface and a power cable.

A procedure to verify correct cabling of all 10 GbE connections of the X-cube switch will need to be developed to ensure no cable-crossing.

[1]Documents related to this project can be found in NRAO Sharepoint under PMD project 430. This cost estimation document will be stored there when it is complete. Access to NRAO Sharepoint is restricted.

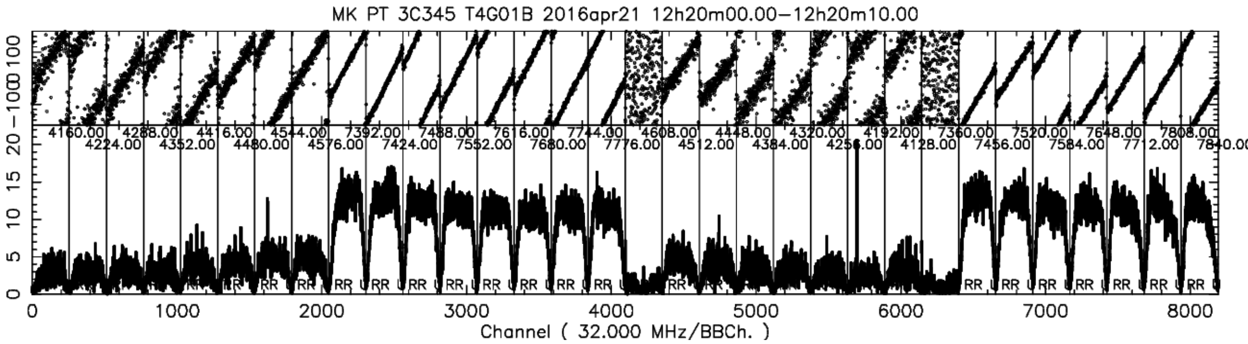

Figure 3: *32 base-band channels, each 32 MHz wide, correlated on the Pie Town to Mauna Kea baseline.* The top panel shows phase as a function of frequency, with the slope indicating a typical residual delay (approx. 20 ns). The bottom panel shows amplitudes which vary due to the structure of 3C345 as a function of baseline length (measured in wavelengths) which span nearly a factor of two across the observing bands (4160 to 7840 MHz). Note channels are not in a natural frequency order. The first 16 channels are those produced by RDBE 1 and the last 16 channels were produced by RDBE 2. Two "non-channels" (17th and 25th) provide no useful data due to the chosen FFT algorithm used in the PFB personality.

3.1.2 Power

The Power Distribution Unit (PDU) is rated at 20A and supplies power to 8 sockets. A additional recorder with up to 18 additional spinning hard drives has been demonstrated to fit within this power budget, but only marginally and with insuffcient headroom for comfort. A replacement with capacity of 30A and 16 sockets has been identified. Since MK and PT are already outfitted with sufficient power capacity in support of the USNO observations only 8 sites need this upgrade.

Most VLBA sites are still operating on a 6kVA UPS. The site power load has been steadily creeping upwards over time to the point that these UPSs are being stressed out. A long term program is underway to replace these with 10kVA units.

3.1.3 Network

Eight sites (all except MK and PT) will require a switch with more than 8 port to replace the FS709. The replacement switch should handle at least 1 Gbps for future upgradability and compatibility with high speed external fiber access. Replacement switches have already been procured for 5 sites in anticipation of supporting high-speed external networking. This leaves a purchase of three more sets (and a spare), plus switch installation at 8 sites to be done.

3.2 Software updates

Several pieces of software will need enhancements to support the 4 Gbps mode in an operational sense. Each piece of software is briefly described below. Figures 5, 6, and 7 illustrate where each piece of software fits into the overall VLBA system.

3.2.1 sched

`sched` is the primary software used by VLBA users to develop observing schedules and the `.vex` file which is used to configure the back-end electronics. It enforces the constraints of the VLBA and will limit observing configurations accordingly. Changes to `sched` would include the following:

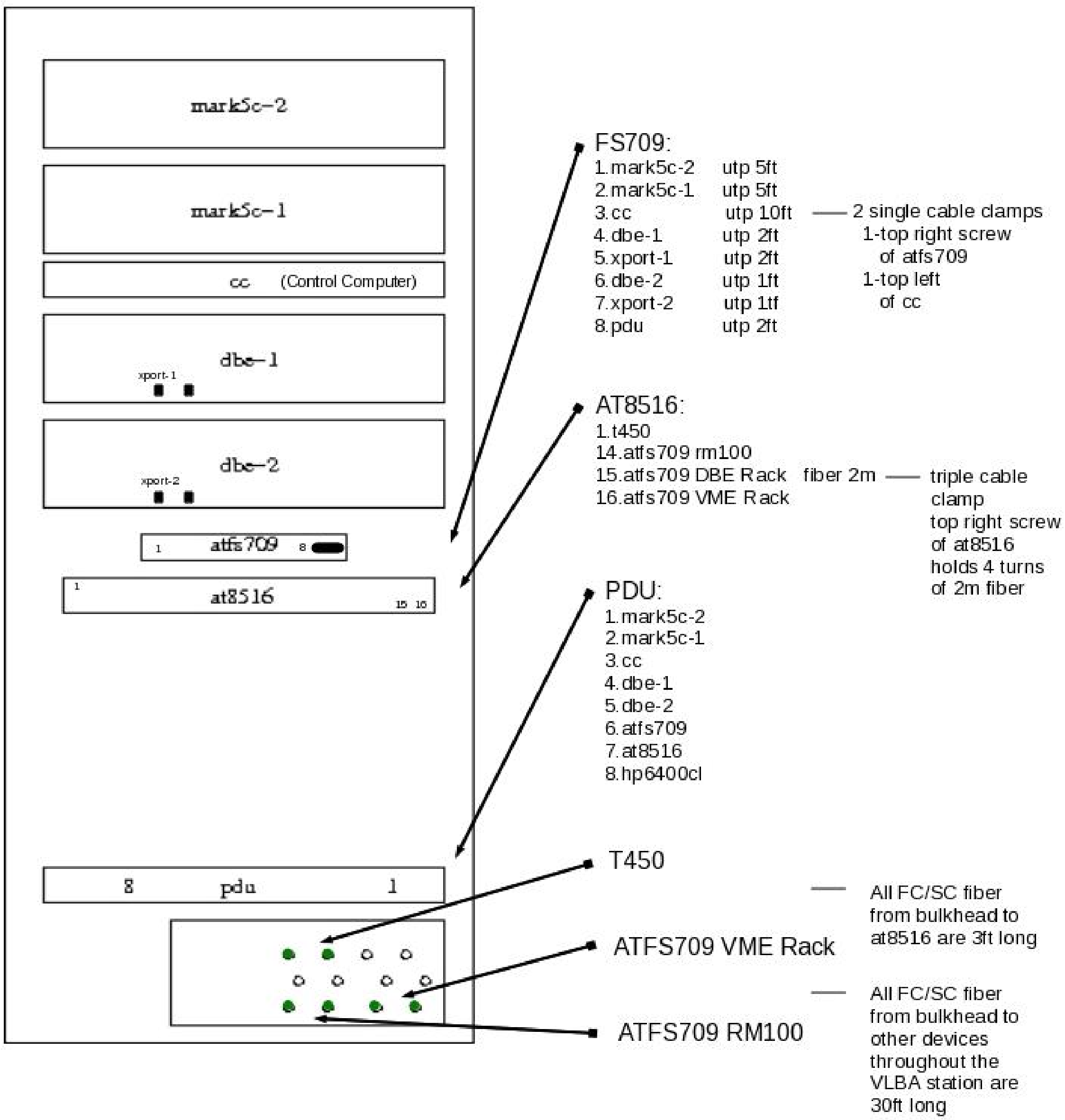

Figure 4: *The rack hosting the VLBA back-end equipment.* FS709 is the local Allied Telesyn 100 Mbps communication switch. AT8516 is the optical 100 Mbps switch. This drawing does not include the X-cube switch. In the current deployment the X-cube switch makes use of FS709 port 1, leaving no room for the Ethernet connection to Mark5C-2. The Power Distribution Unit has has the X-cube plugged into socket 8 as the HP6400CL 10 Gbps Ethernet switch was never deployed. Drawing date: 2010 Aug. 10.

1. Allow a PFB-based mode with 32 channels, each 32 MHz wide. Currently only 16 such channels are allowed.

2. Allow up to four distinct IFs to be used in PFB mode so long as channels can be distributed across 2 RDBEs with each RDBE receiving up to two IFs as input.

3. Allow a DDC-based mode with 8 channels, each 128 MHz wide. Currently only four 128 MHz DDC

channels are allowed.

3.2.2 vex2script

vex2script is responsible for reading a .vex file and producing a VLBA control file that executes the observation. It is in vex2script that the detailed configuration of the recording infrastructure is made, such as assignment of recording channels to RDBEs as described in VLBA Sensitivity Upgrade Memo 39, https://library.nrao.edu/public/memos/vlba/up/VLBASU_39.pdf.

vex2script was modified in the simplest way possible to execute the 4 Gbps tests described above, but the mechanism implemented is not general enough. Changes to vex2script include:

1. Accept the channels defined in the .vex file and schedule accordingly.

vex2script will benefit significantly from code that is shared with DiFX and which was improved in order to support multiple datastreams per antenna.

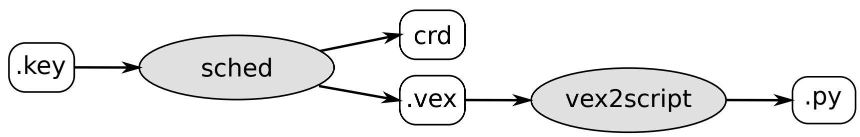

Figure 5: *Relevant observation preparation programs and files.* In this diagram arrows indicate direction of data flow. Ovals represent pieces of software. Rounded rectangles represent files. Components requiring change to support dual Mark5C recorders are shaded.

3.2.3 X-cube switch MIB emulator

In new VLBA hardware a small computer called the Monitor Interface Board (MIB) is responsible for interfacing the Ethernet-based control network to the device. Some software components make use of the same network interface through a purely software “MIB emulator”. In both cases this is where commands are sent and monitor data is produced. The X-cube software-defined switch, which is an Intel-based computer with several Ethernet interfaces, has been somewhat unique in not having any direct monitor and control interface. Its functionality up to now needs no configuration. However, in order to support both existing modes and the new 4 Gbps modes the routing and duplication of packets must be configurable. MIB emulator software exists for the X-cube switch but it has not yet been used in production. In theory all required functionality is in place, so the tasks are:

1. Test the software.
2. Improve as necessary.

3.2.4 Executor

The Executor is responsible for configuring hardware in accordance with the observing schedule. From the start the Executor has had the capability to control multiple recorders and multiple RDBEs; this was successfully demonstrated in the test observations described here. Some effort is likely needed to make the Executor fully capable of executing a mix of 4 Gbps and other observations:

1. Commands to the X-cube switch need to be sent to its MIB emulator. It is thought that code exists for this already but it needs testing and likely some tuning.
2. A mechanism to remove a recorder from the active subarray object is needed in cases where a schedule alternates between 4 Gbps and other observing modes. This mechanism may exist already but would require testing and proper incantations in the output of vex2script.

3.2.5 Operator GUI

The VLBA Operator GUI provides a real-time view of recorder operation. With the exception of the two USNO recorders dual-recorder support is absent. A complete replacement for the current Operator GUI is underway which would likely simplify this new need. Required changes are:

1. Real-time monitoring of two Mark5C recorders.
2. Monitoring of the state of the X-cube switch.
3. Heuristics based on X-cube state and observation documents to know which recorders should be recording at any given time.

3.2.6 xcuberec (optional)

An optional development that would simplify several aspects of VLBA observing would be to migrate recording of the USNO daily observations off the Mark5C recorders and onto the X-cube switches. A program, `xcuberec` has been developed and extensively tested that records data directly to disk files on a disk mounted in the X-cube switch. This option simplifies the USNO operation by not requiring a separate data copy operation, improves the robustness of the observations, and removes the special Mark5C recorder from the data path. This upgrade will likely happen independently of the changes required for 4 Gbps observing but would simplify things greatly. An update to the Operator GUI would be desired if this upgrade is implemented.

3.2.7 mark5c2db

`mark5c2db` extracts key information from the Mark5C monitor stream and puts it into the VLBA10 (legacy) database so that various other software, including `track`, can associate projects with modules. This program needs to be modified as follows:

1. Proper accounting for modules that were recorded on the second recorder need to be made.
2. Skip over any data related to the daily USNO "N-series" observations to avoid headaches in module release.

3.2.8 vex2obs

`vex2obs` extracts data from the monitor database and appends clock, EOP, and module information to the end of the `.vex` file. This information is later used in construction of correlator control files. The changes to `vex2obs` are:

1. The bank on which modules were recorded should be properly captured and stored in the recorder number field in the `TAPE_LOG_OBS` section of the `.vex` file. Note that this will lead to multiple simultaneous recorded modules for 4 Gbps modes.

3.2.9 vex2difx

`vex2difx` takes as input the amended `.vex.obs` file writen by `vex2obs` and generates DiFX control files. Much of the needed infrastructire has been added to `vex2difx` for the support of multiple datastreams per antenna. The additional changes needed relate to Mark5 playback and are:

1. Respect the recorder number assigned to each module in the `TAPE_LOG_OBS` section of the `.vex` file and use this to apportion the recorded channels accordingly. Hooks for this are already in place so the effort should be minimal.

Some complication may arise in cases where a project changes betweein single and dual recorder use during an observation.

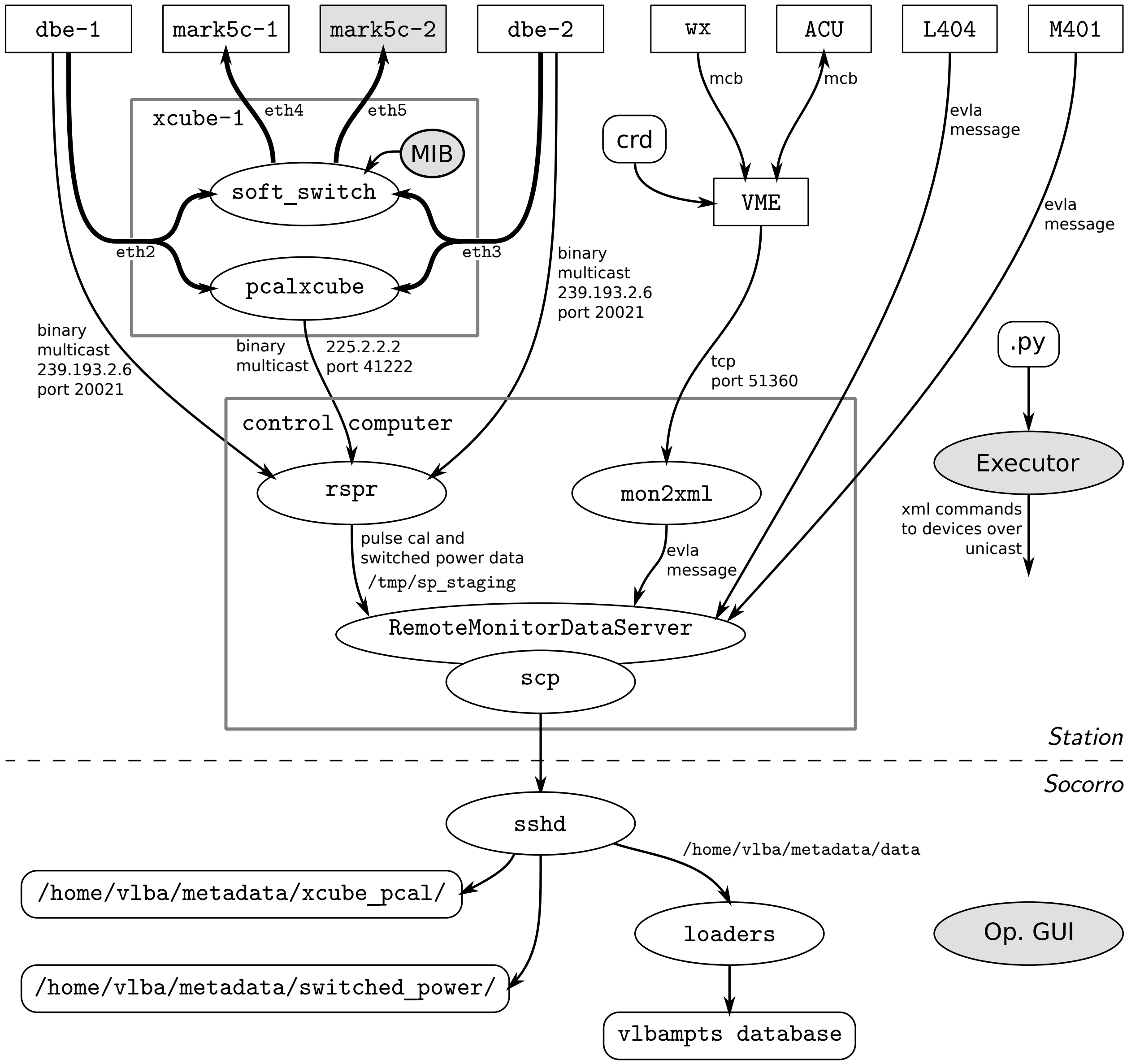

Figure 6: *The real- and near-real-time portions of the VLBA observing system.* In this diagram arrows indicate direction of data flow. Thick arrows (upper left area) represent baseband data while other arrows are low bandwidth monitor data. Ovals represent pieces of software. Overlap of ovals represents one program directly calling another. Rectangles represent pieces of hardware. Note that not all devices are listed. Rounded rectangles represent files and long-term data storage. Control data paths from the Executor and real-time monitoring paths are not shown in detail. Components requiring change to support dual Mark5C recorders are shaded. The data flow in this chart is representative of each VLBA site.

3.2.10 DiFXUI

`DiFXUI` is the operator interface to DiFX at the VLBA correlator. Required changes to `DiFXUI` include:

1. Concept of datastreams and antennas needs to be separated.

2. Multiple Mark5-based datastreams per antenna needs support.

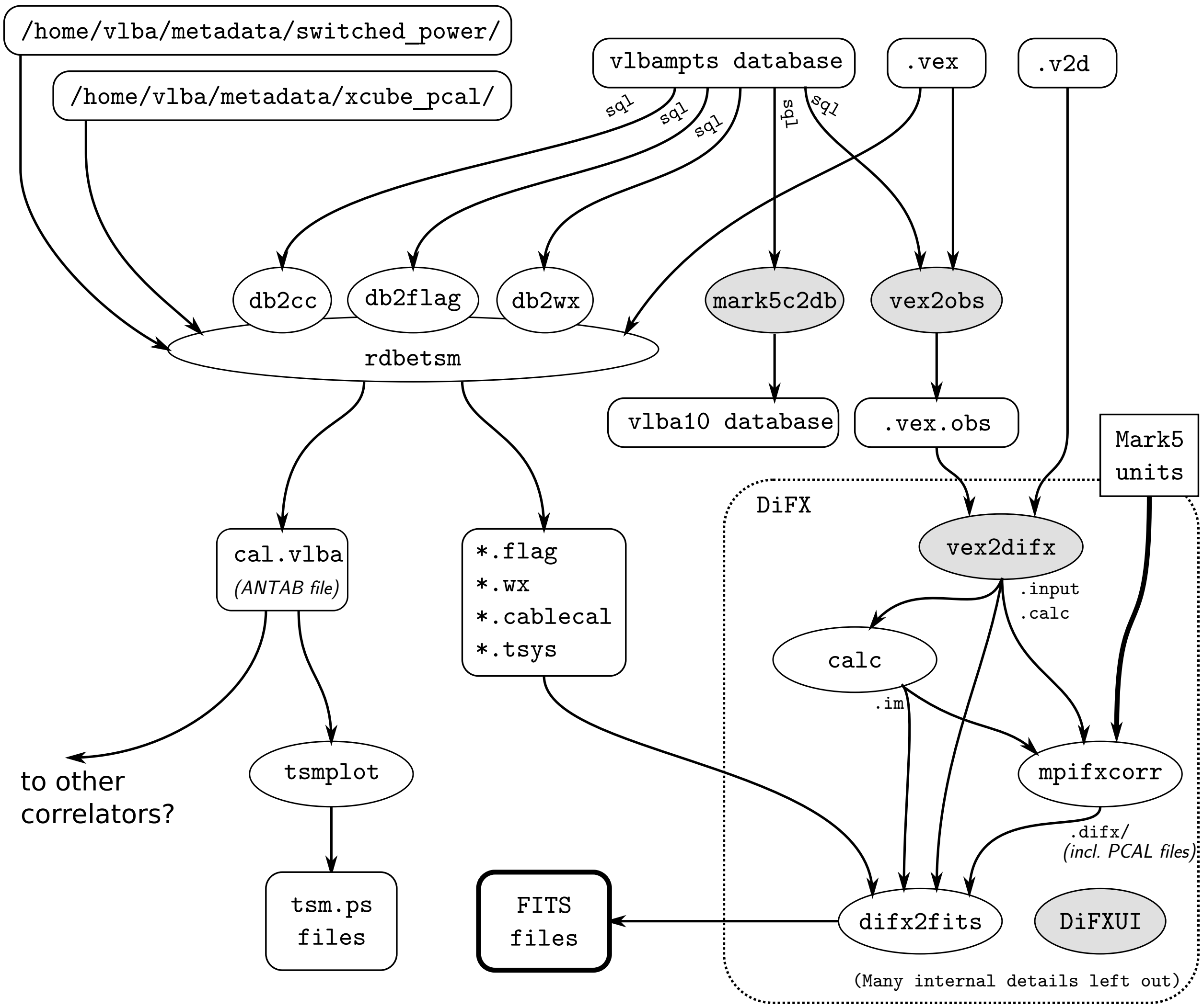

Figure 7: *Relevant portions of the VLBA post-observation software system, including the DiFX correlator.* In this diagram arrows indicate direction of data flow. Thick arrows (from Mark5 units to correlator) represent baseband data while others mainly represent flow of data into or out of a file. Ovals represent pieces of software. Overlap of ovals represents one program directly calling another. Rectangles represent pieces of hardware. Rounded rectangles represent files and long-term data storage. Components requiring change to support dual Mark5C recorders are shaded.

4 Scope reduction option

An operational 4 Gbps deployment that is suitable for GMVA observations only would be slightly simpler. Hardware and infrastructure improvements would not be required at the Hancock (HN) or Saint Croix (SC) VLBA sites. Modifications to `vex2obs` and DiFX (`DiFXUI` and `vex2difx`) would likely not be necessary as less automated correlation could be performed if need be at the Bonn correlator.

This reduced-scope option could be a functional intermediate step towards the full implementation.

5 Other options for 4+ Gbps recording

Early in the VLBA Sensitivity Upgrade Project various options for recording at 4 Gbps were considered (see VLBA Sensitivity Upgrade Memo 11; http://library.nrao.edu/public/memos/vlba/up/VLBASU_11.pdf). The Mark5C design specification allowed for a native dual-bank 4 Gbps operation but this mode was never satisfactorily implemented.

In the past couple years the Mark6 recording system (http://www.haystack.edu/tech/vlbi/mark6/) has been developed with recording capability that vastly exceeds 4 Gbps. Integration of a new recording system such as this into the VLBA systems is likely significantly more work than would be required to for dual Mark5C recording, but it would open up a more natural growth path.

The long term desires for the VLBA are to migrate to real-time data transmission from the VLBA antennas to the correlator, either correlating in real-time, or staging to a spinning disk pool and correlating shortly after observing. At the moment network installation and operation costs are too high, however the cost is dropping.

6 Acknowledgements

Several people contributed to the tests described here, including Tom Baldwin, Jeff Long, William Colburn, Matt Luce, Linda Major, Doug Gerrard, Ephraim Ford, Eric Carlow, Paul Johnson, Brent Willoughby, Austin Shirley, and Ben Simkin. The MPIfR supplied two Amazon boards in support of this test and has pledged ongoing support for contunied work toward wider bandwidths. Many thanks to these folks and the MPIfR!