Event Horizon Telescope
Memo Series

EHT Memo 2013-ETWG-01

EHT Technical Working Group

Future EHT VLBI System Configuration

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Dec 14, 2013 – Version 1.0

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Document history:

- Mar 21, 2019 – Colored text removed as some interpreted this as the document not having been finished. Also added short explanation to the compatibility tables at the end.
- Feb 25, 2019 – Converted to LaTeX.
- Nov 22, 2013 – Document created.

Contents

Table 1. Millimeter Observatories

Tier	Observatory	Comments
1	CARMA JCMT SMA SMT	These are the stations that have been part of 230 GHz EHT-VLBI since 2007 and reliably achieve fringes. The JCMT is scheduled to cease operations under current management in Sep 2014.
2	APEX IRAM-PV	Fringes found in 2013 data on baselines with CARMA!
3	LMT	← 3 mm fringes with SMT achieved recently, but needs 230 GHz Rx
	SPT	← Needs 230 GHz Rx and VLBI equipment
	ALMA	← Beamformer under construction
4	IRAM-PdB	← Focus is on upgrade to NOEMA, new correlator expected but special beamformer software not started yet.
	GLT	← Telescope and systems need to be build/moved to Greenland.
	NRO-45M	← As far as I am aware of, no actual development is presently underway to implement 230 GHz VLBI.
	NMA	← (As previous)

1 Observatories

Table 1 provides a quick overview of the current status of current and planned millimeter observatories.

2 Future VLBI Bandwidth

The majority of the receivers can (or will) be able to do a 4 GHz band in dual-polarization and either double-sideband (DSB) or sideband-separating (2SB) mode. A significant number already have an 8 GHz bandwidth and IF range of 4–12 GHz, which will likely become a de-facto standard across many observatories for the next few years. State-of-the-art mixer development is pushing bandwidth of 16 GHz and IF ranges of e.g. 2–18 GHz.

For future VLBI there currently are two relevant limitations. Firstly, the ALMA correlator is limited to a maximum 16 GHz in aggregate bandwidth per telescope, in practice 8 GHz in both polarizations. Secondly, the ALMA-style 230 GHz mixers (ALMA, SPT, SMT) drop in performance at the both ends of the IF range, in particular over the final GHz. Given that any upgrade of ALMA is probably quite a bit downstream, these suggest to set the target at an aggregate bandwidth of 16 GHz i.e. 64 gbps, leaving the possibility of 128 gbps to a future study.

Besides the fact that an upgrade to 64 gbps already is a major step from current VLBI, it will push the limits of data storage and computing capacity at the correlation center. New VLBI equipment will typically operate in the 16 to 32 gbps range, implying 2 or 4 data chains for processing 64 gbps. Finally, at 345 GHz most receivers have a 4 GHz

bandwidth and IF of 4-8 GHz with little indication of planning to move to larger bandwidths soon.

In summary, the prospective VLBI partners of ALMA at 230 GHz and 345 GHz essentially already are, or can readily be made compatible, with an aggregate bandwidth of 16 GHz and data rate of 64 gbps, significantly larger than present-day VLBI. This suggests a clear roadmap towards using a full 16 GHz of aggregate bandwidth:

Table 2: EHT Roadmap

16 gbps for 2x2 GHz dual-pol or 1x4 GHz single-pol
32 gbps for 2x4 GHz dual-pol
64 gbps for 2x2x4 GHz dual-pol, dual-sideband

3 IF Range

For VLBI the observing band in terms of sky frequencies is what needs to match at each station. For 2SB (or DSB) observations this means that the IF frequency at each station needs to match as well to ensure that the sky frequencies in *both* sideband match. The uppers (USB) and lower (LSB) sideband are separated by twice the IF frequency, defined as the center of the IF range.

In practice, almost certainly dual-polarization will be chosen in preference over dual-sideband, which means that dual-sideband becomes relevant only for the full 64 gbps configuration when both can be accommodated.

Thus for 16 gbps and 32 gbps VLBI the IF frequency at the individual stations is not an issue: the only requirement is that the same sky frequency will be centered within each IF band. The basic requirements for these modes is that the receivers can operate over a 4 GHz band, which is the case for all observatories except the JCMT, both at 230 GHz and 345 GHz. Both the SMA and CARMA will need to implement new 4 GHz wide beamformers. At IRAM-PdB a new correlator and beamformer are part of its NOEMA upgrade.

3.1 IF range 230 GHz

Table 3 below shows the range over which the mixers have a good performance at each observatory, although the actual receivers may operate over a wider or narrower range.

Table 3. IF ranges at 230 GHz

Observatory	IF Range [GHz]	Remarks
IRAM-PV, IRAM-PdB	4–12	
ALMA, SPT, SMT	5–10	
SMA	4–9	
CARMA	2–8.5	
APEX, JCMT, LMT	n/a	Will get new/upgraded receiver
GLT	4–8	First-light Rx

In practice, for the EHT stations this means that the lower limit to the IF range is set by ALMA at 5 GHz and the upper limit by CARMA at 8.5 GHz. The best IF range for a full 4 GHz band is 5–9 GHz based on the difficult-to-change lower limit of ALMA and CARMAs still acceptable performance above 8.5 GHz.

Note that at the SMT cold IF components will need to be replaced to allow the receiver to operate above 8 GHz.

The IF range at the SMA and IRAM-PdB are not contiguous and split into 4 GHz backend sections running from 4–8 GHz and 8–12 GHz. The implications of this for an IF-range of 5–9 GHz will need to be further investigated as well as any beamformer issues impacting the choice of IF range, (but see also section 3.4).

For this evaluation APEX, JCMT, and the LMT are not being considered. The current 230 GHz receiver at APEX is 2SB single-IF i.e. does not output the image sideband. JCMTs future beyond 2014 is uncertain and its current receiver is single-pol DSB. A state of the art 230 GHz receiver still needs to be designed for the LMT and it is reasonable to assume that it will accommodate the chosen IF range.

GLTs first-light receiver will, however, not be compatible with the chosen IF range and only have an overlap of 12 instead of 16 GHz in aggregate bandwidth.

Future VLBI with an IF range from 4–12 GHz between compatible observatories should be kept in consideration.

3.2 IF range 345 GHz

At 345 GHz the common IF range is 4–8 GHz without any further complications.

3.3 Details regarding 230 GHz

- *ALMA:* APP project on-track for delivery of the beamformer. The ALMA OT does not allow selecting an IF-range extending below 5 GHz or above 10 GHz. Although technically this limitation can be overcome relatively easily, get the prospects of getting such change request processed are dim.

- *APEX:* Its current receiver is single-IF. Planning has started for a new dual-pol 2SB 230 GHz receiver.
- *CARMA:* Has a relevant upper limit to the IF of 9 GHz. Design and construction of a 4 GHz beamformer has started.
- *GLT:* Its first-light 230 GHz receiver will be a dual-pol DSB receiver with an IF range of 4–8 GHz.
- *IRAM-PdB:* the beamformer and new 230 GHz receivers with a 4–12 GHz IF are part of the currently ongoing NOEMA upgrade. The full IF range will be split into two 4 GHz bands and the implications for an IF of 5–9 GHz is still under investigation.
- *IRAM-PV:* working with a new 4–12 GHz EMIR receiver.
- *JCMT:* Its 230 GHz receiver is single-pol with a 3–5 GHz mixer. Its cold IF components have been upgraded to work up to 8 GHz. However, its loaner SMA mixer (4–12 GHz) is currently in line to be used for the prototype LMT Rx. Operations of the JCMT beyond Sep 2014 are unclear.
- *LMT:* A first-light single IF 230 GHz receiver is under construction. Will eventually need a full new dual-pol 2SB receiver.
- *SPT:* a dual-pol 2SB 230 GHz is under construction.
- *SMA:* Has plans to install a second set of 230 GHz receivers to enable dual-pol. These will be x3 mixers (same as JCMT) and will use the second master-reference. Beamforming an IF of 5–9 GHz is still under investigation, as it is not easily accommodated with the interim correlator setup.
- *SMT:* uses an ALMA-style mixer HEMT/Isolator limited to an IF of 4–8 GHz. Will need upgrades of the cold IF components to enable the more optimal range of 5–10 GHz.

3.4 Backend considerations

At the single-dish telescopes the IF from the receivers will be *up-down* converted for processing by the VLBI backend. Haystack observatory has designed and used a dual-pol 2 GHz up-down converter that can accept IF frequencies from 1–13 GHz. The covers the range of IF needed for 2 GHz chunks between 4 GHz and 9 GHz.

The beamformer at the interferometer arrays is an extension of the regular correlator and thus will naturally accommodate the operating IF range of the receivers. An exception is the SMA: its interim configuration will consist of the old 4–8 GHz correlator and the new 8–12 GHz SWARM correlator with the integrated beamformer. SWARMs beamformer is thus incompatible with an IF range of 5–9 GHz, but various solutions are being investigated. Nevertheless there is a risk that initial VLBI at 64 gbps will not be able to utilize the full 2 x 4 GHz band on SMA baselines. In this context it is relevant that this limitation is directly associated with a planned upgrade of the SMA to dual-pol capability with actually delivers a larger gain than what would be lost in bandwidth.

4 LO frequency for EHT observations

Normally the center sky frequency, and thus LO frequency, of observations is a parameter that is tunable within the total observing band of a receiver. However, the SPT plans to operate with a fixed-tuned Gunn-oscillator, thus requiring the selection of a LO frequency for future EHT observations.

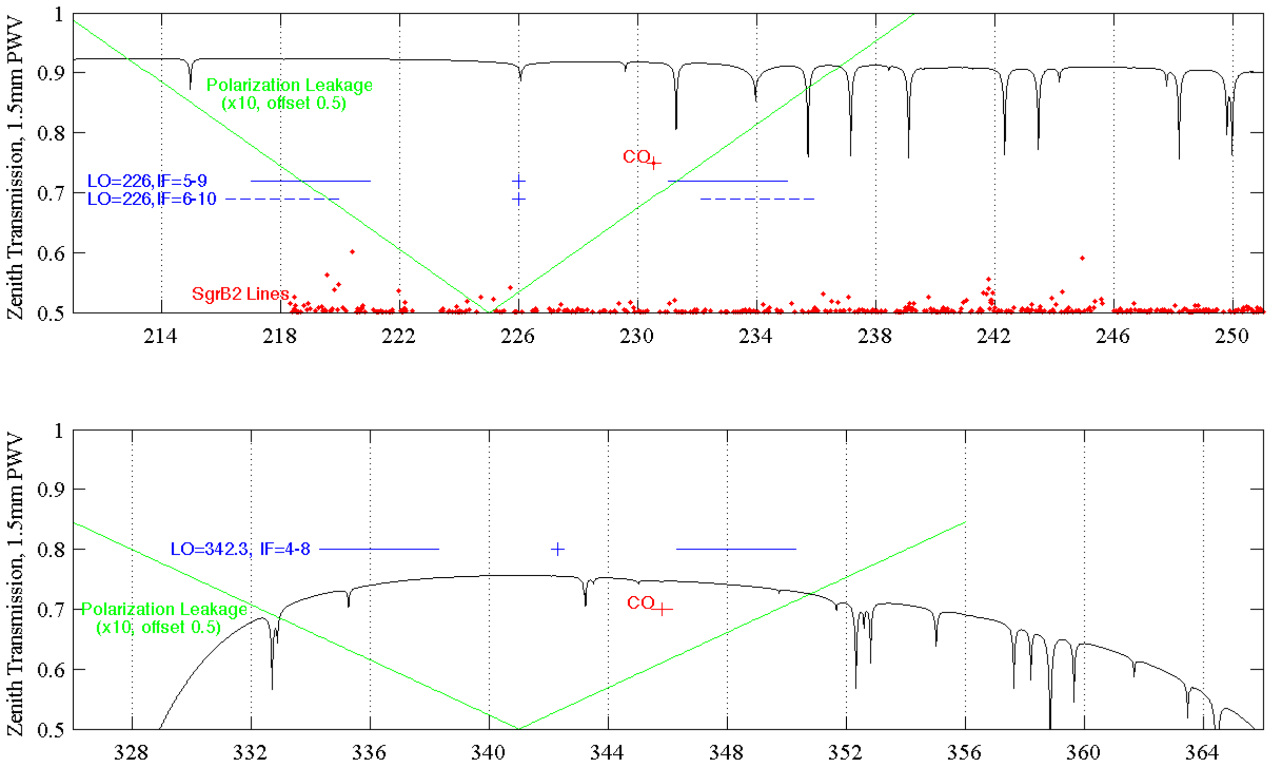


Figure 1: Top: Example for lowest possible LO frequency of 226 GHz. Note that this choice will not allow an IF range that starts below 5 GHz. Bottom: Example for the 345 GHz band with an LO frequency of 342.5 GHz. The plots show the atmospheric transmission (black), absorption features (red), polarization leakage for a subset or EHT stations with 225 GHz and 341 GHz waveplates (green), IF ranges (blue), CO line (red cross).

Key factors are the atmospheric transmission and avoidance of the Galactic CO emission (230.5379 ± 300 km/s; i.e. $\nu \sim 230.3 - 230.8$ GHz). The second constraint leaves three basic choices: both sidebands below, above, or straddling the CO line. Both sidebands below pushes the LO frequency close to ALMA minimum LO frequency of 221 GHz for the band-6 receivers. Both sidebands above, while possible, is not ideal because it pushes the upper sideband towards a less favorable atmospheric transmission conditions.

The simplest option is to put the LO right at the CO rest frequency of 230.54: provided the lower IF range does not come within 0.5 GHz, any future bandwidth will avoid the CO line. If one prefers to bias towards lower sky frequencies, the lowest LO frequency depends on the minimum allowable IF range, 2 GHz: 229 GHz, 4 GHz: 227 GHz, 5 GHz: 226 GHz. Figure 1 gives an illustration of the latter setup, which corresponds to the lowest acceptable LO frequency, but one that does not allow an IF band below 5 GHz.

Drawback of a LO centered on or close to 230 GHz is that strong Galactic CO lines will not be observable e.g. in an IF range outside of the VLBI band. An alternative setup that warrants further study is to place the upper sideband just below the Galactic CO band, but there basically is only a single choice with the LO at ~221 GHz and the upper edge of the USB at 230 GHz. This may be an issue given the tuning range at e.g. ALMA.

The $\frac{1}{4}\lambda$ waveplates used for EHT observations to date are optimized for a frequency of 225 GHz and will need to be modified for use with a significantly different LO frequency. Regardless, polarization leakage will remain an issue given the large IF range especially for dual-sideband operation. For single-sideband operation (i.e. 16 gbps and 32 gbps) it will be advantageous to place the lower sideband at the center frequency of the current waveplates which will place the LO close to the CO line frequency.

In conclusion: considerations based on compatibility with future IF ranges for dual sideband EHT observing as well as restrictions due to the current EHT waveplates for earlier single sideband observing both point to the Galactic CO rest-frequency being a good choice as the LO frequency for the EHT. For both criteria it is probably safe to relax the constraints to allow a LO frequency as low as 229 GHz. An alternative setup with the LO close to 221 GHz warrants further study and will be covered in a subsequent memo. For dual-sideband polarimetry it may be necessary to obtain better-optimized waveplates.

5 VLBI Instrumentation

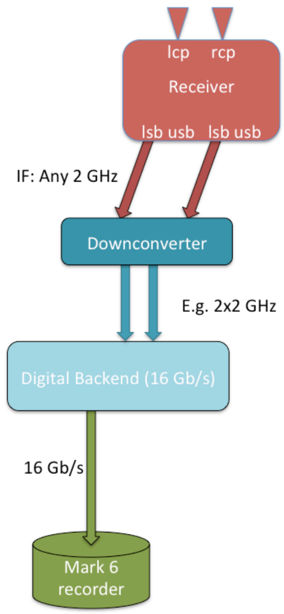
5.1 VLBI Equipment Schedules

Table 4 illustrates the various system layouts for total data rate of 16 gbps, 32 gbps, and 64 gbps, respectively. The downconverters are assumed to have dual-pol 2 GHz bands. The backend is assumed to be 32 gbps, but could instead consist of two 16 gbps units. The recorders are assumed to be 16 gbps units. Note: for phased arrays the downconverter and backend are part of the beamformer.

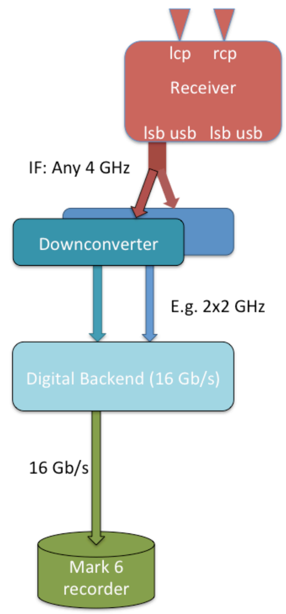
Table 4: EHT VLBI Schematics

16 Gbps

2x2 GHz, 1SB/DSB, Dual-pol

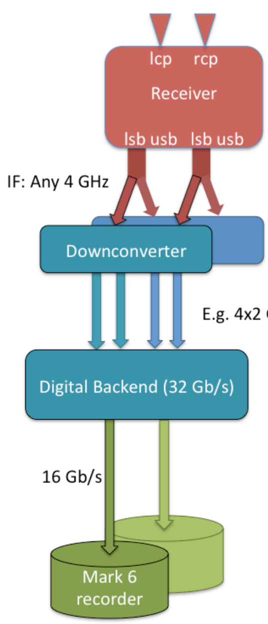


1x4 GHz, 1SB/DSB, Single-pol



32 Gbps

2x4 GHz, 1SB/DSB, Dual-pol



4x2 GHz, 2SB, Dual-pol

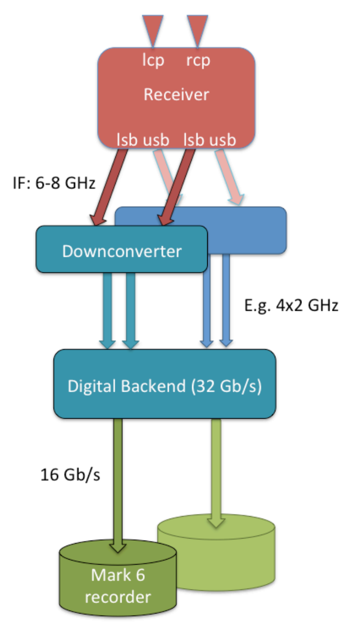
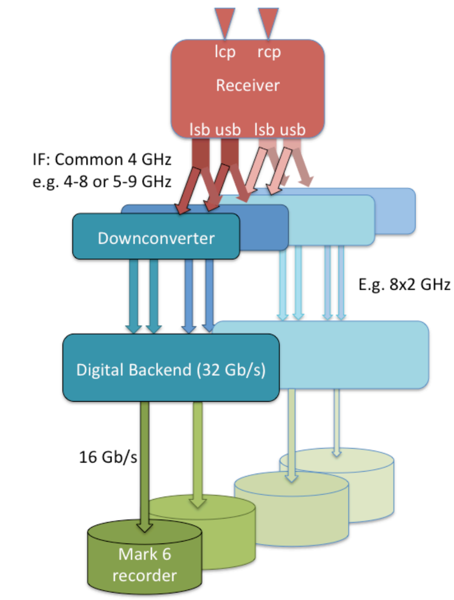


Table 4 – continued from previous page

64 Gbps
4x4 GHz, 2SB, Dual-pol


5.2 Maser

Most observatories already have adequate masers, except:

- SPT: plans to purchase a maser. Additional funds needed
- LMT: needs maser. The 3 mm fringes were obtained using a quartz crystal.
- SMT: old maser should be replaced.
- IRAM-PV: maser refurbished, but replacement should be considered.

The iMaser 3000 from T4Science has been found to work well, but also Symmetricom offers a unit with the required specifications.

Figure 2: iMaser 3000.

5.3 Downconverter

Haystack designed and successfully used a dual-pol 2 GHz downconverter (aggregate bandwidth 4 GHz; see Figure 3) with an input IF range of 1–12 GHz. This unit will thus work for an IF bands up to 13 GHz and is adequate for our purpose. In order to downconvert an aggregate band of 16 GHz four units would be needed. This

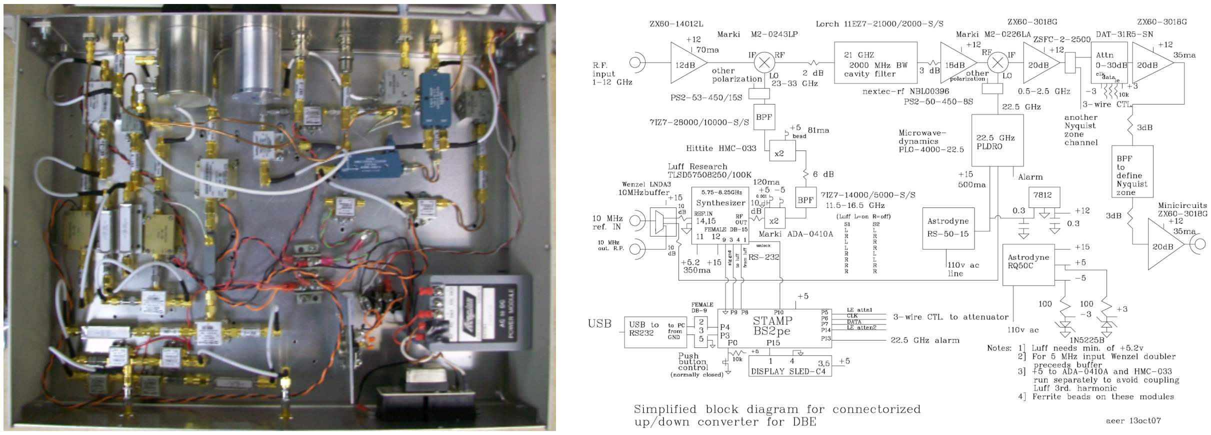


Figure 3: Left: SMT Updown converter; Right: 2 x 2 GHz Haystack Downconverter

number could be reduced to two units if the two channels can be multiplexed each for the separate signal from each sideband from 2SB receivers. Such 4 x 2 GHz units should save both on costs and overall footprint. Alternatively it may be possible to expand the current design to a 2 x 4 GHz model.

Using the current model, for a IF range of 5–9 GHz a set of units can process a 2 GHz chunk of the IF for each polarization from both sidebands. Two of such sets will be needed, centered on an IF input of 6 and 8 GHz, respectively.

5.4 Digital backend

Figure 4: SAO R2DBE.

- SAO is developing a 16 gbps R2DBE, based on the ROACH2 board. This unit can handle 2 IF bands of 2 GHz each.

Figure 5: HATlab DBBC.

- INAF/MPIfR/OSO are developing an up to 128 gbps DBBC3. This development is scheduled for completion by the end of 2014. It can handle upto eight 4 GHz IF bands.

Channelization: APP is working on compensating for the 4000 rather than 4096 MHz clock at ALMA in the DiFX software. ALMAs 62.5 MHz channels will be spaced by 64 MHz for alignment with default VLBI systems. Issues associated with channelization will need future discussion.

5.5 Recorder

Mark 6 16 gbps recorders are now available from Conduent. Mark 5 recorders can be upgraded.

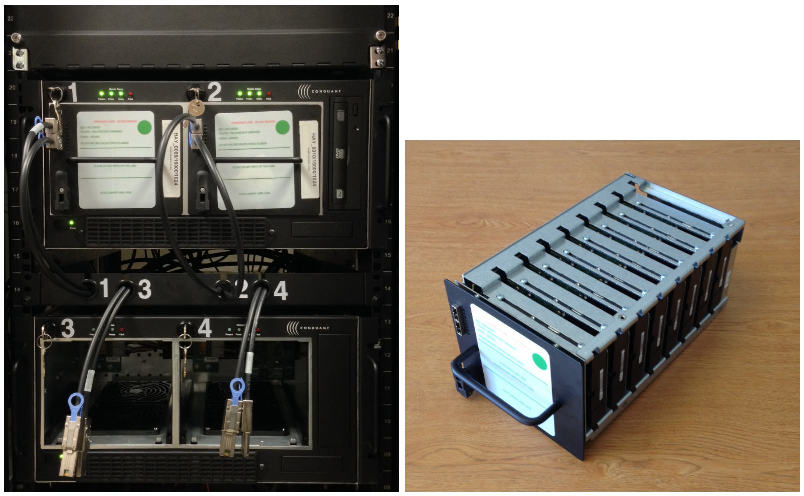


Figure 6: Left: Mark 6 recorder; Right: Removable module with 8 hard drives

5.6 Beamformer

Beamformers that can accommodate bandwidths of 4 GHz will be needed at all interferometer arrays:

- ALMA: the ALMA Phasing Project is on track to have a 64 gbps beamformer in place by the end of 2014.
- SMA: the new SWARM correlator handling data for the IF window of 8–12 GHz will come with a 64 gbps beamformer which will accept 4–8 GHz as input. As mentioned above an IF of 5–9 GHz is problematic to accommodate.
- CARMA: funding for a 64 gbps beamformer, as an extension of their new correlator, is secure, but actual work on its implementation has not started yet.
- IRAM-PdB; a 64+ gbps beamformer is planned as part of the new correlator coming with the NOEMA upgrade, but work on its implementation has not started yet. Preliminary design specifications:
  - Receiver: 2SB, dual polarisation, 8 GHz/sideband/polar, a total of 32 GHz. Actually, the exact numbers are: 3.872-11.616 GHz for the IF range. 4 Ifs (H/L, LSB/USB).
  - IF processor: each of the IF is split in 2 halves through a diplexer with a LO frequency of 7.744 GHz
  - Correlator "digital front-end": each 0-4 GHz band (actually 1.2-3960 MHz) is digitized (5 bits) and sampled (sampling frequency 8.192 GHz). The band is then sliced through a polyphase filterbank in 64

channels of 64 MHz (actually the channels are 128 MHz wide and 50% overlapping, but only the inner 64 MHz is kept). Channel are fixed in frequency (no agility).
  - Beamformer: not yet fully designed, but the plan is to add an adder module for each channel, followed by another polyphase filtering offering 2n MHz wide filters (with tunable n, e.g. 2x32 MHz subbands to match Mark 5C capacities) then a 2 bits requantization.

Consequences: any IF not included within a correlator unit (3.872-7.744 or 7.744-11.616 GHz) will have to be processed from 2 correlator units. Earliest possible availability of the beamformer would be sometime in 2017.

5.7 Storage

The eventual move to 64 gbps recording will increase the data rate significantly. As a benchmark, a full hour of observations with a 100% duty cycle will require 28.8 TB of disk space per VLBI station. Outfitted with four disk packs of 4-TB drives, the total capacity four Mark 6 recorders is about 512 TB or almost two 12-hour blocks of observing with an optimistic, but not unreasonable, duty-cycle of 75%.

In conclusion, present-day 4-TB drives are sufficient for future 64 gbps VLBI. Larger 6TB drives are expected to become available in 2014[1]. Seagate has reached storage densities in the laboratory that would allow for 60-TB drives within the next decade, but the growth in disk capacity has slowed.

More problematic may be the logistics of the total storage needed for a future 64 gbps VLBI run. For example 3 x 12 VLBI hours with 10 stations, observing at a 75% duty-cycle, will require a total of almost 8 PB or two thousand 4-TB drives in 250 disk packs. Numbers like these will require the development of a robust storage management system and handling procedures. Of course, starting with e.g. a 16 gbps system will dramatically reduce the required storage need during the ramp-up phase.

6 Polarimeters and waveplates

An issue for future consideration is whether or not a generic polarimeter needs to be designed with remote control over insertion and rotation of the waveplate. Lack of remote control will impact flexible scheduling observing modes.

7 Water Vapor Radiometers

Few observatories have a proper WVR at the moment or one that may not be sufficiently aligned with the beam. Installing WVRs should probably be regarded as a future upgrade option to improve coherence times and image

[1] In a related development that would be of interest for deployment at high-altitude sites, a closed 6-TB helium-filled drive is already now available from HGST (www.hgst.com; owned by WD)

quality post first EHT observations with ALMA. Nevertheless, almost certainly these will become an integral part of mmVLBI in the future because of longer coherence lengths they will deliver.

A Appendix: Telescope Compatibility Matrix for 230 GHz

Items displayed in bold and red flag 'compatibility issues' that will need to be addresses as part of the implementation of the relevant observing mode. Item in orange are under development already. In subsequent tables for more advanced modes, such items are no longer still colored, but not bold.

A.1 Dual-polarization 2 GHz, one sideband (16 gbps)

	IF [GHz]	Pol	SB	Status
CARMA	1–8.5	DP	2SB	New correlator and beamformer for 64 Gb/s under development.
JCMT	3–6	*SP*	DSB	High Tsys. *Dual-pol option with SMA*. Future uncertain after Sep 2014.
SMA	(4–8)+(8-12)	*SP*	2SB	SWARM correlator and beamformer being commissioned. *Dual-pol option with JCMT.* Planning future upgrade to dual-pol.
SMT	5–10	DP	2SB	
APEX	4–8	**SP**	SSB	New Rx being discussed.
IRAM-PV	4–12	DP	2SB	
LMT	4–8	**SP**	DSB	First light Rx under construction by EHT. Surface optimization needed.
SPT	5–10	DP	2SB	230 GHz Rx under construction, first light expected in 2014(?).
ALMA	5–10	DP	2SB	Beamformer under construction, first light expected in 2014.
IRAM-PdB	(4–8)+(8–12)	DP	2SB	Upgrading to NOEMA. New correlator. Beamformer to be started.
GLT	4–8	DP	DSB	First light Rx. First operation possibly in 2016 (from Thule coast).
NRO-45M	n/a	n/a	n/a	Will need new Rx for operations at 1mm.
NMA	5.5–6.5	SP	DSB	Will need beamformer. Will need new RXs for 2 GHz IF.

A.2 Dual-polarization 4 GHz, one sideband (32 gbps)

	IF [GHz]	Pol	SB	Status
CARMA	1–8.5	DP	2SB	New correlator and beamformer for 64 Gb/s under development.
JCMT	**3–6**	*SP*	DSB	**Needs new 4-8 mixer (now in LMT Rx),** HEMT, Isolator ok. *Dual-pol option with SMA.* Future uncertain after Sep 2014.
SMA	(4–8)+(8-12)	*SP*	2SB	SWARM correlator and beamformer being commissioned. *Dual-pol option with JCMT.* Planning future upgrade to dual-pol.
SMT	5–10	DP	2SB	
APEX	4–8	SP	SSB	New Rx being discussed.
IRAM-PV	4–12	DP	2SB	
LMT	4–8	SP	DSB	First light Rx under construction by EHT. Surface optimization needed.
SPT	5–10	DP	2SB	230 GHz Rx under construction, first light expected in 2014(?).
ALMA	5–10	DP	2SB	Beamformer under construction, first light expected in 2014.
IRAM-PdB	(4–8)+(8–12)	DP	2SB	Upgrading to NOEMA. New correlator. Beamformer to be started.
GLT	4–8	DP	DSB	First light Rx. First operation possibly in 2016 (from Thule coast).
NRO-45M	n/a	n/a	n/a	Will need new Rx for operations at 1mm.
NMA	5.5–6.5	SP	DSB	Will need beamformer. Will need new RXs for 2 GHz IF.

A.3 Dual-polarization 4 GHz, sideband separating (64 gbps)

	IF [GHz]	Pol	SB	Status
CARMA	1–8.5	DP	2SB	New correlator and beamformer for 64 Gb/s under development.
JCMT	**3–6**	***SP***	DSB	**Needs RX/mixer.** *Dual-pol option with SMA.* Future uncertain after Sep 2014.
SMA	**(4–8)+(8-12)**	*SP*	2SB	SWARM correlator and beamformer being commissioned. Planning future upgrade to **dual-pol. Needs solution for IF=5-9 GHz.**
SMT	**5–10**	DP	2SB	Needs new **HEMTs and Isolators** for IF above 8 GHz
APEX	**4–8**	SP	**SSB**	**New Rx** being discussed.
IRAM-PV	4–12	DP	2SB	
LMT	**4–8**	SP	DSB	**First light Rx inadequate.** Surface optimization needed.
SPT	5–10	DP	2SB	230 GHz Rx under construction, first light expected in 2014(?).
ALMA	5–10	DP	2SB	Beamformer under construction, first light expected in 2014.
IRAM-PdB	(4–8)+(8–12)	DP	2SB	Upgrading to NOEMA. New correlator. Beamformer to be started.
GLT	**4–8**	DP	DSB	**First light Rx inadequate.** First operation possibly in 2016 (from Thule coast).
NRO-45M	n/a	n/a	n/a	Will need new Rx for operations at 1mm.
NMA	5.5–6.5	SP	DSB	Will need beamformer. Will need new RXs for 2 GHz IF.