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# “Mixed Mode (Broadband vs. S/X) Configuration Issues”

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## Mixed Mode (Broadband vs S/X) Configuration Issues

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In order to establish robust geodetic ties between new broadband stations and the legacy S/X network, a series of observing sessions is required that include both broadband and S/X stations. These sessions are referred to as mixed mode sessions. There are a number of compatibility issues that complicate mixed mode observing. The purpose of this document is to outline those issues and to make recommendations for a useable compatibility mode.

### Background

There are two ***receiver front ends*** that need to be considered (See Table 1):

- VGOS Broadband. Broadband front ends are dual linear polarization with a frequency range of 2-14 GHz. Flexible RF-to-IF conversion is achieved using Up/Down Converters (UDCs), one per received band. The Haystack UDC has a frequency resolution of 0.4 MHz; but others may use sub-multiples of 0.4 MHz.
- Legacy S/X band. S/X band is a dual band (S-band = ~2.2-2.4 GHz; X-band = ~8.2-9.0 GHz) front end, each band using a single circular polarization, RCP (although LCP is also available at a number of stations), with fixed frequency RF-to-IF conversion. Values of LO frequency and bandwidth for these receivers vary from location to location although a significant number of stations use a standard NASA geodetic front end with S/X LOs of 2020/8080 MHz and bandwidths of 240/800 MHz.

| | **Legacy S/X** | **VGOS** |
|---|---|---|
| **Input Frequency Range (GHz)** | S: ~2.2-2.4<br>X: ~8.2-9.0 | 2-14 |
| **Polarization** | RCP<br>(LCP also at some stations – but not used) | Dual Linear |
| **RF-to-IF Conversion** | Fixed frequency | Up/Down Converter (UDC)<br>or Direct Sample/Digital |
| **# of Bands** | 2 (S and X) | 4 |
| **Bandwidth/Band** | S: ~240 MHz<br>X: ~800 MHz | 4x512 MHz or<br>4x1024 MHz |
| **LO** | Fixed frequencies<br>(differ by station) | Programmable:<br>Resolution = 0.4 MHz |

*Table1. Summary and comparison of receiver front end specifications*

There are a number of ***receiver back ends*** that need to be considered:

- Analog Data Acquisitions Systems (DASs) See Table 2. There are two main analog DASs:
    - Mark 4 Data Acquisition Rack (DAR):
        - Two IF inputs in the 100-500 MHz range and another in the 600-900 MHz range. [Note: The native range of the Mark 4 baseband converter is 100-500 MHz. The 600-900 MHz IF input range is aligned using an internal down-converter.]
        - 10 KHz LO frequency resolution
        - Output bandwidth decreasing in factors of 2 from 16 MHz (although 8 MHz is the highest frequency used operational due to poor performance at 16 MHz)
        - 14 USB/LSB base band converters (BBCs)
    - VLBA geodetic DAS:
        - Four IF inputs in the 500-1000 MHz range. [Note: Input bandwidths greater than 500 MHz are aligned to the 500-1000 MHz IF input range using external up- or down-converters.]
        - 10 KHz LO frequency resolution
        - Output bandwidth decreasing in factors of 2 from 16 MHz (although 8 MHz is the highest frequency used operational due to poor performance at 16 MHz)
        - 14 USB/LSB BBCs
- Digital Base Band Converter (DBBC). See Table 2. The DBBC has 2-4 (typically 3) 512 MHz IF inputs. It can operate with two different bit code personalities:
    - Digital Down Converter (DDC) personality. This is a digital implementation of an analog BBC with:
        - Frequency resolution of 10 KHz
        - Output bandwidths that decrease in factors of 2 from 16 MHz (with a 32 MHz option now under beta test)
        - A total of 16 USB/LSB outputs [In the DBBC, IF selection is hardwired and organized in groups of 4 DDCs. The standard geodetic DBBC is wired for 8 DDCs at X-band and 8 DDCs at S-band].
    - Polyphase Filter Bank (PFB) personality. This is essentially an FFT with a pre-filter added to improve channel isolation:
        - Effective LO frequency resolution equal to the PFB channel bandwidth, i.e. 32 MHz
        - A single hard coded output bandwidth of 32 MHz
        - One PFB per CORE board, four per DBBC
        - Up to 15 USB or 15 LSB outputs per PFB [USB or LSB depends on the LO chain and the zone of the antialias filter]

| | Legacy Analog | RDBE | | DBBC | |
|---|---|---|---|---|---|
| | | DDC | PFB | DDC | PFB |
| **# of IFs** | Mark 4: 3<br>VLBA: 4 | 2 | | 2-4 | |
| **IF range (MHz)** | Mark 4:<br>2x(100-500) &<br>1x(600-900)<br>VLBA:<br>4x(500-1000)<br>[See notes in text.] | Each IF can be:<br>(0-512), (512-1024), or (1024-1536) | | Each IF can be:<br>(0-512), (512-1024), (1024-1536) or (1536-2048) | |
| **IF selection** | Mark 4: Flexible via patch panel.<br>VLBA: Programmable w/ restrictions | Choice of either IF for each DDC | Hardwired: 1 PFB per IF input, 2 PFBs total | Hardwired in groups of 4 DDCs | Hardwired to 4 PFBs |
| **LO res** | 10 KHz | 15.625 KHz | 32 MHz | 10 KHz | 32 MHz |
| **BW (MHz)** | 1/2/4/8/16<br>(8 is the operational maximum) | 1/2/4/8/16/ 32/64/128 | 32 | 1/2/4/8/16/<br>(32 in beta testing) | 32 |
| **# of BBCs, DDCs or PFB outs** | Mk4: 14<br>VLBA: 14 (geodetic version) | 4/4/4/4/4/ 4/2/1 | 15 per PFB, 16 total | 16 | 15 per PFB, 60 total |
| **Sideband** | U and/or L | U and/or L | all U or all L (depending on LOs and Nyquist zones) | U and/or L | all U or all L (depending on LOs and Nyquist zones) |
| **Notes** | None | Channels cannot straddle 128 or 384 MHz boundaries | none | None | None |

*Table 2. Summary and comparison of receiver back end specifications*

- ROACH-based Digital Back End (RDBE) See Table 2. Each RDBE has two 512 MHz IF inputs with four RDBEs required per broadband system and potentially fewer for an S/X back-end. Like the DBBC, the RDBE also has two bit code personalities:
    - DDC personality (astronomy):
        - Frequency resolution of 15.625 KHz with a restriction that bands cannot straddle 128 or 384 MHz.
        - Output bandwidths that decrease in factors of 2 from 64 MHz
        - A total of 4 USB/LSB outputs per RDBE.
    - PFB personality (geodesy):
        - Effective LO frequency resolution equal to the PFB channel bandwidth, i.e. 32 MHz
        - A single hard coded output bandwidth of 32 MHz (with 8 and 16 MHz versions under consideration)
        - Two PFB's per RDBE (with a quad version under development)
        - Up to 15 USB or 15 LSB outputs per PFB [USB or LSB depends on the LO chain and the zone of the antialias filter]
- Other Digital Back Ends. A number of other DBEs have been developed. These are currently beyond the scope of this document.

There are a number of ***criteria that a good mixed mode configuration*** either requires or should possess:

- Spectral alignment. For two stations, only the spectral regions that overlap will correlate. This requires:
    - LO alignment. The same effective LO needs be used at both ends of a baseline. If this cannot be achieved during data acquisition, it is still possible, with some limitations, to achieve the final LO alignment in the correlator.
- BW alignment. Although processing is easiest if the same bandwidth is acquired at both ends of a baseline, it is still possible, with some limitation, to use "zoom" mode in the correlator to extract a fraction of the input spectrum at a station and hence reconcile different bandwidths.
- Polarization alignment. It is necessary that polarizations be reconciled.
    - For legacy S/X systems, only one circular polarization signal, RCP is acquired at each station. Full sensitivity for that polarization requires only the correlation of a single polarization product, e.g. RCP*RCP.
    - For broadband VLBI systems which use linear polarization, uniform sensitivity with parallactic angle requires that both polarization signals are acquired and that all polarization products are correlated, i.e. V*V, V*H, H*V, and H*H.
    - For mixed mode observing, two linear polarization products need to be correlated against a single circular signal to get the same sensitivity as a single circular polarization signal from each antenna, i.e. V*RCP plus H*RCP is equal in sensitivity to

RCP*RCP. For stations with linear polarizations, this doubles the front- and back-end receiver requirements, the data transmission requirements, and the correlation requirements. This is normally not a problem if the station is already intended for use in the broadband network since the double capacity will already be built into the system. However, if double rate data transmission is a problem at a site, the construction of circular polarization from two linears can be considered.

  - Dual circular polarization at legacy S/X stations. A number of legacy S/X stations have receiver front ends that produce both RCP and LCP outputs. It has been proposed that, wherever available, both circular  polarizations should be acquired. The inclusion of the second polarization essential doubles the amount of acquisition hardware and data transmission that is required. Whenever a baseline includes two dual polarization sites (either both are dual circular, both are dual linear or the polarizations are mixed), it is recommended that all four polarization products should be correlated.

- <u>Greater sensitivity.</u> VGOS broadband antennas are in general smaller than S/X legacy antennas, typically with a ratio of about 12:20 in diameter. This results in reduced sensitivity on the broadband vs legacy S/X baselines and hence unacceptably long integration times on those baselines. To make up for loss of sensitivity on the mixed baselines it is proposed that higher data rates be used. As an easy first fix, it is recommended that the 1-bit sampling typically used in R1 sessions be replaced by 2-bit sampling. This immediately doubles the data rate and roughly halves the integration time required to achieve the same SNR. To go beyond this, wider channel bandwidths need to be considered.
- <u>S-band RFI avoidance.</u> Although wider bandwidth channels are beneficial to increase sensitivity at X-band, they may cause problems at S-band where RFI needs to be avoided. Investigations are required to see how wide a channel bandwidth can be used at S-band before RFI becomes a problem.
- <u>200 ns PCAL ambiguity resolution.</u> The 5 MHz PCAL reference signal is reduced in frequency by a factor of five (to 1 MHz) in the antenna units of legacy antennas. However, the div5 circuit that implements the division is not initialized to an epoch. As a result, whenever the PCAL 5 MHz reference is interrupted (e.g. for a cable cal +/- test) the potential exists for the timing of the PCAL pulse train to be offset in increments of 200 ns. Since the raw astronomical signal is not itself affected, the impact of applying a PCAL correction to the raw data is to transfer the n x 200 ns PCAL discontinuities to the astronomical delays. In the past, this was a disincentive for using frequency sequences with other than 5 MHz minimum spacing (e.g. 8 MHz) since the data ambiguities (125 ns for 8 MHz) beat with the 200 ns PCAL ambiguities. This will also be the case for the frequency sequences generated by DBBCs and RDBEs that operate

in PFB mode since they, of necessity, have minimum frequency spacings of 32 MHz. If, however, all PCAL tones are extracted and applied (as is easily possible with the DiFX pulse cal detectors), the SBDs of the PFB 32 MHz channels can efficiently resolve the 31.25 ns MBD data ambiguities. At the same time, it should be easy to resolve the 200 ns PCAL ambiguities. Unless antenna cables are changed, PCAL delays should remain reasonably constant at the 200 ns level making the 200 ns discontinuities easy to detect and correct. If a nominal 200 ns ambiguity is assigned as a standard for a site, it is conceivable that delays could be made consistent even between sessions.

- <u>PCAL frequency offset.</u> Coherent signals can corrupt PCAL tones if their respective frequencies coincide. This occurs in a number of ways (of which the latter two listed below can be mitigated by offsetting the net LO frequency such that the tones are not found at integer MHz values in the baseband channel):
    - Internal LO signals and their images, clock signals and their harmonics, and external RFI signals (sometimes radiated directly by the PCAL unit) often occur at integer MHz values. Since the PCAL tones are also at integer MHz values, it is inevitable that some PCAL tones will be corrupted. However, if care is taken in the RF design, the number of tones corrupted should be small. Given that modern VLBI systems detect all PCAL tones, the vast majority of tones will be useable. In addition, the systematic character of the good tones will make it easier to identify and eliminate (even automatically) the corrupt tones.
    - Because anti-alias filters are not perfect, PCAL tones outside of the sampled band will be aliased into the band. Furthermore, if the tones occur at integer MHz values in the baseband channel, the aliased tones lie directly upon the in-band tones of interest. This corruption can be reduced using improved anti-alias filters, but a better solution is to offset the LO such that the tones no longer occur at integer MHz values. This in turn offsets the frequency of the aliased tones from the in-band tones.
    - Sharp edges produced by digitization introduce harmonic content to a signal. If the PCAL tones lie at integer MHz values their harmonics lie directly on other PCAL tones thus corrupting them. This can be mitigated by offsetting the net LO frequency such that tones do not lie on integer MHz values. For example, if the LO is offset by 10 KHz, as is standard practice in legacy sessions, then tones lie at 0.01, 1.01, 2.01,…. MHz. Since 1.01 MHz is the $101^{st}$ harmonic of 0.01 MHz, the 10 KHz offset greatly reduces PCAL harmonic corruption. On the other hand, with the broadband systems, offsets are in multiples of 0.4 MHz in which case corruption begins with the $5^{th}$ harmonic making mitigation of harmonic corruption significantly less effective. [However, the corruption could be reduced further if PCAL data from RDBE PFB

input pulse cal detectors (that use the 8-bit sampled input data) are used. Due to the finer steps of the 8-bit sampled input data, harmonic distortion due to digitization is significantly reduced over what can be expected in the 2-bit re-quantized channel data that is sent to the correlator. If harmonic distortion in the correlator PCAL detectors is shown to be a significant problem, data from the RDBE input pulse cal detectors could be transmitted to the correlator and used in fringing.]

- PCAL tone visualization. In legacy systems, a 10 KHz filter and oscilloscope allow the visualization of PCAL tones. This is required for data quality analysis and trouble shooting. It is recommended that a similar type of visualization be incorporated into the broadband and mixed mode configuration.

It is assumed that mixed mode correlation will be done with a software correlator (in most cases DiFX). Although compatibility at the observation level is desirable, a number of ***compatibility issues*** have been addressed directly ***in the DiFX correlator***:

- Offset bands. The correlator can correct for small frequency offsets of the bands (Done but not fully tested).
- Different bandwidths. "Zoom" mode can be used to align data taken with different bandwidths (Done but not fully tested).
- Sideband reversal. If data are taken with opposite sideband orientation, one of the sidebands can be reversed with a simple digital manipulation (Done but not fully tested).
- Different polarizations. Linear polarization can be correlated against circular polarization. To get full sensitivity, however, both linear polarizations must be correlated and the outputs added. This doubles the data rate generated by broadband (linear polarization) sites (Done but not fully tested).
- Multi-tone PCAL extraction. The detection of all PCAL tones through the use of a pulse cal algorithm allows single band delays to efficiently resolve multi-band ambiguities and hence eliminate the need for ambiguity resolution during analysis (Done, I think).
- Handle 200 ns PCAL ambiguities. The PCAL pulses have a 200 ns ambiguity due to the fact that the epoch of the antenna unit div5 circuit is indeterminate. This can be corrected during fringing. (Not done)
- Complex vs Real. The correlator can handle either real or complex inputs. (Done but not fully tested).

**General Restrictions and Recommendations for Mixed Mode Observing**

- A total of 16 output channels should be used. This has the following benefits:
    - It allows the generation of good frequency sequences
    - It is achievable with existing digital back ends

    - It is nearly compatible with legacy analog back ends where only 14 channels are available.

- Because of IF distribution limitations of the DBBC, it is recommended that channels be distributed as 8 S-band and 8 X-band.

- Frequency sequences should be designed to produce efficient and robust delay functions. It is important that, regardless of the 1st LO frequency at a particular S/X station, no RDBE DDC band straddles 128 or 384 MHz in the baseband sampled input.

- An output channel bandwidth of 32 MHz should be used since this is currently the only bandwidth available in either DBBC or RDBE PFB mode. This bandwidth is directly compatible with the 32 MHz output channel option in RDBE DDC mode and with the 32 MHz output channel option in DBBC DDC mode that is currently being beta tested. It is however incompatible with the 8 MHz maximum operational bandwidth of legacy analog systems and will require “Zoom” mode in the correlator if it is to be used. The use of 32 MHz channel bandwidths will help improve system sensitivity in general but may have other problems at S-band where RFI avoidance is an issue. If S-band RFI avoidance becomes a significant concern, PFBs may need to be upgraded to handle 16 MHz or perhaps even 8 MHz output bandwidths.

- A PCAL offset of 200, 400, 600, or 800 KHz should be used. This is compatible with the 400 KHz step size of the Up/Down Converters (UDCs) used at broadband sites. This is not a problem for DBBC DDC mode since it has a frequency step size of 10 KHz; but *is* a problem for RDBE DDC mode since it has a frequency step size of 15.625 KHz (which cannot produce a 400 KHz offset). There are three options for solving the RDBE step size problem. Residual band alignment could be done in the correlator, the RDBE DDC bit code and control software could be revised to generate 10 KHz steps, or special purpose hardware (up/down converter with offset LOs) could be developed to offset the band frequency.

- To operate in mixed mode sessions, broadband stations require either three RDBEs, or a single DBBC2010 (which is essentially equivalent to two DBBCs). At the present time only RDBEs are available at operating broadband stations. To be useable at broadband sites, RDBEs must operate in PFB mode while the DBBC2010s (which have 8 IF inputs and up to 32 USB/LSB channels in DDC mode) can operate in either PFB or DDC mode. [Recall that the dual linear polarization front ends used at broadband sites double acquisition requirements to a total of six 512 MHz IF inputs (2 X-band and 1 S-band for each of V-pol and H-pol) and a total of 32 output channels (16 for each of V-pol and H-pol.]

- To operate in mixed mode sessions, legacy S/X stations can operate with four receiver back-end options:
  - A DBBC in DDC mode. DDC mode allows arbitrary LO offset, output bandwidth and sideband selection and hence reconciles many compatibility issues. A standard DBBC can produce 16 USB/LSB outputs which are enough to handle the circular polarization inputs at S/X stations.
  - Four RDBEs in DDC mode. Once again, DDC mode allows arbitrary LO offset, output bandwidth and sideband selection and hence reconciles many compatibility issues. Each RDBE can produce 4 USB/LSB outputs so four RDBEs are required to generate the 16 USB/LSB outputs which are needed to handle the circular polarization inputs at S/X stations. The 15.625 KHz LO resolution of RDBE DDC mode will however require that the LO offset feature of the correlator be used for final LO alignment when co-observing with stations that use 400 KHz LO resolution (i.e. broadband stations).
  - Two RDBEs in PFB mode. Compared to the previous option, this is a more economical RDBE option with respect to the number of units required although its inflexibility leads to the need for additional special purpose hardware. The need for the additional hardware is due partly to the lack of uniformity of S/X front ends. Although a number of stations use standard NASA front ends with 2020/8080 MHz LOs and 240/800 MHz bandwidths, LOs and bandwidths at other stations vary considerably. Both to compensate for the potential gross misalignment of SX first LOs and to implement fractional-MHz LO offsets to improve PCAL detection, an additional special purpose hardware unit such as an up/down converter with offset LOs is required.
  - A Mk4 or VLBA analog back end. This option has the disadvantage of 8 MHz output channel bandwidths which requires that “Zoom” mode be invoked in the correlator. The 8 MHz channels also reduce sensitivity. For most stations, the use of analog back ends is a temporary expedient until a digital back end can be deployed.

- Five deployed instrumentation configurations have been identified that need to be compatibility tested:*
  - BB_RDBE_PFB(32, 0.4)
  - SX_RDBE_DDC(32. 0.40625)
  - SX_DBBC_DDC(32, 0.4)
  - SX_ANAL_BBC(8, 0.4)
  - SX_ANAL_BBC(16, 0.4)

* nomenclature shorthand for instrumentation configurations has the following elements:

- receiver front end (BB – broadband; SX – S/X band),
- receiver back end (RDBE, DBBC, or ANAL),
- channel structure (PFB, DDC, or BBC),
- output channel bandwidth (8, 16, or 32 MHz),
- LO offset (0.0, 0.01, or 0.4 MHz)