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Differences Between VLBI2010 and S/X Hardware

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Abstract

While the overall architecture is similar for the station hardware in current S/X systems and in the VLBI2010 systems under development, various functions are implemented differently. Some of these differences, and the reasons behind them, are described here.

1. Scope

This paper compares various aspects of the station hardware in S/X-band geodetic VLBI systems and in forthcoming VLBI2010 systems. Components in the signal path from the antenna feed down to the data formatter are treated. Outside the scope of this paper are the antenna structure itself, the data formatter and recorder, the time and frequency standard, and ancillary equipment (e.g., meteorological instruments). The discussion here of VLBI2010 is biased toward the hardware under development for the NASA proof-of-concept system. Other groups are investigating alternative approaches, some of which are described in other papers in these proceedings.

2. Drivers Behind Design Decisions

Table 1 summarizes the most important characteristics of the S/X and VLBI2010 systems as they relate to the hardware design. For VLBI2010, it is assumed that the primary observable is the so-called“broadband delay,” which is described in [4].

Table 1. Some S/X and VLBI2010 Characteristics

	S/X	**VLBI2010**
No. polarizations	1	2
No. observing bands	2	4
Bandwidth per band	∼200 MHz / ∼800 MHz	1 GHz[1]
Center frequencies of bands	∼2.3 GHz / ∼8.6 GHz	Tunable over 2–14 GHz
Total recorded data rate	128–512 Mbps	32 Gbps[1]
Delay precision per observation	10–30 ps	∼4 ps

Compared with S/X, VLBI2010 will record more bandwidth over a wider frequency span and will therefore “see” more RFI. In order to avoid RFI, the frequency locations of the four VLBI2010 bands must be adjustable, possibly from session to session. This wider frequency range and band tunability are the primary drivers behind many of the differences in hardware design.

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[1] The bandwidth and data rate of the NASA proof-of-concept system are half these values.

3. Antenna Feed

S/X feeds are designed to receive circularly polarized (CP) radio waves, not linearly polarized (LP). The primary advantage of CP feeds is related to the fact that the relative orientation of the two feeds on a VLBI baseline changes as a source is tracked across the sky, for all antenna mount types besides equatorial. For LP feeds, this change in orientation causes each parallel- or cross-hands fringe amplitude to vary with time, and in some cases can cause the amplitude to pass through a null. In contrast, for CP feeds the amplitude is independent of feed orientation.

Constructing a CP feed with low loss and good polarization purity is relatively straightforward for a fractional bandwidth of order 10%, as for S/X, but it is difficult for bandwidths exceeding an octave. Almost all wideband feeds that have been, or are being, developed (e.g., the Eleven feed [3]) and could be used in VLBI2010 are intrinsically LP. There are at least three options for creating CP signals from two orthogonal LP signals:

- Add a wideband quadrature hybrid after the feed to create circular from the two linears.
- After the sampler, create circular from the two linears in the digital domain [1].
- Record both LP signals at each station; after correlating all LP parallel- and cross-hands, create CP visibilities from the four LP cross-products.

The choice among these options (and others) has yet to be made for VLBI2010.

4. Low-noise Amplifier

The essential features and performance of an S/X and VLBI2010 low-noise amplifier (LNA) are similar: multi-stage, cryogenically cooled, transistor amplifiers with 30–40 dB gain and 5–20 K noise temperature. Unlike the S/X case, however, where only one LNA is required per polarization/band, the design of some VLBI2010-suitable feeds (e.g., [3]) entails the use of two, and perhaps even four, LNAs per polarization, with their outputs combined in one or three hybrids.

The wider bandwidth of the VLBI2010 system makes it more likely that RFI will fall within the LNA frequency range. Even if the RFI falls outside the frequency range of the recorded data, it can degrade the data SNR if it is strong enough to saturate the LNA or the post-LNA electronics. The electronics must therefore have sufficient output power capability to withstand any in- or out-of-band RFI without saturating. Notch filters could be employed to attenuate severe, fixed-frequency RFI, but it may not be possible to insert them ahead of the LNA.

5. Frequency Downconversion

For both S/X and VLBI2010, downconversion from the sky frequency to the frequency of the recordings is normally done in two steps: first from the sky frequency (RF) to an intermediate frequency (IF) somewhere in the range 100–2000 MHz, and then from IF to baseband, which extends from DC to <50 MHz.

5.1. Downconversion from RF to IF

Figure 1 illustrates two downconversion techniques used at cm wavelengths. The upper one is common in S/X systems, where the RF frequency band of interest never changes. The IF output from the mixer is the same as the RF input except shifted down in frequency by the local oscillator (LO) signal. In the absence of any filtering ahead of the mixer, RF signals at two frequencies can appear at the same IF output frequency: one at RF1 = LO + IF (the upper sideband = USB) and another at RF2 = LO − IF (the lower sideband = LSB). The "image rejection" filter in the RF path ensures that the output signal comes from just one input sideband and is not contaminated by the "image" frequency sideband.

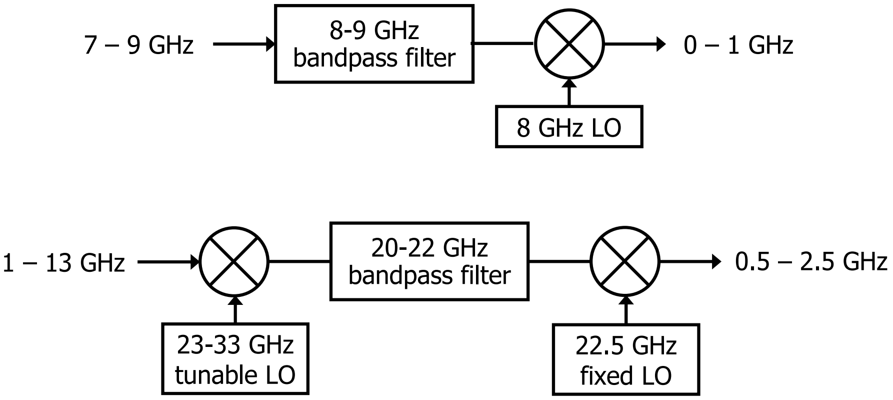

Figure 1. Simplified block diagrams of two types of single-sideband frequency downconverters. *Top:* Fixed-frequency downconverter, in which the 8–9 GHz input is translated down to 0–1 GHz, and all other input frequencies are blocked. *Bottom:* Tunable up/down converter [6], in which the 2-GHz-wide portion of the input spectrum that is translated down to 0.5–2.5 GHz varies with the first LO frequency. The input frequency corresponding to the output center frequency of 1.5 GHz is (1st LO − 21 GHz).

The above technique is impractical for VLBI2010, since the RF observing bands must be adjustable, and high-quality filters that are tunable over 2–14 GHz do not exist. An alternative scheme, which has been implemented in the NASA proof-of-concept test-bed, is the so-called up/down converter (UDC) illustrated in the lower part of Figure 1. Here the downconversion is carried out in two steps, first raising the frequency by mixing the input signal with a high-frequency LO, and then dropping the frequency to IF by mixing with a fixed-frequency LO. A bandpass filter between the two mixers provides image rejection. By changing the first LO frequency, the input RF frequency that appears at a given output frequency can be changed.

A potential future candidate for a tunable VLBI2010 RF-to-IF downconverter is an image-rejection, or single-sideband (SSB), mixer. Such a mixer employs two mixers driven by a common LO and phasing techniques among the signals to generate separate outputs for the input upper and lower sidebands, without the need of a filter. As with the UDC, the output can be tuned to different input frequencies by varying the LO frequency. It has not yet proven possible to build an SSB mixer operating over the wide VLBI2010 bandwidth with acceptable image rejection (of order 50 dB). But recent developments [2] in mixed analog/digital circuit design demonstrate that such an SSB mixer might be feasible in the near future. An advantage of an SSB mixer is that it does not use high-frequency (>20 GHz) components, which tend to be costly and less phase-stable.

Four downconverters per polarization are required to support the four-band observations of VLBI2010. Considerations of size, maintenance, and thermal control, among others, argue for placing the downconverters in the control room, rather than on the antenna, where they are located in nearly all (but not all) S/X receivers. The VLBI2010 RF signals will be brought down over optical fiber, instead of the coaxial cable used in most (but not all!) S/X systems.[2]

5.2. Downconversion from IF to Baseband

Until recent years, all S/X systems used analog baseband converters (BBCs) to downconvert from IF to baseband. In each BBC, an SSB mixer provides separate USB and LSB outputs. The multiple frequency channels per band needed for bandwidth synthesis are realized by multiple BBCs, each with a different LO frequency.

In principle, VLBI2010 could also use analog BBCs, but digital back-ends (DBEs) provide an alternative that is far more flexible, electrically stable in phase and gain magnitude, and affordable. DBEs under development at several institutions are described in papers in these proceedings. DBE firmware comes in two flavors:

- Digital downconverter (DDC or DBBC): Each DDC functions like an analog BBC, with a tunable LO to downconvert two IF sidebands on either side of the LO to baseband. As in analog systems, multiple DDCs are needed to provide the multiple baseband channels for bandwidth synthesis.
- Polyphase filterbank (PFB): A PFB splits the input into 2^N equal-width frequency channels, which are in effect all downconverted simultaneously to baseband on separate outputs. The input-to-output frequency mapping is much less flexible in a PFB than in a DDC, but that loss of flexibility ought not to be a significant limitation for VLBI2010.

An obvious difference between analog BBCs and DBEs is that signal sampling/digitization occurs after the BBC but before the DBE. With analog baseband bandwidths generally $\leq$16 MHz, the sample clock need run no faster than 32 MSps. In VLBI2010, however, the analog bandwidth defined by the anti-alias filter at the sampler input will be 1024 MHz, and the sample clock must run at 2048 MSps. (As noted in Table 1, the bandwidth and clock rate in the proof-of-concept system are half as large.)

6. Phase Calibration

A phase calibration system enables corrections for temporal variations in: (1) relative LO phases between BBCs within a band, (2) relative LO phases between bands, and (3) phase/delay drifts in RF or IF cables or electronics. The first type of correction is critical for S/X geodesy but is unnecessary with the super-stable, digital-equivalent LOs of a (properly functioning!) DBE. On the other hand, the second is important for VLBI2010 but is irrelevant to S/X unless the phase delay observable is being used. Even aside from the third factor, it is thus apparent that phase calibration is needed for both S/X and VLBI2010.

Compared with an S/X calibration system, a VLBI2010 system must operate to a somewhat higher frequency ($\sim$14 GHz vs. $\sim$9 GHz). A lower temperature sensitivity is also desirable, to help meet the more stringent VLBI2010 performance goals. A new calibrator design [5], which has been adopted for the NASA proof-of-concept system, generates the calibration pulses with a high-speed

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[2] An early exception on both counts was the c.1995 Green Bank 20-meter receiver, which transmitted the S/X RF signals over optical fiber from the antenna to the control room, where the downconversion took place.

comparator and digital logic gate, rather than with a tunnel diode as in older S/X designs. The temperature sensitivity of <1 ps/°C is better by an order of magnitude over S/X.

A potential problem for any VLBI2010 calibration system is overload in the RF analog electronics when the pulse is "on". For the X-band portion of an S/X system with a bandwidth of ∼1 GHz and a pulse repetition rate of 1 MHz, the peak pulse power is typically ∼10 dB stronger than the system thermal noise. The pulse/noise power ratio scales with bandwidth, so that in the 12-GHz VLBI2010 bandwidth, the pulse will be ∼20 dB above the system noise, and amplifiers may be in danger of saturating. A method adopted in the proof-of-concept system to reduce this danger is to attenuate the pulses, while at the same time increasing the pulse rate from 1 to 5 MHz. The increase in rate has two effects: it reduces the number of tones in the frequency domain, from one every 1 MHz to one every 5 MHz, and it increases the amplitude of each of the remaining tones by a factor of five. By balancing this amplitude increase against the decrease from the pulse attenuation, the strength of the tones can be maintained at a level high enough to ensure satisfactory phase measurement precision and immunity from spurious signal contamination.

The pulses should be injected into the receiver as close as possible to the point where the microwaves enter the receiver. In S/X receivers this is normally done in a directional coupler between the feed and LNA. This method may not be practical in VLBI2010 receivers because of the nature of the wideband feeds. Instead, injection for each polarization may occur after the LNAs and combiners. Alternatively, pulses could be radiated into the feed from a small antenna mounted on the main antenna structure. Multipath is a potential problem with this approach.

Most S/X systems include a cable measurement system for measuring variations in the electrical length of the cable (coax or optical) carrying the reference signal to the pulse generator. Use of cables with low sensitivity of delay to temperature and mechnical stress may make a cable measurement system unnecessary in VLBI2010, but this issue requires further study.

7. Acknowledgments

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