Correlating and Fringe-fitting Broadband VGOS Data

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Abstract The great promise of increased precision and accuracy in the broadband VGOS system is accompanied by great challenges in processing the data it generates. The large spanned bandwidth necessitates ionospheric correction within the fringe-fitting process. Frequency sequences must be chosen not only on the basis of group delay precision and ambiguities, but also the ability to connect phase between bands, decouple delays from the ionosphere, and possibly to go to a phase-delay observable. The desire to use the system in conjunction with legacy S/X geodetic systems raises the issue of cross-correlating linearly- and circularly-polarized observations, mismatched bands, and unequal sample rates. This paper elaborates on these issues and describes how they are handled within the HOPS post-processing software.

Keywords VLBI, broadband, calibration

1 Introduction

As systems become more capable, there is generally a concomittant rise in complexity; the VGOS broadband geodetic VLBI system is no exception. Fortunately, there has been a parallel, even more dramatic increase in the capability of computing systems, so the tools are at hand to cope with the ensuing complexities. Here we document some of the new and modified algorithms used in the *fourfit* fringe-fitting program.

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2 New Complexities Introduced by VGOS

Ultimately, the group delay observable is estimated by observing the change in interfereometric phase over a range of frequencies; the delay error is inversely proportional to the spanned bandwidth. By utilizing the full spectrum from about 3 GHz to 13 GHz, the VGOS system leverages a very wide spanned bandwidth compared to the legacy S/X band systems. At the same time, the *sampled* bandwidth has been significantly increased, to 2 GHz or more. Since the station sensitivity is directly proportional to the sampled bandwidth, this increase allows smaller, cheaper, and more agile antennas to be employed.

There is, however, a price to be paid for the increased frequency coverage and bandwidth, principally because:

- Single coherent fits across 8–10 GHz require treatment of ionosphere and source-structure effects at fringe-fitting time.
- VGOS uses dual linear polarization, since circularly polarized feeds that work well over a 2 octave frequency range are difficult to realize.
- The typical data volume has increased to 43 TB/day/antenna, assuming 8 Gb/s data rate and 50% observing duty cycle.
- Array homogeneity is reduced due to the mixture of VGOS and legacy S/X stations:
  - bandwidths/sample-rates are no longer equal,
  - there is a mixture of circular and linear polarizations,
  - frequency sequences mismatch,
  - sidebands mismatch.

In addition to these added complexities that are necessitated by the move to a wideband system, there are other challenges that have arisen as a by-product of general system improvement. The Mark 6 recording system (Cappallo et al. 2013) improves upon Mark 5 for performance and ease of use, but it constitutes another data format needing to be supported. Also, the move to complex sampling in the RDBE 3.0 offers efficiencies in both hardware and software, but it requires new code to deformat and correlate the data.

2.1 Phase Calibration and Connection

Phase calibration signals are injected at the receiver as a series of pulses at intervals of 200 ns, which can also be considered as a series of tones at 5 MHz spacings. These tones follow the same signal path as the radio-astronomical data down from the front end, and experience the same delay through the system prior to digitization (leg B in Figure 1). Since the upward path (leg A) can also experience time-varying delays due to phenomena such as cable stretching, leg A's delay will be measured independently by a cable delay calibration subsystem, and that delay contribution will be removed from the A + B − C combination. Leg C, which is typically a short cable run within the control room, combined with a small amount of timing electronics in the digitizer, is very stable over time, and appears simply as a clock offset.

The phases of all tones in each channel are extracted, and they are used to find out the instrumental delay in each channel. The 5 MHz tone spacing results in an ambiguity of the delay determination of 200 ns; i.e., the true delay is 0 or more increments of 200 ns in addition to the delay determination. This is handled within *fourfit* by allowing the user to specify *a priori* in which 200 ns range the delay is expected to lie. In modern digital backends, channels fed by the same IF and sharing the same cabling and anti-aliasing filter have very similar instrumental delays. Thus one can solve for a single delay per IF and apply it to all channels.

In current practice there are three parameters that are adusted during the fringe-fitting process:

1. **singleband delay** – the delay of each single channel

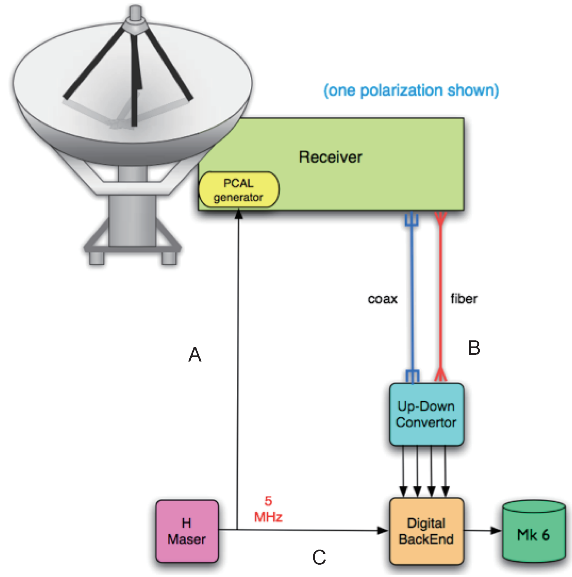

Fig. 1 Phase calibration paths: the delay measured by the phase cal tones is that of paths A + B − C. Path B is in common between the tones and the astronomical data, whereas the delay along path A must be measured by a cable delay calibration system.

2. **multiband delay** – the group delay found by estimating the linear phase change across multiple frequency channels
3. **delay rate** – the rate of change of delay

The historical reason for having two delays comes from instrumental causes: the single channels can have significant cabling and anti-aliasing filter differerences. With the move to digital backends, multiple channels share the same wideband anti-aliasing filter. Also, multiple phase cal tones are extracted from each channel, allowing the measurement and correction of each station's instrumental delays. In this manner we hope to use only a single delay in the fringe-fitting process.

2.2 Ionosphere Removal

In the S/X geodetic system independent group delay estimates are made for X-band and S-band, and a linear combination of these delays, $\tau_g = 1.081\tau_x - 0.081\tau_s$, is used to give a group delay measurement that is nearly free of ionospheric effects. One drawback of this system is that both the S and X band obervations have

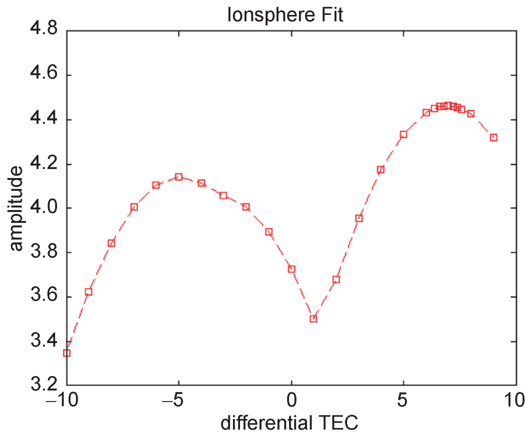

Fig. 2 Ionospheric fit – correlation amplitude as a function of differential TEC in TEC units. A complete fringe fit at multiple points for trial values of the ionospheric differential TEC is performed, and the code finds the interpolated maximum. The algorithm used is that a range of coarse values is specified, the maximum within the range is found, then a second pass fine search is done around the maximum. Although the efficiency of this algorithm could possibly be improved, it has proven a very robust mechanism for finding the maximum value. This example of the fitting process uses 19 coarse points spread over a dTEC from −10 to 10 TEC units.

to have a high enough signal-to-noise ratio so that a good detection can be made in each band. In constrast, the VGOS system is designed to work with very short scans, in which the individual bands may not provide a reliable detection, and in which all four bands need to be combined coherently in a fit. Since this fit also spans a wide frequency range, it is necessary to fit and remove the differential ionosphere from the group delay estimate.

The phase contribution in radians due to the ionosphere, $\Delta\phi$, is

$$\Delta\phi = -8.448x10^9 dTEC/f, \tag{1}$$

where f is the observing frequency in Hz, and $dTEC \equiv TEC_b - TEC_a$ is the differential TEC for baseline ab in TEC units (1 TEC unit = 10^{16} elec/m^2). Since phase is only measured modulo 2π, there is a non-linear dependence of phase upon the dTEC parameter in the model, which restricts the manner in which a fit might be performed (see Figure 2 for a brief description of the coarse-to-fine search algorithm used in *fourfit*).

2.3 Linear Polarization

In order to achieve reasonably good feed characterstics across the full frequency range, the VGOS design uses linearly polarized feeds. This adds significant complexity to the signal processing tasks, as all four polarization products must be produced and then combined in an optimal fashion to estimate group delay. A pseudo-Stokes-I (Intensity) observable can be formed, which is accurate to first order in the polarization leakage D-terms (Corey 2011). The pseudo-Stokes-I observable is formed as

$$I = (\overline{X_a \star X_b} + \overline{Y_a \star Y_b})cos(\delta p) + (\overline{X_a \star Y_b} - \overline{Y_a \star X_b})sin(\delta p), \tag{2}$$

where δp is the differential parallactic angle between sites a and b, and $\overline{X_a \star Y_b}$ is (for example) the time-averaged correlation product of site a's X polarization with site b's Y polarization.

2.4 Choice of Observable

Traditionally, geodetic VLBI has relied upon the group delay observable, as determined by the slope of phase vs. frequency across the span of several hundred MHz in a single band. The group delay can also be used with VGOS, with a much broader effective band; by connecting phase across multiple bands, we in effect form one large band – perhaps as much as an order of magnitude larger than was previously achievable. The error in the resulting group delay estimate, $\sigma(\tau_g)$, is given by

$$\sigma(\tau_g) = 1/(2\pi s\rho), \tag{3}$$

with signal-to-noise ratio s and rms spanned-bandwidth ρ.

If the system is sufficiently stable, then the residual phase left over after the best-fit delay model has been subtracted is slowly-varying. Its determination is equivalent to finding the y-intercept of a linear fit of phase vs. frequency. This means that the frequency span over which the phase is being determined is from 0 to the mean observing frequency, and thus

$$\sigma(\tau_p) = 1/(2\pi s\overline{f}) \tag{4}$$

with mean frequency $\overline{f}$. The error has then decreased by the ratio

$$\sigma(\tau_p)/\sigma(\tau_g) = \overline{f}/\rho, \quad (5)$$

which is ≈ 4 for the currently planned observing frequencies. If the phase delay observable is to be successful, then both the instrumental drifts in phase and the unmodeled phases due to source structure, which can vary as a function of both time and frequency, need to be sufficiently small.

2.5 System Complexity

The design choices described above lead to increased complexity in the execution of an experiment using the VGOS system. The placement of the frequency channels, for example, should be carefully considered, especially since there are somewhat contradictory criteria, whose effects need to be balanced:

- the channels should be spread apart to increase group delay precision;
- the channels should be spread fairly evenly to make phase connection between bands more robust;
- it is desirable to place the channels to decrease the correlation between the f group delay and the ionosphere's signature of 1/f;
- if there is a mixture of legacy stations, then the channels should be located where there is as much overlap with the legacy channels as possible.

In the VGOS system there are two polarizations, each with four bands of eight channels. Polarization-dependent phase corrections need to be determined for each antenna system, since the phases are dependent on some uncalibrated portions of the front end. The flood of data, with scans at intervals as low as 30 s or so and close to a petabyte of raw data per experiment, will stress the data-processing pipelines at the correlation centers. Efficient bookkeeping and quality control will be essential.

3 Transitioning from Legacy Systems

It is desirable to keep some compatibility between the broadband VGOS system and the legacy S/X band systems. This will establish continuity of the terrestial reference frame, and, through the ties of VLBI observations, there will also be better continuity of the celestial reference frame. For these reasons, it is expected that parallel observations will be made for some years after the introduction of the VGOS system. Thus the technical difficulties entailed in joint observations need to have satisfactory solutions.

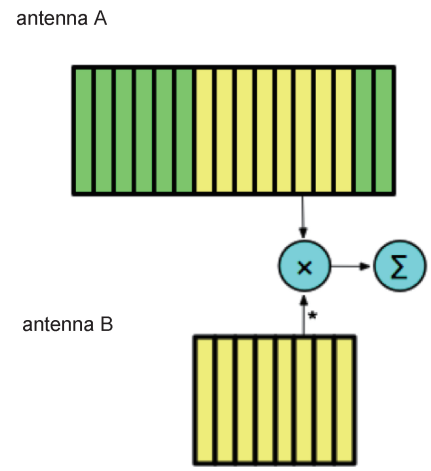

Fig. 3 Correlation of non-matching bandwidths by ensuring channel alignment within the F-stage of an FX correlation.

3.1 Mismatching Bandwidths, Sample Rates, and Channel Alignment

In general, recent practice with the legacy geodetic observing mode has been to use a bandwidth of 8 MHz, and thus a Nyquist sampling frequency of 16 MHz. On the other hand, the VGOS current standard is channels of 32 MHz bandwidth, sampled at 64 MHz. Furthermore, the local oscillator (LO) for the legacy setup is such that channels start at xxxx.99 MHz to try to preserve phase cal purity, while the broadband channels typically start at yyyy.40 MHz.

Cross correlations between the systems, in so-called "mixed mode" are accomplished (see Figure 3) by picking a narrow channel width, δf, in the F stage of an FX correlation, which satisfies the following two conditions:

- δf divides evenly into both station's channel bandwidths,
- the edges of the resulting narrow channels line up.

For the frequency setup mentioned above, $\delta f = 10\,\text{kHz}$ satisfies these conditions. Then, in the cross-multiply, or X, stage of the correlation the corresponding narrow channels are paired off, multiplied, and summed.

In the *DiFX* program, which is a software correlator (Deller et al., 2011), this is accomplished using "zoom" mode. Zoom mode was originally intended for selectable high spectral resolution in portions of the processed band, but it also works as a way of implementing the necessary machinations for mixed mode. It handles the chore of sideband conversion of one of the signals, if the mismatching bands fail to match in sideband (i.e., upper x lower). New code was written to synthesize an output VEX file that correctly describes the narrower intersecting bands that result from zoom mode, in order to allow correct post-processing of the data.

3.2 Mixed Polarization

The legacy S/X band observing mode has been to use right circular polarization (RCP), whereas the new VGOS systems are dual linear polarization (XY). When there are multiple polarization products, the noise products contain statistically independent information, and we can maximize the sensitivity of the delay observation by coherently combining all available polarization products. In the most general case of dual circular polarization correlated against dual linear polarization, we have four products (XL, XR, YL, YR), and the appropriate linear combination for the complex visibility would be

$$V = (a_{xl}\overline{X \star L} + a_{yl}\overline{Y \star L})e^{i\delta p} + (a_{xr}\overline{X \star R} + a_{yr}\overline{Y \star R})e^{i\Sigma p}, \quad (6)$$

where δp and Σp are respectively the differenced and summed parallactic angles, and the a_{pq} are unit-magnitude complex phasors representing (minus) the calibration phase between polarization states p and q. The unit phasors are used to counter-rotate the complex fringes so that they will line up coherently. It is the expectation (and hope) that the phases will be very slowly varying, so that the calibration phasors need to be solved for only infrequently during an experiment, and they can subsequently be used over a long span of time. Note that this formulation for using the mixed polarization products differs from the earlier pseudo-Stokes-I in Equation 2, for there has been no effort here to correctly normalize the amplitudes. This simplification should only slightly affect the group delay estimate, but it would complicate the use of mixed-mode visibilities for imaging.

4 Future Work

Though many modifications have been made to the correlation and post-processing software to allow the efficient use of the VGOS broadband data, there are still desirable capabilities that have yet to be implemented:

- develop a $\phi(f)$ phase mode for source structure which would be calculated for each observation and applied in the fringe-fitting process, in order to permit phase connection across the bands for less point-like sources,
- correct for the known constant phase signature of the digital filters within each band,
- remove the current operational need for multiple passes (one per observing band) through the correlator,
- automate the generation of phase cal masks, which are used to exclude any phase cal tones that are corrupted by RFI,
- automate the generation of delay and phase calibrations for the VGOS multi-polarization-product data, and
- increase the size and efficienty of the computing clusters to handle the expected increase in observing and data rates.

Much of this work can be summarized simply, by noting that we need to achieve much better automation in the data pipeline for the anticipated needs of VGOS.

Acknowledgements

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