Increasing Space Very Long Baseline Interferometry Sensitivity Through Higher Data Rates

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For future space very long baseline interferometry (SVLBI) programs, ways have been studied for raising instrument sensitivity by increasing the baseline mission effective 256-MHz observation bandwidth, and correspondingly the spacecraft downlink data rate, by a multiple of between two and four. However, the challenge is to accomplish this within the constraints of the 37- to 38-GHz downlink band as well as the spacecraft transmitter restrictions. This article is concerned with the sensitivity gains obtainable through higher data rates, including considerations for an uncommon correlator mode, as well as a non-power-of-two sampling rate increase. The article concludes with a summary of the practical augmentations needed on spacecraft and ground implementations for increasing sensitivity relative to the baseline mission.

I. Introduction

The VLBI Space Observatory Program 2 (VSOP2) baseline data rate is 1.024 Gb/s, based on 2 bits per sample of a Nyquist (equivalent) 256-MHz bandwidth (BW). Using quadrature phase-shift keying (QPSK) modulation and simultaneous left circularly polarized (LCP) and right circularly polarized (RCP) carriers, this downlink data rate can be accommodated within the 37- to 38-GHz space research band. Details concerning the basic link design may be found in [1].

There is a strong desire to raise instrument sensitivity by increasing the effective 256-MHz BW, and accordingly the spacecraft downlink data rate, by a multiple of between two and four. (Expansions beyond this appear unrealistic for VSOP2.) But the challenge is to do this within the constraints of the 37- to 38-GHz band and the (already) restricted spacecraft transmitter power [or effective isotropic radiated power (EIRP)].

Section IV of [1] provides rationale on modulation techniques and associated EIRP increases needed to accomplish data rates above 1.024 Gb/s. This article is concerned with the sensitivity gains obtainable through higher data rates, including considerations for an uncommon correlator mode, as well as a non-power-of-two sampling-rate increase.

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II. Correlator Sensitivity as a Function of Quantization Levels

Radio telescope RF signals consist of the summing of a weak source (observable) with relatively strong receiver noise, the result being that the signal-to-noise ratio (SNR) is SNR << 1. At each telescope, the RF is converted to baseband (usually by means of single-sideband (SSB) demodulation), following which Nyquist-rate sampling and amplitude quantization to 1 bit (two levels) or 2 bits (four levels) take place. Such coarse quantization is necessary because current very long baseline interferometry (VLBI) digital correlators are limited in their computational capacity and speed due to complexity and cost considerations.

There is a penalty paid for using 1-bit or 2-bit quantization. When two radio telescope signals observing the same source are quantized to the same number of levels, the resulting cross-correlation SNR or sensitivity[2] is degraded by η_{QBB}, with the subscript value B designating the number of sample bits used by each telescope. It is well known that, when SNR << 1, $\eta_{Q11} = 0.637$ (-1.96 dB) for 1-bit sampling and $\eta_{Q22} = 0.881$ (-0.550 dB) for 2-bit processing [2 (Section 8.3),3 (Chapter 4)].[3] These results are valid for SNR $<$ 10 dB.[4]

Note particularly that these quantizing efficiencies result from 1-bit $\times$ 1-bit or 2-bit $\times$ 2-bit cross-correlations. Interestingly, 1-bit $\times$ 2-bit cross-correlation is not addressed by the two references just cited, but it is of considerable interest to space very long baseline interferometry (SVLBI). Before exploring this further, the degradation factor η_{Q12} needs to be determined. Kogan [4] is the only source I am aware of that addresses this correlator mode.[5] His motivation concerned bringing antennas that have only two-level digitizers into the very long baseline array (VLBA), and he was mainly concerned with the fringe stopping procedure for the FX correlator. However, Kogan notes a very important relationship for low SNRs, namely:

$$\eta_{Q12} = \sqrt{\eta_{Q11}\eta_{Q22}} \qquad (1)$$

Using the above values for η_{Q11} and η_{Q22}, $\eta_{Q12} = 0.749$ (-1.26 dB) for 1-bit $\times$ 2-bit sampling.

I have independently verified all quantizing efficiencies using the computer program *Mathematica*.[6] Table 1 summarizes low SNR cross-correlation efficiencies as a function of the number of signal quantization bits used for Nyquist sampling.

III. Increasing VSOP2 Sensitivity

As stated in Section I, the VSOP2 baseline employs 2 bits per sample for a total bandwidth of 256 MHz, with a resulting link bit rate of 1.024 Gb/s. One approach for increasing sensitivity is by raising BW, because sensitivity is a function of $\sqrt{\text{BW}}$.

[2] More fully, the sensitivity threshold. As used in this article, increased/decreased sensitivity is equivalent to higher/lower SNR.

[3] The four-level threshold voltages are set at $\pm 1\sigma$ of the input waveform, and the quantization weightings are ± 1 and ± 3.

[4] There is no practical difference in loss if the two signals being cross-correlated have considerably different SNRs, as long as both SNRs are less than 10 dB.

[5] I am indebted to Jon Romney of the National Radio Astronomy Observatory for providing me with this reference. When I first conceived of using 1-bit $\times$ 2-bit cross-correlation for SVLBI, I conferred with Jon regarding its practicality. He informed me that the VLBA correlator does not presently support this mode, but could if additional software were installed.

[6] *Mathematica* calculations involve straightforward evaluations of the underlying expressions without resort to low SNR approximations and are, therefore, valid for all SNRs.

Table 1. Cross-correlation efficiencies.

Signal pair quantization	Relative cross-correlation
None	1.000
2 bits × 2 bits	$\eta_{Q22} = 0.881$
1 bit × 2 bits	$\eta_{Q12} = 0.749$
1 bit × 1 bit	$\eta_{Q11} = 0.637$

A way to handle doubling of the 256-MHz BW, without any tangible impact to the spacecraft, is to use 1-bit sampling on the spacecraft while maintaining 2-bit sampling at all ground radio telescopes. This means that even though the spacecraft instrument's effective bandwidth is doubled, downlink characteristics (bit rate, carrier spectra, and required EIRP) are unchanged.

Normally, doubling the bandwidth of the observable increases cross-correlation sensitivity, by $\sqrt{2} = 1.41$, provided the system maintains 2-bit × 2-bit cross-correlation. But if the quantization of the spacecraft's signal is concurrently decreased from 2 bits to 1 bit, this full improvement is not achieved. The penalty for going from 2 bits × 2 bits to 1 bit × 2 bits is the ratio η_{Q12}/η_{Q22}. Thus, the actual sensitivity increase obtained for doubling BW while downgrading to 1-bit × 2-bit cross-correlation is

$$\text{sensitivity}_{\text{2BW \& 1×2 bits}} = \frac{0.749}{0.881}\sqrt{2} = 1.20 \tag{2}$$

This is a modest sensitivity increase, but nevertheless an increase that has virtually no impact on the spacecraft or the ground tracking stations. The most serious consequence is that each ground radio telescope will have to record 2.048 Gb/s rather than 1.024 Gb/s, and the correlator(s) will have to process 1 bit × 2 bits.

By way of extension, it seems natural to inquire into what it takes to go to 3 BW and 4 BW. The 3-BW case represents a non-power-of-two increase in bandwidth and bit rate (a situation not usually considered). In both cases, there is a far more dramatic impact on the spacecraft than for doubling BW. Mindful of the constraints for the downlink 37- to 38-GHz band, it becomes necessary to abandon QPSK modulation and substitute M-ary phase-shift keying (M-PSK) or M-ary quadrature amplitude modulation (M-QAM) forms. Correspondingly, higher EIRP is required through some combination of more transmitter power, a larger transmitting antenna, and restricted link operational conditions. All of these issues have been addressed in [1, Section IV].

Table 2 summarizes the pragmatic sensitivity-increase choices. (Note that BL denotes VSOP2 baseline sensitivity.) The last entry in Table 2 introduces the alternative of analog transmission. An equivalent analog bandwidth of 1.024 GHz easily fits into the 37- to 38-GHz band by subdividing[7] and placing 512-MHz-wide analog signals in each of the orthogonal polarizations. (A slightly more limited bandwidth would require only a single polarization.) Digitization is then accomplished at the ground tracking station. Analog transmission, unlike M-QAM, requires no innovative designs and components to implement. The spacecraft implementation is relatively easy, and the ground system requires no special data decoders. But it does have some potential drawbacks, especially its being subject to atmospheric effects from which digital transmission is virtually immune. But there are reasonable solutions to the analog system problems, which seem to make analog transmission a viable and far more cost-effective alternative to M-QAM.

[7] This may not even be necessary if the radio telescope simultaneously receives 512-MHz-wide LCP and RCP signals.

Table 2. Sensitivity-increase options.

System factors		Spacecraft telescope			Ground telescope	
Sensitivity increase	BB BW, MHz	Modulation form	Bits per sample	Bit rate, Gb/s	Bits per sample	Bit rate, Gb/s
BL	256	QPSK	2	1.024	2	1.024
BL × 1.20	512	QPSK	1	1.024	2	2.048
BL × 1.47	768	8-PSK	1	1.536	2	3.072
BL × 1.70	1024	16-PSK or 4-QAM	1	2.048	2	4.096
BL × 2.00	1024	Analog[a]	(2)	(4.096)	2	4.096

[a] Analog transmission is subject to troposphere coherence losses, requiring phase-transfer-based corrections to obtain the near-full-sensitivity increase indicated. Sampling takes place at the ground tracking station.

Table 3 summarizes the practical augmentations[8] needed on spacecraft and ground implementations for increasing sensitivity relative to the baseline mission.

IV. Conclusion

It has been shown that one means of increasing sensitivity by a factor of 1.2 is to expand bandwidth, but regress to 1-bit rather than 2-bit sampling on the spacecraft, while maintaining 2-bit sampling at ground radio telescopes. As data rates increase, it also becomes necessary for the spacecraft to employ M-PSK or M-QAM modulation in order to meet the constraints for the downlink 37- to 38-GHz band. The most realistic near-term options are 8-PSK and 16-PSK (or perhaps 4-QAM). However, there remain several outstanding practical problems regarding the implementations for various hardware elements at Gb/s data rates. Waveform generators, modulators, and RF power amplifiers are the most challenging devices, requiring substantial advanced developments if they are to provide adequate signal transfer fidelity for 16-PSK or 4-QAM.

References

[1] J. C. Springett, "Achieving Future Space Very Long Baseline Interferometry Gigabits-per-Second Data Rates," *The Interplanetary Network Progress Report 42-149, January–March 2002*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–26, May 15, 2002. http://ipnpr.jpl.nasa.gov/progress_report/42-149/149G.pdf

[2] A. R. Thompson, J. M. Moran, and G. W. Swenson, Jr., *Interferometry and Synthesis in Radio Astronomy*, second edition, John Wiley & Sons, 2001 (first edition 1986).

[3] R. A. Perley, F. R. Schwab, and A. H. Bridle, eds., *Synthesis Imaging in Radio Astronomy*, Astronomical Society of the Pacific Conference Series, Socorro, New Mexico: Bookcrafters Inc., 1989.

[8] The reader should be familiar with [1] and [5] in order to appreciate some of the annotations provided by Table 3.

[4] L. Kogan, "Correction Functions for Digital Correlators with Two and Four Quantization Levels," *Radio Science*, vol. 33, no. 5, p. 1289, September–October 1998.

[5] J. C. Springett, "Space Very Long Baseline Interferometry Ground Station Segmented Architecture," *The Interplanetary Network Progress Report 42-149, January–March 2002*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–17, May 15, 2002.
http://ipnpr.jpl.nasa.gov/progress_report/42-149/149H.pdf

Table 3. Practical considerations for sensitivity increase.

Sensitivity and modulation	Impact on spacecraft	Impact on ground tracking stations	Impact on ground radio telescopes and correlator
BL × 1.20, QPSK	None, except for providing the 1-bit per sample mode. No additional EIRP needed.	None on hardware. None on operations.	Record 2.048 Gb/s. Correlator operates in 1-bit × 2-bit mode.
BL × 1.47, 8-PSK	Requires 8-PSK modulator that likely can be constructed using analog circuits. Additional 3.0-dB EIRP needed for 8-PSK, plus 1.8 dB for data rate, or observe ground tracking restrictions in elevation versus weather.	Augmentation of QPSK Gb receiver or advanced application-specific integrated circuit (ASIC) needed. Restrictions for no additional EIRP: antenna elevation >20 deg for worst weather, or 90% or better weather for <20 deg.	Record 3.072 Gb/s. Correlator operates in 1-bit × 2-bit mode.
BL × 1.70, 16-PSK	Requires 16-PSK modulator. Analog circuits appear unsuitable; needs digital technology not yet available. Additional 7.1-dB EIRP needed for 16-PSK, plus 3.0 dB for data rate, or observe ground tracking restrictions in elevation versus weather.	Augmentation of QPSK Gb receiver or advanced ASIC needed. Rsestrictions for no additional EIRP: antenna elevation >20 deg, along with 90% or better weather	Record 4.096 Gb/s. Correlator operates in 1-bit × 2-bit mode.
BL × 1.70, 4-QAM	Requires 4-QAM square-root raised-cosine modulator and linearized transmitter. Analog modulator unsuitable; needs digital technology not yet available. No additional EIRP needed for 4-QAM, plus 3.0 dB for data rate, or observe ground tracking restrictions in elevation versus weather.	Augmentation of QPSK Gb receiver or advanced ASIC needed. Restrictions for no additional EIRP: antenna elevation >15 deg for worst weather, or 90% or better weather for <15 deg.	Record 4.096 Gb/s. Correlator operates in 1-bit × 2-bit mode.
BL × 2.00, analog	Requires constant-envelope converter "modulator." Probably the same EIRP as for 4-QAM (to be determined).	Dual-pilot receiver needed, but uses standard data acquisition terminal for data conversion. Troposphere corrections required.	Record 4.096 Gb/s. Correlator operates in 2-bit × 2-bit mode.