OVLBI-ES MEMO NO. 59

PULSE CALIBRATION FOR ORBITING VLBI

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1.0 INTRODUCTION

In a receiving system that is subject to variations in cable lengths, local oscillator phases, and other imperfections, it is conceivable that such effects can be removed by a calibration system that injects a stable tone into the receiver very near its input, and then measures the complex amplitude of this tone near the receiver output. In practice, especially at microwave frequencies, it is difficult to generate the calibration tone in such a way that it is significantly more stable than the variations that it is intended to remove, so the method has rarely been successfully used for this purpose.

However, in VLBI a related technique has been used for a different purpose, especially since its popularization by being incorportated into the widely-disseminated Mark III recording system. Although it is difficult to make the absolute phase of a single tone stable enough to be a good calibrator, the relative phases of a "comb" of tones can be made to have a stable and known relationship. This is accomplished by generating a periodic stream of very short pulses, and using this as the calibration signal. Pulse widths of only a few psec are practical, and these can be generated at rates of a few MHz. In the frequency domain, this corresponds to a comb of tones spaced at the pulse repetition rate, where the individual tones contain usable power up to several tens of GHz. By locating the pulse generator very close to the receiver input and injecting its signal via a directional coupler or similar device, the coherence of all tones across the receiver's input passband is assured. Typically the receiver includes downconversion to baseband; the tones are then at low frequencies where they can be easily detected by synchronous detectors that are implemented digitally.

This technique has been useful in certain VLBI systems (especially Mark III) because those systems achieved wide receiving bandwidth by combining many narrow-bandwidth channels. Each channel typically had at least one L.O. and filter independent of the others, and might also have separate cables and other components. To allow the channels to be combined coherently after correlation, it is necessary to know their relative phases; this can be accomplished using the calibration tones described above. In more recent systems (e.g., the VLBA), smaller numbers of wider channels are used, and coherence between them is maintained by design [footnote 1], making the calibration tones much less critical to successful operation. Nevertheless, they remain useful as diagnostic probes of system performance.

{1. The Mark III video converters contain L.O. synthesizers whose phase is undetermined within a factor of 5MHz/10kHz=500, and is not repeatable over multiple re-tunings to the same frequency. The VLBA baseband converters use a design that avoids this problem.}

In orbiting VLBI, both the VSOP and Radioastron spacecraft will include pulse calibration injection at the inputs of their receivers. The number of baseband channels is small (typically 2 for VSOP and 4 for Radioastron) and the designs ensure that the relative phases of the channels should be stable, so the main use of these calibration signals ought to be diagnostic. However, it has been suggested that the VSOP receivers may be subject to significant phase instability as a result of large temperature swings in the instrument package; it is therefore hoped that the calibration signals can be used to remove these.

2.0 DESIGN CONSIDERATIONS

I'll concentrate here on the OVLBI case, although many of the points are applicable to ground telescopes as well.

2.1 Injected Tone Level

Whereas the baseband signals will be coarsely digitized prior to correlation (with at most 4 quantization levels), it is necessary to keep the injected calibration signal power much smaller than the noise power. Otherwise, the total signal will not have the gaussian probability distribution that is assumed in interpreting the correlator output. Typically, the total calibration signal power (in all tones) is 1% or less of the total noise power over a given bandwidth.

2.2 L.O. Tuning

The pulse generation technique causes the tones to be at harmonics of the pulse repetition rate. Thus, if the rate is 5 MHz, then the tones are at harmonics of 5 MHz at the receiver input; that is, the frequencies are "round" numbers. But this is not necessarily true after conversion to baseband, since one or more L.O.s could be tuned to "non-round" frequencies. In the Mark III, VLBA, and Mark IV receiving systems, this is typically done by setting the final L.O. (in the baseband converter) to 10 kHz away from a harmonic of the calibration tone spacing. However, for VSOP and Radioastron, this is not possible. Both spacecraft have a tone spacing of 1.0 MHz, and they also have L.O. tunability only to harmonics of 1.0 MHz. Therefore the baseband frequencies of the tones will also be harmonics of 1.0 MHz.

As I mentioned, the baseband signals are coarsely digitized, and synchronous detection of the tones is typically accomplished digitally. For the OVLBI missions, this is certainly the case since there are no tone detectors on the spacecraft and only the digitized signals are sent to the ground. The coarse quantization is a highly non-linear process, causing distortion of the signal; the effect on gaussian noise is well understood, but here we consider the effect on the calibration signal. The distortion will generate harmonics of each tone; if these fall on top of other tones, then the various tones can no longer be detected independently. This is part of the reason that existing ground systems usually shift the calibration tones so that they are not harmonically related. But for VSOP and Radioastron, they will all be multiples of 1~MHz. This effect can be made arbitrarily small by reducing the strength of the calibration signal; it may be negligible at the 1% level. (Analytic calculation of the strength of the harmonics is difficult, so simulations are planned in order to get quantitative estimates.)

2.3 Tone Detectors

Synchronous detection of the tones is implemented in digital hardware so that it can be accomplished in real time. (It could be done in software if non-real-time results were acceptable, and if only a small fraction of the samples need to be processed.) It is assumed that the tone frequency is exactly known, and that the pulse repetition oscillator was coherent with the sampling clock. Then the detector synthesizes the sine and cosine of the tone frequency using the sample clock, and computes the sum of the products of these synthesized tones with the received samples. The two sums are accumulated for some predetermined integrating time. The synthesized sine and cosine are, of course, numbers of finite precision; in practical detectors, they are coarsely quantized (several bits). This means that their spectra include harmonics of the desired tone, and if other tones at those frequencies are present in the spectrum, then they too will be detected.

2.4 Sensitivity

For weak tones, the SNR obtained in integrating time T is

SNR = E_sig E_ext P T / 2N

where E_sig is the SNR efficiency of the signal digitizer; E_ext is the efficiency of the extractor's representation of sine and cosine; P is the power in the tone; and N is the power spectral density of the system noise. For ideal quantization at the Nyquist rate, E_sig is 0.637 for 2-level digitizers and 0.?? for 4-level. The extractor efficiency is

E_ext = (power in fundamental)/(total power)

and this is 0.84 for 2-level (square wave) representations and 0.94 for simple 4-level representations. Thus, even in the worst case (2-level signals and 2-level sine/cosine), we get SNR ~ 2500 for T=1sec when the calibration tones are spaced every 1.0 MHz and constitute 1% of the total power.

3.0 VSOP SATELLITE PROPERTIES

3.1 Calibration Tone Power Level: [I don't know this value, but it ought to be well under 1% of the total power.]

3.2 Calibration Tone Frequencies: Harmonics of 1.0 MHz, all bands.

3.3 L.O. Tuning: Harmonics of 1.0 MHz, all bands. Only the last L.O. is tunable. (The block diagram for this L.O.'s synthesizer shows that its phase detector operates at 0.25 MHz, so it should be relatively easy to implement tunability at this resolution. However, the commanding of the synthesizer seems to provide for only the 1.0 MHz resolution.)

4.0 VLBA FORMATTER PROPERTIES

At all U.S. tracking stations, calibration tone extraction will use hardware that is part of the VLBA Formatter. The feature is part of the Digital Switch Module, which operates on the *input* signals of the Formatter. Details are given in [1-4]. Properties of this device, as installed at the NRAO and DSN tracking stations, include:

4.1 Input signal arrangement. The input signals to the Formatter have already been "fanned out" to 16 bitstreams by the Decoder. For VSOP, the 16-bit word rate is always 8 MHz (for a total rate of 128 Mb/s). In VSOP's 2-channel modes, this is 8 bitstreams per channel; in 2-bit modes, half of each channel's bitstreams come from each bit. For example, in the 128-2-2 mode we have 4 bitstreams for each of the original sampler output bits on the spacecraft.

4.2 Tone extractor arrangement. The extractors can be configured in either of two ways. First, each extractor can treat any two input bitstreams as a sequence of 2-bit samples; in this mode, a total of 8 independent extractors is available, and each uses a 2-bit representation of sine and cosine. Second, each extactor can treat any single input bitstream as a sequence of 1-bit samples; in this mode, a total of 16 extractors is available and each uses a 1-bit representation of sine and cosine. (Actually, mixed modes are possible in which some extractors operate each way, but these are not very interesting.)

4.3 Numerology. There is a total of 16*2=32, 32*2=64, or 32*1=32 tones in all channels, depending on mode. But since there are at most 16 extractors, not all tones can be extracted at once.

4.4 Aliasing. Due to the fanout, each extractor can "see" only a subset of the samples from a channel. In 128-2-2 mode, each extractor's data is undersampled by a factor of 4, and in the other modes it is undersampled by 8. This means that many of the tones will be aliased so that they appear at lower frequencies. Because the VSOP tones are harmonically related, tones will appear on top of each other. For example, in 128-2-2 mode an extractor set for 1.0 MHz will also detect the tones at 7.0, 9.0, and 15.0 MHz. However, a group of 4 extractors can "see" all samples in 128-2-2 mode, and 8 extractors can see all samples in the other modes. By taking the proper linear combinations of the outputs of such group of extractors, all the aliased tones can be separated. (Exactly how to do this will be the subject of a separate report.) Here is the complete table:

Mode	No. extractors/group	Tones extracted by group
128-2-2	4	1, 7, 9, 15 MHz
		2, 6, 10, 14
		3, 5, 11, 13
		4, 8, 12, 16
128-2-1 or 128-2-2	8	1, 7, 9, 15, 17, 23, 25, 31
		2, 6, 10, 14, 18, 22, 26, 30
		3, 5, 11, 13, 19, 23, 27, 29
		4, 8, 12, 16, 20, 24, 28, 32

It thus takes 4 groups of 4, or 16 extractors total, to get all 16 tones from one channel in 128-2-2 mode; and 4 groups of 8, or 32 total, to get all 32 tones in the other modes. The total number of extractors remains equal to the total number of tones extracted, but there are restrictions on exactly which ones are accessable if not all are extracted.

4.5 Extractor harmonic responses. As mentioned in 2.3 above, the coarse representation of sine and cosine will cause each extractor to be sensitive to harmonics of the desired frequency. For Radioastron and VSOP, tones at these harmonics will be present. For the actual representations in the VLBA formatter, these sensitivities are theoretically (see [3]):

Trig Functions	Relative voltage sens. 3rd	5th	7th	Phase Error due to 3rd	5th	7th harmonic
1 bit	35%	20%	14%	20	11	8 deg
2 bit	22%	9%	5%	13	5	3

Here the phase error assumes that the tone at the harmonic frequency has the same amplitude as the desired tone. There is theoretically no sensitivity at the even-numbered harmonics. George Peck has conducted some tests using VLBA samplers and baseband converters that demonstrate these sensitivities and confirm the predictions of the above table.

4.6 Setup procedures. The process of setting up the mode and extraction frequency of each tone extractor takes about 10 seconds after the appropriate command is given to the Formatter. During this time, no data is sent to the VLBA tape recorder. (The latter is a result of the way that the Formatter's firmware is organized. Although it is not fundamental to the hardware design, we should assume that it will not be changed before VSOP launch.) It is therefore very undesirable to change the tone extractor configuration during a tracking pass.

5.0 RECOMMENDATIONS

In view of the spacecraft and tone extractor properties described in sections 3 and 4 above, it is recommended that the following setups be used for tone extraction at the U.S. tracking stations for VSOP:

5.1 In all modes, use only the 2-bit representations of sine and cosine, so as to minimize the harmonic responses. For mode 128-2-1, where the signal has only 1 bit per sample, the extractors can be programmed to operate with the LSB fixed at zero. This means that a total of only 8 extractors is available.

5.2 In mode 128-2-2, assign 4 extractors to each channel. Program these as a single group, all tuned to 1.0 MHz, and therefore extracting the aliased tones at 1.0, 7.0, 9.0, and 15.0 MHz.

5.3 In mode 128-2-1, assign all 8 extractors to one channel so as to allow the aliased responses to be separated. Program them as a single group tuned to 1.0 MHz, thus extracting 1, 7, 9, 15, 17, 23, 25, and 31 MHz.

5.4 In mode 128-1-2, there is only one channel. Use all extractors as a single group at 1.0 MHz, just as in mode 128-2-1.

Because of the setup time and data blanking (see 4.6 above), these setups should be established prior to a tracking pass and should remain fixed throughout the pass. If desired, different sets of tones (within the same group as given in 4.4 above) can be extracted on different tracking passes.

ACKNOWLEDGMENTS

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