November 1982

VLB ARRAY MEMO No. 148

The Pro's and Con's of Frequency Switching

or

How Many Frequency Channels Does the VLBA Need?

David B. Shaffer
Phoenix Corporation

My recent memo (VLBA #125) emphasized the need for several frequency channels in each of two observing bands for astrometric and geodetic observations with the VLBA. I have since looked more closely at the problem and can argue with more conviction for a specific minimum number of channels for the 2.3 and 8.4 GHz bands. A parallel problem is how to achieve that number of channels. I feel that a system that records all channels simultaneously should be chosen, for the reasons outlined below.

2.3 GHz (S-Band) Channelization

In September and October 1980, we saw S-Band group delay effects due to the ionosphere of up to about 100 nsec. This was the day/night range, during a period of extremely high solar activity. We spent an inordinate amount of time resolving delay ambiguities for our then-current ambiguity spacing of 40 nsec (three frequency channels, 75 MHz total spacing, 25 MHz unit spacing). Thus, an ambiguity spacing of at least 100 nsec, and preferably more, such as 200 nsec, is needed for convenient analysis, meaning a 5 MHz unit spacing is desired. Thus, to cover about 100 MHz total, a frequency array with a maximum spacing of 20 units is needed. The minimum acceptable array is a 6-element zero redundancy configuration (ZRC) (with some spacings absent) that spans a total of 17 units, or 85 MHz. A 7-element ZRC has a total length of 25 and would permit a 4 MHz unit spacing, or an ambiguity spacing of 250 nsec. If 100 nsec delay lobes are tolerable, a 5-element ZRC, of total length 11, would suffice. The current NASA/GSFC/Haystack/MIT S-Band configuration is the 6-frequency array mentioned above.

If, ultimately, fewer but broader band recording channels are decided upon, the single band delay window will help to constrain the ambiguity search range. Even a 50 MHz passband system (delay function almost 50 nsec FWHM) should have >50 nsec ambiguity spacing, or a maximum unit cell of <20 MHz. A 4-element minimum redundancy array has a maximum length of 6 and would be OK for this case. Hence, 4 channels is the absolute minimum, and 6 channels is highly desirable for any S-Band observations.

8.4 GHz (X-Band) Channelization

At X-Band, ionospheric delay fluctuations are reduced by the square of the X/S frequency ratio: 0.075. So, ionospheric variations will be less than 10 nsec for almost all observations.

X-Band observations span a frequency range of 300-400 MHz. If a 10 nsec ambiguity could be tolerated, the unit spacing can be as large as 100 MHz. In this case, a 4-frequency array would be adequate, and even a 3-frequency array could span 300 MHz. However, given the fact that new sources and/or stations with poorly known positions will be included occasionally in VLBA observations, and that other problems will appear from time to time like clock breaks and/or clock wander, it seems prudent to shoot for a little wider ambiguity spacing. Twenty nsec is a desirable minimum, for which 4 frequencies is not quite adequate (a total spanned bandwidth of just 300 MHz). Five or six frequencies allow spacings of 30-50 nsec for spanned bandwidths of 350-400 MHz. The current Mark III practice is to use 8 frequencies, spanning 340 or 360 MHz with a unit spacing of 10 MHz. The resultant 100 nsec lobes make for very easy ambiguity resolution.

Frequency Switching or Simultaneous Frequency Channels?

As noted above, the availability of at least 12 frequency channels is highly desirable for good, easy astrometric/geodetic analysis. There are two ways to record these channels: All dozen or so simultaneously, as in the Mark III system; or by frequency switching a few channels among all the frequencies, as in the old Mark I system or in some of the VLBA design studies. (A third mode would be to have many separate frequency channels, but with the data multiplexed onto fewer tape tracks. A fourth mode would have a few (switched) frequency channels that would be multiplexed onto a multi-track recorder like the Mark III Honeywell unit. This scheme would merely replace 16 VCR's with one tape drive!) The first two modes are certainly technically feasible, as evidenced by the Mark III and Mark I systems and by Craig Moore's memo (VLBA #138) about frequency switching and settling times. Hence, it appears that other factors will determine the final choice. I feel that accuracy, suitability, expense, and convenience should be considered. For all of these except expense, I feel a Mark III-like system is superior, as argued below.

Accuracy -- Accuracy depends first of all on an adequate SNR - if you can't see it, you can't measure it! As far as the recording system goes, SNR depends only on the total number of bits that are recorded and correlated. Since either recording system (VCR or instrumentation recorder) can write bits at roughly the same rate, the question is what, if any, differences are there in the quality of delay and rate measurements made with switched or unswitched systems.

The group delay, which is the most precise astrometric observable other than true phase, is the partial derivative of phase with respect to frequency, or the phase slope across the synthesized passband. Any temporal variations in instrumental or atmospheric phase will show up as a spurious extra group delay. i.e.

$$\Delta\tau_{group} = \frac{\partial\phi}{\partial\omega} = \frac{\partial\phi}{\partial t}\frac{\partial t}{\partial\omega}$$

where $\partial\phi/\partial t$ is the phase variation rate and $\partial t/\partial\omega$ is the frequency switching rate. If $\partial\phi/\partial t$ is constant, such as caused by equipment drift or the atmosphere when a source is rising or setting at low elevations, a bias error will appear on the group delay. If $\partial\phi/\partial t$ is random, such as from an unstable atmosphere, the noise level on group delay measurements will be increased. For simultaneous frequency recording, these phase changes do not cause a group delay error (they will cause a rate error) since all frequencies change phase at the same rate, except for small dispersive effects.

For a phase drift of 1 degree/second throughout a scan, corresponding to a residual fringe rate of 0.0028 Hz (small in comparison to actual values found in low elevation observations for instance), the group delay effect at X-Band is

$\Delta\tau_g$ = 27 psec for 1.0 sec dwell time and a 100 MHz step,

$\Delta\tau_g$ = 6 psec for 0.2 sec dwell time and a 100 MHz step,

and $\Delta\tau_g$ = 55 psec for 0.2 sec dwell time and a 10 MHz step.

The first value is almost half of the rms scatter in the best baseline solutions, as well as comparable to or larger than typical delay errors due to noise alone. Thus, for switching times of a second or so and not unusual phase drifts, the obtainable accuracy of the system is compromised. Switching rates less than one second are clearly necessary, especially for small frequency jumps.

Suitability -- Switched observations are probably unsuitable for some pulsar observations. These observations would be aimed at measuring the interstellar scattering of pulsar radiation or pulsar astrometry. Because of dispersion, pulses arrive at different times at different frequencies. It is important to be able to follow single pulses over a range of frequencies, as well as time-slice individual pulses to recover scattering information. For astrometry, individual pulses must be detected over the whole synthesized bandpass. At the lowest planned VLBA frequency, 330 MHz, and pulsar dispersion measures of 10 to 100, pulses move through frequency at a rate of 430 to 43 MHz per second. It is unlikely that LO's could be coherently switched fast enough to follow low dispersion pulses. Clearly, it seems more suitable to record as many frequencies and as wide a frequency range as desired instantaneously, and then leave further analysis for post-processing, where the data can be treated with a wide range of parameters at the option and leisure of the experimenter. Otherwise, his choice of data will be forever constrained by the particular setup at record time.

Expense -- This seems to me to be the main argument in favor of a frequency switched system. The expense of 14 duplicate signal paths is undeniably more than for 4, and the cost of an instrumentation recorder is well in excess of the cost of 16 VCR's. It is not clear, however, what the cost and reliability of the "Wurlitzer" video cassette changer is. Mark III tapes as currently used cost a factor of 5-10 more per bit stored than VCR tapes used at 4 Mbs. The hoped-for upgrade in Mark III recording density (12-20x) and the planned upgrade in VCR recording density (3x) bring the tape costs closer, but the VCR probably still wins out by a factor of 2 to 3 in tape cost. A 4-channel frequency switched system can be correlated on a four channel per baseline correlator, but the correlator and subsequent fringe analysis must deal with the complexity of keeping track of the several frequency slices. As noted earlier, dwell times should be well under 1 second per frequency. Hence, the correlator must dump the cross-correlation coefficients quite often, and it will not be possible to reduce the data flow by pre-fringe averaging in the correlator accumulators. Rather, hardware or software averaging must be done somewhere else, adding to the complexity and cost of the correlator system. Correlator dumps every 2 to 5 seconds would be quite adequate with the simultaneous system.

If more than 1% of the Array time will be spent on astrometry or pulsar observing, it seems sensible to spend the extra 1% or so it would require to outfit the Array for simultaneous recording.

Convenience -- The overall complexity of a switched system: keeping track of the switching rate and frequencies, the additional correlator dumps, the recording and bookkeeping for 16 VCR's running in parallel, etc. cannot help but inconvenience the user. Even if it is all computerized and mostly transparent to the user, it will surely cause him some sleepless nights as he wonders what he has forgotten to do. I think some of this matter of convenience applies also to the normal (fixed frequency) mode of VLBA observing. The thought of 16 tape recorders whirring away at each of ten sites is nightmarish. The VCR's are also inflexible as to recording speed. For line experiments that need less than two MHz of bandwidth, the VCR's cannot be slowed down to save tape, and the number of lag channels in the correlator must be increased to give adequate frequency resolution. With an instrumentation recorder, the bit and tape rate may be slowed down as desired, and fewer correlator lag channels are needed for a given frequency resolution.