VLB ARRAY MEMO No. 508

Decision Scheme for Phase and Delay Tracking

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At the last Design Review meeting in Green Bank, we reconsidered the concept of tracking the natural interferometer fringes by appropriate modulation of one or more local oscillators at each observing station, rather than in the correlator. We had previously considered and rejected this approach for a variety of reasons, some of which are mentioned further below. While none of these reasons were individually thoroughly compelling, in combination we felt they outweighed the primary advantage of potential cost reductions in the correlator. Indeed, since one of the correlator design concepts under consideration at that time was based on an existing VLSI element already incorporating fringe rotation, the cost reduction might well have been negligible.

However, current circumstances suggest that it would be advisable now to evaluate seriously the feasibility and cost impact of this "alternative scheme", as I'll call it henceforth. We have experienced unanticipated major increases of estimated cost in several project areas, including the correlator; more recent correlator designs foresee developing our own semi-custom gate array; and budgetary constraints have imposed substantial delays on correlator construction. In this memorandum I propose an agenda for conducting this evaluation, and arriving at (another) "final decision".

GENERAL CONSIDERATIONS

It is important to realize at the outset both the depth and breadth of the study which will be required. The impact of the alternative scheme will be greatest for the electronics group, which (I assume) will have to design and build the additional station equipment, and in the correlator, where the detailed design and perhaps much of the general architecture as well may be radically changed. Within these two major foci, the evaluation must be pursued to sufficient depth that the overall cost impact can be assessed accurately, and that doubts as to the soundness of digitally-controlled analog fringe tracking can reasonably be answered. Beyond the two areas of primary impact, we will also have to consider the potential impact on several other VLBA subsystems — chiefly monitor-and-control and post-processing — and on the Array's general capabilities.

Clearly this evaluation will not be accomplished without a substantial commitment of resources. In our earlier discussions, in fact, one deterrent to more serious consideration of the alternative fringe-tracking scheme was the degree and duration of effort necessary to verify its suitability. Having now decided to undertake such a study, we should organize it so as to minimize the potential for wasted effort. Therefore I have proposed a decision scheme in two phases, distinguished essentially by the duration of the tasks involved. A relatively short initial *definition phase* is required primarily to specify in detail a single alternative for later cost analysis; other short-term tasks in this phase include a preliminary cost and feasibility assessment, and a study of capability and compatibility issues. At the conclusion of the definition phase, we should be able to reach a provisional decision either to abandon the alternative approach or to ratify it pending the result of the main *cost-analysis and demonstration phase.* The remainder of this memorandum outlines the objectives, personnel requirements, and schedules I suggest for each of these phases.

DEFINITION PHASE

In the discussion in Green Bank, it emerged that several variants of the alternative scheme have already been precluded by the existing design for the IF-to-video converters and other components of the data-acquisition subsystem. As a result only one fundamental fringe-tracking technique is to be considered: the implementation of a high-precision phase-shift unit which modulates the "stationary" reference signal from the frequency standard. The modulated signal then serves as a phase reference to *all* intermediate oscillators, and perhaps timing signals, throughout the receiving and data-acquisition subsystems.

While it is probably fortunate that the exclusion of other variants reduces the scope of the evaluation study, nevertheless a number of sub-variants remain unspecified. To make possible a sufficiently thorough evaluation, it will be essential to reduce the multiplicity of possible schemes by defining a single coherent alternative. This scheme should represent the best compromise among the several requirements of technical simplicity, cost reduction, and observing flexibility; of particular importance in the latter category are capabilities for observing multiple phase centers and/or wide fields, and for inclusion of "foreign" stations in VLBA observations. The statement of the alternative scheme should specify all stages of both phase and delay tracking it encompasses, and indicate explicitly its impact (or potential impact) on all VLBA subsystems.

In parallel, the specifications which the station phase-shift unit must meet will have to be developed. Separate specifications will probably be desirable for the required phase accuracy, and for the precision of accountability in transmitting the actual values used to later processing stages. The most severe scientific constraints driving these specifications are likely to be the requirements for phase-stabilization of the Array. And while a final feasibility determination must await the later cost-analysis and demonstration phase, a preliminary assessment based on the specifications should be undertaken to verify that further effort is warranted. The cost of the phase-shift unit will be of interest to non-VLBA observatories contemplating participation in joint observations, so a preliminary cost estimate should be available as early as possible in this phase.

The objectives of the definition phase are outlined in greater detail in the following questions and commentaries:

- *What technique will the phase-shift unit use?* The primary concept under consideration at present involves multiplying the 100 MHz frequency standard signal up to 10 GHz, applying a digitally-controlled analog phase modulation, and then dividing down again to provide a modulated 100 MHz reference.

- *What fringe model will be applied?* The station fringe model could be a very rudimentary version subject to later (post-correlation) correction, or a complex, very accurate model requiring no subsequent correction — or something between these extremes.

o *How will the fringe model be implemented?* Possibilities range from piecewise linear to cubic-spline interpolations. Generally, higher-order implementations allow longer intervals between model updates.

o *What phase error can be tolerated?* This is the phase accuracy specification. One of the principal objections raised in the previous discussion of the alternative scheme was the strong doubt (in some quarters) that digitally-controlled analog fringe tracking could achieve the stability necessary for the most exacting observations.

o *Will the sample clocks be driven by the modulated or the stationary reference signal?* The former case accomplishes both coarse and fine delay tracking intrinsically with the phase tracking.

o *How and where will phase switching to cancel DC offsets be implemented?* One incentive to reconsider the alternative scheme was the realization that otherwise beats between low natural fringe rates and the phase-switching cycles could generate a spurious correlation. It still remains to decide whether to clock the phase switch according to the modulated or the stationary reference signal, and at what point in the signal paths to insert the switching.

o *How much will the station phase-shift unit cost?* While we anticipate a significant *net* cost reduction for the VLBA as a whole, internally the alternative scheme transfers some cost from the correlator to the stations. For non-VLBA stations this represents an *increase* in the cost of acquiring VLBA-compatible equipment, which if too great may compromise the availability of these stations for joint observations with the VLBA.

o *Will fringe model parameters be calculated locally or centrally?* This question is closely related to the next; neither appears at present to have a very attractive answer.

o *How will the model parameters be made available to later stages of processing?* The model could be: recorded in the framing blocks on the video tape; transmitted to the array control computer over the monitor-and-control links and logged there; or reproduced when required using the same algorithms and parameters.

o *How precisely must these logged or reproduced parameters correspond to the actual behavior of the phase-shift unit?* This is the model accountability specification.

o *What additional burden (if any) will be imposed on the monitor-and-control system by phase-shift command and logging transactions?* This answer will be determined by the decisions on the previous three questions.

o *What operational problems may result from defining the interferometer's phase center at observing time?* Care will have to be taken to ensure that identical source positions and earth-rotation parameters are used at all stations. And updates to the software driving the station phase-shift unit will have to be managed carefully.

o *Will post-correlation* phase *tracking be implemented, and if so within what limits?* Such a capability is essential if correlation at offset phase centers is to be supported. Observations of multiple phase centers within the primary antenna beam, or of sources with poorly known positions, were regarded as vital in our earlier discussion of the alternative scheme, although multi-pass processing was seen as a reasonable price for supporting them. The maximum residual fringe phase rate at the half-power point of the primary beam is about 19 Hz on the longest terrestrial baselines, independent of observing frequency.

o *Will post-correlation* delay *tracking be implemented?* This corresponds in an obvious way to the previous question, and should be easy to implement in combination with the phase tracking, except at low frequencies where the primary beam becomes very broad.

o *How will the volume of archive data be affected?* Probably not at all, but this possibility should not be forgotten.

o *What changes in calibration procedures may be necessary?* The alternative scheme is more similar to the VLA case than are current VLBI observations. This may allow some simplifications in software, but may also bring some new problems which must be corrected.

o *How will the overall performance of the Array be affected?* Obviously this answer depends on many of the foregoing. Most sub-variants of the alternative scheme eliminate one or more of the sensitivity loss factors which arise in the conventional approach. Some effects responsible for baseline-dependent phase and amplitude errors ("closure errors") should vanish, while others may arise. If offset phase centers are not supported, or only within a limited region, the Array's observing capabilities will be restricted.

o *Will the rest of the "Global Array" go along with the alternative scheme?* The alternative correlator will be incompatible with data received and recorded conventionally. In the previous discussion of the alternative scheme, this compatibility issue was, to my mind, the most critical issue; joint observations with other stations in a global array are a *sine qua non* for achieving the maximum scientific potential of the VLBA. Informal polls suggest, however, that most observatories of the European VLBI Network would in fact be willing to implement the station phase-shift unit, and these plus NRAO's own facilities (and, possibly, the DSN antennas) should suffice to establish a global array based on the alternative scheme. The Australia Telescope has already adopted this scheme within both its arrays.

Adoption of the alternative scheme would have, obviously, far-reaching implications throughout the VLBA project. Until the definition phase is resolved, the large number of sub-variants represent uncomfortable open questions interfering with the ongoing design effort. Thus, we should complete this phase as expeditiously as possible by mounting a concerted short-term effort, which should have as many participants as needed to reach a quick conclusion. I would suggest forming an ad-hoc group composed of two or three members each from the electronics and correlator groups, one each from the data recording, monitor-and-control, and post-processing groups, and one or two members of the system engineering group. Establishment of a computer conference dedicated to this topic might facilitate early discussions; negotiation of the final definition and specifications would require several (two to four?) telephone meetings.

Most of the definition phase could be completed quite soon. A target completion date of 1986 February 1 would seem to allow ample time to accomplish the objectives quickly but thoroughly. One exception will be determining the extent of global cooperation in the alternative scheme. We cannot solicit input from other observatories until we can describe the specific alternative scheme in better detail, and give a preliminary cost estimate, so this external aspect of the definition phase will have to extend somewhat longer, say to 1985 March 15.

Cost-Analysis and Demonstration Phase

This main phase of my proposed decision scheme is much more straightforwardly described. We will have committed ourselves (if we go this far) to adopting a specific well-defined alternative scheme, provided that it can be implemented satisfactorily and at a cost saving. Almost the entire effort can be restricted to the electronics and correlator groups; other VLBA subsystems need no longer be directly involved, unless the assessments during the definition phase indicated significant cost impact.

In the electronics area, the objectives of this phase will be completion of the detailed design of the station phase-shift unit, construction of one or two prototypes, and demonstration of performance within the specifications established during the definition phase. An accurate cost projection for quantity production should emerge easily from the prototype. Following the suggestions of those who would be involved, I recommend that we plan to commit about two full-time equivalent engineers for about six months, until about August 1986.

For the correlator, the effort will have to focus on developing a completely new design. The current design will provide a good starting point, but major changes in the architecture will probably be warranted by the substantial simplifications (and, probably, some complications) under the alternative scheme. This will be a much larger effort than the design of the phase-shift unit, but we cannot afford to commit much manpower to the correlator at present, and no correlator prototyping is planned until at least 1988–89. I think it's clear we will have to be satisfied with a rather noisier cost estimate on the alternative correlator than for the phase-shift unit. Two full-time equivalent engineers and/or system scientists should be able to produce a usable result on about the same six-month timescale.

The final demonstration will require a joint effort of both these groups to perform as realistic a simulation of actual VLBI observing conditions as possible. It should be possible to use one or (preferably) two prototype phase-shift units with Mark 3 recording equipment and existing correlators to demonstrate that the entire scheme is satisfactory.

What Should We Call It?

We need a succinct name with some mnemonic value to use in place of "alternative scheme" as this evaluation goes ahead. We have often spoken of "fringe rotation at the stations", but this ignores the delay-tracking aspect which may become an important feature of the scheme. (Also, "FRAS" is already a well-established British acronym — and in German means something like "swill".) In AT jargon, the same concept is called the "unified clock scheme"; this covers both aspects, but conveys no information as to what is actually meant. I prefer something like "wavefront clock scheme". One memorable but irreverent acronym is "clock referred to antenna pointing". Other suggestions, serious or otherwise, are welcome.