Final Report of the Observing Strategies Sub-Group of IVS Working Group 3: VLBI2010

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1 Introduction

WG3 has been divided into 7 sub-groups. This is the progress report of the Observing Strategies Sub-group. The topics for consideration are:

- Frequency bands, RFI
- Source strength/distribution/structure
- Antenna-network structure and observing strategies
- Field system and scheduling

2 Requirements

In order to constrain the scope of this document, it will be helpful to consider the future accuracy requirements of geodetic VLBI. The strictest requirements come from scientific applications where it is generally agreed that long-term accuracy of geodetic reference frames will be needed at the level of 1mm or below [1] [2] [3]. Since WG3 is looking a decade or more into the future, it would be prudent to aim for accuracies significantly below the 1mm level to avoid premature obsolescence. In addition, it is generally agreed that VLBI observations of EOP are required continuously.

What does 1mm accuracy mean in terms of the primary geodetic VLBI observable, the delay? In terms of systematic error, the answer is clear. If you want to guarantee unbiased long-term accuracy below the 1mm level, then the sum total of all systematic contributions to delay must be below 3ps (1mm equivalent light travel). It goes without saying that this is a daunting task.

With respect to random measurement error, the answer is less clear-cut since the connection between delay precision and final results involves complex interactions that include elements such as network size and geometry, the observing schedule, etc. In addition, measurement error is only one component accounting for the random variations of delay. Also included are the stochastic behavior of both the clocks and the troposphere. Obviously, a proper understanding of delay measurement error must be made in the context of these two other components.

A rough idea of the requirement was, however, obtained by scaling the post-fit residuals of a typical R1 experiment by the ratio of the achieved R1 baseline precision relative to the target precision of 1mm (see Appendix A). The analysis assumed:

- That all other effects external to the observations, such as mapping function errors, antenna deformation, and loading effects, were negligible.
- That the delay uncertainty due to SNR is the dominant contributor to the formal position uncertainty.
- That a comparable amount of delay noise was added from unmodelled effects.

As a result of the analysis, it was estimated that a median delay measurement error of 4ps is required to achieve 1mm baseline precision within a 24-hour session. Based on the above caveats, this should be taken as an upper limit to the delay precision requirement.

Having analyzed the contribution of delay measurement error, it is also important to study the effect of the stochastic behavior of the clocks and troposphere (see Appendix B). Using CONT94 data, a number of solutions were performed involving various combinations of realistic and unrealistic troposphere and clock behavior along with delay precisions of 0, 4 and 16ps. As a result of the analysis, it was found that even for a delay precision of 4ps, the formal error of the station vertical component was still about 3mm within a 24-hour session. Clearly, at the level of 4ps measurement error and for the number of observations per hour of the CONT94 sessions, atmosphere and clock-like behavior dominate the error budget and form a barrier to moving below 3mm uncertainty in the vertical component of the baseline.

It is an important conclusion of this section that one focus of VLBI2010 needs to be to find more effective approaches for handling the troposphere and clock-like parameters. This is clearly a limiting factor and remains a frontier area for geodetic VLBI. R&D experiments, simulations, focused analysis initiatives, etc need to be a major focus within the IVS to try to find a way through this barrier.

3 Large-N/Small-D (LNSD) Square Kilometer Array (SKA) Antenna/Receiver Developments

VLBI2010 comes at an opportune time to take advantage of recent (and planned) developments in the construction of low-cost high-performance 6-12m radio antennas, broadband feeds and low-noise receivers for radio astronomy [5]. These developments are part of the proto-typing efforts of the US concept for the Square Kilometer Array (SKA), which involves the use of a large number (4400) of phased 12m antennas, and is referred to as the Large-N/Small-D (LNSD) concept.

Initially, the US concept involved a much larger number of 6m antennas each with a Tsys of 42K. However, it was realized that a significant cost saving could be achieved if Tsys were brought down to 18K. Since this results in more expensive receiver electronics, the optimum antenna/receiver cost point was calculated to occur for 12m antennas. Achieving Tsys=18K requires cryogenic cooling of the feed in addition to the LNA and is still in the experimental phase.

A prototype version of the initial 6m concept, referred to as the Allen Telescope Array (ATA), is currently under construction. An innovative automated manufacturing process referred to hydroforming makes possible the production of a low-cost lightweight rigid reflector with a reproducible high accuracy surface; and an innovative feed and LNA design have made possible 1-11 GHz continuous frequency coverage using a single receiver. Since a large number of these antennas is required for the completed ATA, a key design goal is that the system be robust, low maintenance and require minimal operational attention, all important features for unattended operation of a geodetic VLBI station.

The new 12m concept will require continued development work in 3 main areas:

- Low-cost construction of a 12m Ka-band antenna including the development of a capability to cut and reassemble them so that they can be transported,
- An increase in frequency coverage from 1-11 GHz to 0.15-34 GHz using three receiver bands at 0.15-1.5 GHz, 1.2-11 GHz and 11-34 GHz, and

- Optimization and cryogenic cooling of the feed so that a Tsys of 18K can be achieved. (Actually, Tsys=18K is only anticipated for the 1-11 GHz part of the spectral coverage, with Tsys=45K for 11-34 GHz).

It will be interesting to keep the performance parameters of the ATA and LNSD antennas in mind as you read on, since they are a very good fit to the sensitivity and spectral requirements being considered for VLBI2010. It is also important to realize that although the costs of the ATA and LNSD antennas are low, there is a significant "tooling" cost of about $6M to get started in the low-cost production of the reflector. For this reason, it may turn out to more cost-effective to use the exact reflector being produced for the LNSD even if a smaller antenna would be adequate for our purposes.

Reducing station capital and operating costs will enable a significant increase in the number of geodetic VLBI sites. When the recent antenna/receiver advances are coupled with new low cost disk recording systems and digital data acquisition systems (DAS), the potential exists for a breakthrough in the cost of geodetic VLBI stations.

4 Frequency Bands, RFI

Troublesome S-band interference and the move by the NASA Deep Space Network (DSN) from S/X band to X/Ka band are motivating a review of the frequency allocations used for geodetic VLBI. Regardless of which bands are selected, it is clear that a large separation (greater than a factor of 2) is required between the highest and lowest frequencies to effectively calibrate the ionosphere. Reasons have been proposed for frequency coverage all the way from L-band to Ka-bands, e.g.:

- There is interest in L-band because it will allow observation of GNSS satellites (GPS, Glonass, Galileo). Direct comparisons can then be made with the GNSS, and observational access to the geocenter by VLBI may be possible.
- Observations at S/X band will allow the continuation of the 30-year history of CRF in those bands.
- Observations at X/Ka band is attractive because sources tend to have less structure at higher frequency, there is less interference at those frequencies, and the wider bandwidths will allow more precise group delay determinations. Ka-band observations will also support the CRF requirements for planetary navigation of spacecraft by NASA. On the negative side, sources tend to be weaker at Ka-band and everything technological is more difficult, e.g. antenna surface accuracy, support structure and pointing, coherence, etc.
- Frequencies near the 22 GHz water vapour line are interesting because they may enable line-of-sight calibration of water vapour content.
- More dense frequency coverage may be desirable to allow phase delay determination at moderate SNR. Phase delay is typically about an order of magnitude more precise than group delay. [See Appendix C for an example using three broad bands at S-band, C-band and X-band.]

4.1 RFI

In this communications intensive world, it is almost certain that problems with RFI will intensify, and although current attention is focused on S-band, other bands will no doubt also be affected in the future. As a result, it is important for geodetic VLBI to develop a strategy to minimize the impact of RFI. Here is a suggestion of a 3-step process:

- To begin, it makes sense to avoid spectral regions which are a problem everywhere on Earth, e.g. commercial satellite downlink and broadcast allocations. Fortunately, with these removed, there are still significant spectral regions available, e.g.
    - 2.69 to 3.4 GHz,
    - 4.8 to 6.7 GHz,
    - 7.75 to 10.7 GHz,
    - 12.75 to 17.3 GHz, and
    - 22.0 to 37.5 GHz.
- Next, when VLBI sites are being selected, low local interference should be set as a criterion. Sites should typically be located away from large urban areas, airports, military installations, communications repeaters, satellite ground stations, etc. Once a good site has been found, working with local regulatory agencies can ensure that within reasonable limits the low RFI situation will continue into the future.
- Finally, the frequency structure used and the DAS design should be robust against RFI. For example,
    - Frequency structures that depend on critically spaced narrow channels should be avoided since RFI can cause serious degradation if even one of the channels is compromised. Broad continuous bands will not have this shortcoming.
    - The DAS should be designed such that only the frequencies affected by RFI will be degraded and not entire broad-band channels. In order to achieve this, a VLBI receiving system needs to have a large dynamic range. Linearity for 30dB above the noise floor would probably be a good rule of thumb. This includes amplifiers, mixer, splitters, etc. and even samplers. Unfortunately, large multi-bit samplers are in conflict with the usual VLBI rule of thumb to never use more than 2-bit samples, applied to maximize interferometric information density during data transmission to the correlator. The following process would make it possible to sample with a large multi-bit sampler but still transmit only 2-bit data to the correlator:
        - Sample the data with a large number of bits,
        - Use a dynamic digital filter to cut out the RFI,
        - Requantize to 2-bits,

- Transmit the 2-bit data to the correlator.

Although this approach would work, it might be difficult to implement. A simpler approach would to be to implement an FX correlator but with the Fourier Transform (F) applied at the station and only the Cross-multiply (X) applied at the correlator. The data could then be multi-bit sampled initially and requantized to 2 bits after the Fourier Transform for transmission to the correlator. In this way, only the channels affected by RFI would be degraded.

4.2 Frequency Bands

The choice of observing frequency bands is dependent on several factors including the available RFI-free bandwidth; the relative separation between frequency bands (which affects the SNR needed to estimate ionosphere-corrected delays and ambiguity-free phase delays); typical source correlated flux density; and System Equivalent Flux Density (SEFD), which is a measure of the overall antenna/receiver system sensitivity.

A major motivator for moving away from the current standard S/X frequency bands and toward higher frequencies is the growing RFI pollution at S-band worldwide. As pointed out in Section 4.1, however, improvements in data-acquisition hardware should allow the spectral excision of narrowband RFI from broadband frequency channels, so RFI-contaminated regions of the electromagnetic spectrum that are unusable with present-day VLBI hardware may once again be usable in the future. In addition, the typical bandwidth of currently used VLBI feeds is ~10%, or ~200 MHz at S-band. When attempting to record 100 MHz or more of spectrum at S-band, the options for arranging the frequency channels so as to avoid strong RFI are limited. With present-day technology, however, much wider feed (and receiver) bandwidths are possible, as demonstrated by the decade-plus bandwidths of the ATA feeds. The possibilities for finding RFI-free spectral regions are thereby increased.

Whether or not S-band continues to be a primary observing band in the long term, it must be retained in the short term, together with X-band, in order to provide continuity with the historical geodetic record acquired at S/X VLBI stations over the preceding decades. Many of the new antennas will be constructed close to existing antennas. Before the latter are decommissioned, joint observations involving old and new antennas need to be conducted over a multi-year period, in order to provide reliable geodetic ties (including potential seasonal variations) between the old and new. Perforce those observations must be carried out in the frequency bands supported by the old systems. Such overlapping observations should also afford a transition from a CRF defined at S/X to one defined at X/Ka or whatever new set of frequency bands is chosen.

Most proposals for new observing bands call for higher frequencies. Advantages of migrating to frequencies above X-band include simpler, more compact source structure on average, lower RFI levels in general, and wider bandwidths, which allow more precise group delay determinations as well as greater flexibility in the placement of frequency channels within a band. (With the advent of multi-octave feeds, however, the notion of a "wider bandwidth" within a frequency band loses much of its meaning.) Disadvantages are the generally lower source flux densities and the greater technical challenges of achieving low SEFD, adequate phase coherence (including instrumental and tropospheric effects), and sufficiently accurate antenna pointing for large antenna structures.

In order to keep the error in the estimate of the geometric delay τ_{geo} under 4 ps, any contamination from the ionosphere must of course be <4 ps. The daytime ionospheric delay can easily exceed this amount for frequencies below 100 GHz. Accurate geodetic VLBI measurements above 100 GHz are currently precluded by high system temperatures and low correlated flux densities, as well as by poor tropospheric phase coherence at all but the driest sites. We are thus forced to correct for the ionosphere in our measured delays. External systems such as GPS that can sense ionospheric conditions are either not precise enough or not dense enough in space and time to provide the information needed for the VLBI corrections. It is therefore necessary that the ionospheric delay be estimated from the VLBI observables themselves.

In order to measure the ionospheric delay with the requisite precision without placing unrealistic demands on the achievable SNR, a ratio of approximately 2:1 or greater between the highest and lowest frequencies is called for. Ka-band (~32 GHz) has emerged as a strong candidate to be paired with X-band, in large part because the DSN is moving from S/X to X/Ka for spacecraft navigation and telemetry. Another option is to pair Ku-band (~16 GHz) with X-band. In the next few paragraphs we consider these two options, along with the traditional S/X.

First we estimate what the required SNR is to achieve an error of 4 ps in the ionosphere-corrected group delay τ_{geo} (sources of error other than noise are ignored here) from the group delays measured in each band. Under the assumptions that (1) the total spanned bandwidth in each band is 30% of the center frequency, (2) the rms spanned bandwidth is 40% of the total bandwidth (this is typical of the frequency sequences currently in use), and (3) the delay error in each band contributes equally to the error in τ_{geo} (i.e., the error in each band is $4/\sqrt{2}$ ps), the required SNRs are:

S/X	*X/Ku*	*X/Ka*
SNR(S) = 16	SNR(X) = 22	SNR(X) = 4
SNR(X) = 59	SNR(Ku) = 41	SNR(Ka) = 16

With sufficiently precise estimates of the group delays in both bands of a pair, it is possible to resolve the phase ambiguity in each band. Under the assumptions in the preceding paragraph, the standard error in resolving each ambiguity will be ≤ 0.1 cycle for the following SNRs:

S/X	*X/Ku*	*X/Ka*
SNR(S) = 15	SNR(X) = 24	SNR(X) = 15
SNR(X) = 15	SNR(Ku) = 24	SNR(Ka) = 15

The delay τ_{geo} may then be estimated from each pair of ambiguity-free phase delays. The standard error in τ_{geo} obtained in this manner is <2 ps in all three cases, when the SNRs are as given in the table above.

Comparison of the two tables above shows that the SNR requirements are minimized when using phase delays to estimate τ_{geo} for S/X and X/Ku. For X/Ka, the X-band SNR requirement is lower when the group delay-only approach is used, but the precision of the phase delay-inferred τ_{geo} is much better.

The SNR calculations to this point have been made using theoretical bands without regard to RFI potential. In Section 4.1 it is pointed out that it will probably be best to avoid *a priori* parts of the spectrum allocated to commercial satellite downlink and broadcast since they will cause problems everywhere on Earth. In Appendix C. A Phase Delay Scenario, three of the bands suggested in section 4.1 are used in a phase delay analysis, e.g.:

- S-band: 2.69 to 3.4 GHz,
- C-band: 4.8 to 6.7 GHz,
- X-band: 7.75 to 10.7 GHz.

With these RFI friendly versions of S and X band (without introducing C-band yet), it was found that an SNR of 29 was required for unambiguous phase resolution. This is nearly double the SNR shown for the S/X entry in the table above. The degradation can be attributed to the combination of the following three effects:

- The RFI friendly bandwidths are somewhat less than 30% of the centre frequency.
- The X to S-band frequency ratio is 3:1 instead of 4:1.
- Completely filled bands are assumed (with an rms bandwidth factor of .28) instead of optimized bandwidth synthesis (with an rms bandwidth factor of .40).

Fortunately, a significant further reduction in the SNR requirements can be achieved by observing in an intermediate band. For instance, with the addition of C-band, an SNR of 14 in each of the three bands suffices to resolve the phase ambiguities in each band, thereby leading to a standard error in τ_{geo} of only 1.5 ps. Similar results are obtained for an X/Ku/Ka three-band configuration.

In addition to the primary VLBI observing bands, there are at least two other frequency bands that could yield useful information:

Extending the frequency range down to L-band would allow direct observation of GPS satellites. Such observations could be used to tie the satellites into the VLBI-based CRF and TRF, and it would also give VLBI observational access to the geocenter.

If the receiver/backend were equipped with stable total-power radiometers at two or more frequencies in the range 20-32 GHz, an antenna could be operated as a water vapor radiometer. The measured brightness temperatures around the water vapor line at 22.2 GHz can be inverted to produce estimates of the delay due to water vapor, which is the major source of short-term (seconds to ??) variations in the tropospheric delay.

What can be concluded from the above discussion? For example, can we make a recommendation about the question of a move to X/Ka-band? Although there is growing pressure to make this move, and in some circles it is almost a foregone conclusion, there is also good reason for caution. To see why this is, consider a discussion of the main reasons *for* a move to Ka-band:

- **S-band RFI can be avoided**. A panic over recent S-band RFI from digital satellites is probably the initial motivation for considering a move to Ka-band. However, a whole new approach to RFI management will make this a much weaker argument (see Section 4.1). In addition, other technologically simpler solutions might exist using, for example, X/Ku-band.
- **Wider spanned bandwidths can be used to achieve more precise group delay determinations**. This might have been true for old-style feeds. However, with the new decade feeds and LNA's being developed for the ATA and LNSD this is no longer a strong argument. Many examples have been shown in this section of how adequate delay precision can be achieved at modest SNR using any of S/X, S/C/X or X/Ku band. In addition, super-wide bandwidths will require a complex and potentially expensive RF/IF system requiring many filters, mixers and LO's.
- **Establishment of a Ka-band CRF to support planetary navigation**. It is unlikely that the IVS will be able to provide a dense enough Ka-band CRF for navigation, so special purpose densification along the spacecraft path will be required for tracking purposes anyway.
- **Simpler source structure**. Indications are that sources tend to have less structure at Ka-band, although it is still not known whether or not they are more positionally stable. This tendency is, however, tempered by the fact that sources are typically weaker and systems significantly less sensitive at Ka-band, making the population from which to select good candidate sources much smaller.

There are also reasons *not* to move to Ka-band:

- Everything is more technologically difficult at Ka-band, e.g. Tsys, surface accuracy, coherence, etc.
- Sources tend to be weaker at Ka-band.
- Effort will be required to establish and maintain an adequate connection between the X-band and Ka-band CRF's.

However, having said all that, it is worth mentioning that the 12m antennas being designed for the LNSD array will have an adequate surface for Ka-band and both 1.2-11 GHz and the 11-34 GHz feeds and LNA's will be provided and cryogenically cooled. Adopting this entire package and taking advantage of the development work for this potentially billion-dollar project will leave open all spectral options contemplated for VLBI2010, including L-band and Ka-band. If we were to decide on the LNSD 12m antenna/feed/LNA option, the choice of whether or not to actually install RF/IF electronics for all options could be left to a later time, or even retro-fitted if necessary. The use of frequencies near 22 GHz, enabling accurate line-of-sight WVR corrections, will also still be open which may turn out to be a more significant contribution to improved geodetic VLBI performance than the use of Ka-band.

5 Source Structure

The ideal geodetic reference source is a simple *structureless* compact object. Unfortunately, most compact radio sources have at least some structure. In order to reduce the complications of data analysis required to correct for source structure, we propose that a fair amount of effort be expended to identify sources with minimal structure to be used for geodetic observations. The alternative is to correct for source structure. It seems to us that it will be easier in the long run to use the simplest sources rather than expend the observing time and analysis efforts necessary to make structure corrections.

An on-going set of VLBI observations at 15 GHz allows us to estimate what sensitivity is needed in order to reach a desired number of sources with simple structure. Initial results from a continuing study of a complete sample of flat spectrum (compact) sources is reported in Kellermann *et al.* [6] and Zensus *et al.* [7]. These authors have mapped their objects with the VLBA at 2 cm. Their sample is equivalent to an all-sky sample comprised of about 200 sources with flux densities greater than about 1.5 Jy. Of this sample, somewhat less than 10% of the sources are classified as *compact, having little structure*. This fraction of simple sources is similar to the results of Fey and Charlot [8] [9] who classify 17% of their sample as having structure index 1 (indicating structure effects less than 3 ps or so at 8GHz), and the scintillator survey of Lovell *et al.* [10] who find about 10% of sources at 5 GHz show interstellar scintillations indicative of very compact components (but not necessarily indicative of simple structure only). Lovell *et al.* indicate that weaker sources are more likely to contain scintillating components, consistent with brightness temperature limits for compact sources, perhaps indicating that weaker sources may overall have simpler structure.

Some 400 to 600 sources uniformly distributed in the sky is sufficient for good geodetic measurements. At this source density, there is a source per every 70-100 square degrees, or perhaps more relevant, a source (on average) within 6 or 7 degrees of any arbitrary direction. Of course, a denser grid of sources, by a factor of at least ten and perhaps as much as a hundred, is desirable for phase referencing VLBI observations. We concentrate here on the geodetic source network, which can be readily observed with the modest antennas discussed elsewhere in this report. The densification of the source grid will require either or both observations of weaker sources and/or source structure corrections. Such observations seem better left to larger antennas whose locations have been optimized for source measurements *i.e.* the VLBA, EVN, and cooperating stations).

Starting from the Kellermann [6], Zensus [7], *et al.* survey, and taking 10% as the fraction of compact sources, we can estimate the source strength that will provide the desired sky density. We assume that the number of sources scales with flux density (S) as $S^{-3/2}$. (This assumption corresponds to a Euclidean universe uniformly filled with sources drawn from a single luminosity function - and if anything underestimates the number of flat spectrum sources at intermediate flux densities (*i.e.* 0.02 to 2 Jy). See Figure 15.6 in Verschuur & Kellermann [11]. Extrapolating with the $S^{-3/2}$ assumption indicates that at a flux density of about 0.20 Jy there will be 400 simple, compact sources in the sky, and at about 0.16 Jy, there will be some 600 good sources available. At these same flux densities, there will be ten times as many flat spectrum sources altogether, or 4000 - 6000 sources, many of which will be suitable for a denser celestial reference frame and as phase reference sources (after the source structures have been determined). In order to reach 40,000 compact sources over the entire sky (a density of about one per square degree), sources as weak as 40 - 50 mJy will have to be observed.

Even the geodetic reference frame sources, at 0.16 - 0.20 Jy, are near the limit of observability with the putative high efficiency, low system temperature 6 meter antennas. The denser grid of reference frame sources requires at least the 12-meter antennas, and preferably larger, given that many of these sources will have significant structure and the correlated flux densities on longer baselines will be a fraction of the total source strength.

As mentioned at the beginning of this section, we believe that it is better to find the most compact reference objects, rather than rely on structure corrections. In order to make reliable structure corrections, the continually changing structure of the sources must be determined. (This is not to say that the set of simple sources will not change. A single source may at times fall in the **simple** category, and then develop structure. A monitoring program will be necessary to keep the source catalog up-to-date.) For highest accuracy, the structure must be known at all the bands (at least two, possibly more) used for ionospheric correction. If we are to determine our own structure corrections, it will be necessary to correlate *all the baselines* used for (most?) experiments. Adequate maps require phase closure data, which comes only when there is data from all baselines. At this time, VLBI map making is still somewhat of an art, as well as a skill. Some research into automating map making, at least to the level of picosecond corrections, should be part of the VLBI 2010 efforts.

There might still be some uncertainty about the overall stability of the radio source reference frame. The reference frame defined by galaxies and quasars should be quite adequate. For even relatively nearby galaxies such as M87 (20 Mpc), a typical random motion of several hundred km/sec corresponds to a motion of only a few microarcseconds per year, a factor of ten or so below our target of 1mm (3 ps). What is not yet known is how well the core of a compact source is really attached to the supermassive black hole which is presumed to mark the actual nucleus. In some models for compact sources, the core is actually somewhere near the base of, and therefore part of, a jet of material being expelled from the black hole. Superluminal motion, generally taken to be the relative speed of jet material with respect to the core, is often many tens or even hundreds of microarcseconds per year. In some cases, a similar speed might actually be occurring in the core itself, if it is indeed part of the jet structure. Careful measurements of the stability of the geodetic frame at the tens of microarcseconds level will be necessary, as even the simple compact sources may actually be moving.

6 Source Strength/Distribution

The source strength/distribution requirements are different for TRF/EOP on one hand and CRF on the other. The primary goals, empirically and somewhat arbitrarily, would be to have at least 60 geodetic sources available for any TRF/EOP network geometry and to have at least 400 "stable" astrometric sources uniformly distributed over the sky to realize the ICRS.

To have 60 sources to schedule an arbitrary network it is probably necessary to have twice that number overall. Using the same logic as in Section 5, this would imply a minimum source strength cut-off of about .45 Jy.

The astrometry aspect is more open since there is no reason to assume that the existing astronomical observatories will soon disappear. It would be important to retain their participation in CRF and TRF/EOP observing. In the long run, a question is whether the VLBI2010 network would depart in some unbridgeable way from the current astronomical capability, (e.g., use X/Ka) and require a self-sufficient CRF activitiy. In this case more sensitivity would be required to get to the 400 source level. If the astronomical users need even more sources for phase referencing at the geodetic frequencies, some non-VLBI2010 stations would be needed, but the geodetic side could still contribute.

7 Sensitivity Issues

Increased sensitivity has a number of benefits, e.g.:

- The precision of the delay observable increases proportionately.
- Shorter scans can be used (which is an important element in acquiring more scans per day).
- System performance can be evaluated more readily.
- Weaker sources can be observed (which is important for selecting low structure positionally stable sources and for achieving a more uniform distribution of sources).

In general, sensitivity is defined based on the weakest source that needs to be observed and the minimum SNR required per observation. Unfortunately, it also comes at a price. Sensitivity is a function of antenna diameter, antenna efficiency, system temperature, bandwidth and integration time. The impact on antenna diameter is of particular interest since antenna cost increases approximately as the cube of the diameter. Making an informed trade-off between sensitivity and antenna diameter will have significant impact both on system cost and future performance potential.

In Appendix D. Some Sensitivity Examples, some sensitivity examples have been analyzed specifically for the 6m ATA antennas and the 12m LNSD antennas. Four interesting examples have been extracted and are summarized in the table below.

Antenna Diameter(m)	eff(%f)	Tsys(K)	Bit Rate	Tint(s)	SNR	Smin(Jy)
6	60	42	2.e9	240	24	.46
6	75	18	2.e9	30	24	.42
12	60	42	2.e9	120	24	.16
12	75	18	2.e9	15	24	.14

In all cases, SNR=24 and Bit Rate=2.e9 have been used. SNR=24 was selected because, in appendix D, it was shown that, with the S/C/X frequency band scenario, this SNR was sufficient to unambiguously resolve rf phase and hence achieve a delay uncertainty of 1.5ps. Bit Rate=2.e9 was selected because it can already be achieved today and is a conservative prediction for sustained operation in 2010. Examples 1 and 2 assume 6m antennas while examples 3 and 4 assume 12m antennas. Examples 1 and 3 assume ambient feeds while examples 2 and 4 assume cryogenically cooled feeds and shaped reflectors. In Section 6 it was shown that a 0.45 Jy flux cut-off was adequate for

TRF/EOP observations, and a 0.2 Jy flux cut-off was adequate for ICRF observations. What can be learned from the table?

- The first example is for the 6m antennas that are already being manufactured for the ATA. With this antenna, a list of 120 TRF/EOP sources can be observed using integration times up to 240s. This is marginal performance since the large integration times will compromise the number of observations that can be achieved in a day.
- The second example is also a 6m antenna but with a cryogenically cooled feed and shaped reflector. In this case, all 120 TRF/EOP sources can be observed using integration times below 30s making this a completely adequate antenna for TRF/EOP (assuming 120 sources are in fact an adequate number).
- The third example is for a 12m antenna with ambient feed. All TRF, EOP and CRF sources can be observed using integration times up to 120s. This antenna is adequate for all IVS applications.
- The fourth example is for a 12m antenna with cryogenically cooled feed and shaped reflector. All TRF, EOP and CRF sources can be observed using integration times up to 15s. This would be an ideal antenna for all IVS applications and could possibly lead to the acquisition of thousands of observations per day per station.

8 Antenna Configurations

The ability to observe more than one source at a time may have advantages, e.g.:

- The clock contribution to the delay observable will disappear in the differenced data.
- It may allow more scans per day.
- It may allow more than one type of observation to be made at a time, e.g. CRF simultaneous with EOP.

In the past, although the benefits of multi-beam VLBI have been appreciated, it has never been implemented due to the high cost of antennas. The recent reduction in cost of high performance small to moderate size antennas, e.g. those for the ATA and LNSD arrays, may make this option worth reconsidering.

8.1 Implications of Multiple Antennas at Geodetic VLBI Stations

In the past, geodetic VLBI was typically done with 20m-class antennas and bit-rates of 56 or 112 Mbps. In recent years, much higher sustained bit-rates have become feasible making the use of smaller cost effective antennas a tempting possibility. This makes the use of multiple antennas at a station a practical option.

There are two reasons to consider the use of more than one antenna at each station:

1. If more than one source is observed simultaneously, the contribution of the clock disappears in the differenced data. There is strong evidence that removing the clock from a *normal* adjustment may improve the usually troublesome vertical

component significantly (i.e. by about a factor of three). However, the effect for *differenced* data has not been investigated. Careful simulations are encouraged if there is interest in pursuing this option further.

2. There is also the tantalizing possibility that more antennas will increase the number of observations per day. To see the extent that this is true, a more detailed analysis follows.

In Appendix E. Examples with Two Antennas at Each Site, some scenarios are explored involving two antennas at each site. It is shown that for two 12m antennas (with 180 degree/min slew rates) at each site, in excess of 2880 observations can be expected per day. This is a significant advance over current capabilities. It is important that IVS, as part of its VLBI2010 activities, encourages investigations using simulations etc. to determine whether the benefits of a greatly increased number of observations per day warrants the addition of a second antenna at each site. A second scenario which might prove to be optimum from a cost-benefit standpoint would be to use one 12m and one 6m antenna at each site, assuming of course that the 6m antenna were restricted to observing stronger sources.

8.2 Many Small Antennas – Few Large Antennas

When the number of desired stations is very large, it will be cost-effective to use a scenario where a few stations have large antennas and the rest have small antennas (and the small antennas are only correlated with the large antennas). This is made possible by the fact that sensitivity in VLBI is proportional to $D1 \cdot D2$. As a result, a 6m antenna operating with a 24m antenna (or phased array of 4-12m antennas) will have the same sensitivity as a pair of 12m antennas. This scenario has some drawbacks:

- It is less robust since the loss of a single large antenna will have a much larger effect.
- Only small-large baselines can be correlated.
- Sub-netting is less flexible.

Strategies can be found to mitigate most of these problems. However, if 12m antennas are affordable at each site, this would be a much better solution.

9 Observing Strategies

The IVS delivers global geodetic scale and orientation by contributing to the ITRF, ICRF and EOP through a series of observation types, each optimized for its own specific purposes. This somewhat complex strategy does a good job of making the best use of available resources. However, it requires compromises which limit performance.

For example, the VLBI contribution to the ITRF is established primarily through a series of 8-station observations in which certain core stations are observed repeatedly while the rest are added cyclically. Clearly, observing all stations simultaneously would provide a more robust result. This is currently not possible because of the limited number of inputs to existing correlators. Although the goal of using all available stations simultaneously will not happen immediately, the situation may improve in the not too distant future. All Mk4 correlators were built as 16-station correlators, but they have been equipped with only seven to nine station inputs. With the introduction of the much lower cost Mk5B to replace both the Mk4 playback system and station unit, the input from all sixteen stations will be affordable.

There are also compromises with respect to the measurement of EOP. For example, the full set of EOP is only guaranteed to be determined twice per week. Although UT1-UTC is determined an additional 5 times per week using short 2-station observations referred to as the Intensives, it would be better to determine the full set of EOP daily and continuously. This is currently not possible due to a lack of station availability. In addition, larger and better distributed networks would make EOP more robust and improve the connection to the ITRF. Unfortunately, increasing network size puts further stress on station availability. The situation is not likely to improve without adding a number of VLBI stations dedicated to geodesy and designed specifically to be operationally efficient, e.g. robust and capable of unattended operation.

There are a number of challenges which must be addressed when optimizing an observing strategy that includes ICRF, EOP and ITRF, e.g.:

- **ICRF challenges:**
    - Establish and maintain the position, flux and structure of the 400-600 "stable" sources required for robust geodetic VLBI observations. This needs to be carried out in all required frequency bands. It has been shown (Section 5) that this will require an ability to observe sources with fluxes as low as 0.2-0.15 Jy respectively. Sources need to be observed a number of times per year to monitor stability and some mapping capability is required to establish the degree of structural complexity.
    - A uniform distribution of sources is required. As a result, antennas need to be more of less uniformly split between the northern and southern hemispheres.
    - Weaker sources need to be monitored to support the densification required by other applications such as astronomical phase referencing. It is assumed that these observations will be carried out in collaboration with the astronomical community as it will require the use of larger more sensitive antennas. Perhaps formal agreements need to be undertaken to better establish the nature of the collaboration.
- **EOP challenges:**
    - Since EOP are required at many time scales including sub-diurnal, continuous observations are required.
    - Since EOP are aggregate parameters, i.e. they result from observations at a number of stations, more stations will improve the result.
    - Since the ITRF defines the non-rotating Earth-fixed frame, a large enough number of stations is required (16?) to establish a robust connection between the EOP network and the ITRF.
    - Since (for some applications) variations in EOP are more important than absolute angles, using a consistent network will improve the results.

  - Since one of VLBI's main contributions is long-term stability of EOP, it is important to monitor network bias. This can be done effectively by periodically observing simultaneously with two networks and comparing the results.
  - Low latency in the delivery of results is important for some applications (although, in these applications, the highest precision is not required).
- **ITRF challenges:**
  - Observing frequently throughout the year will allow annual and episodic effects to be monitored.
  - A capability to observe using a large network will enable a robust connection amongst all VLBI TRF sites.
  - Since one of VLBI's important assets is twenty years of uninterrupted data, it is important to carefully continue as many station records as possible into the future. In some cases collocating new stations with old stations can accomplish this. However, it might also be advantageous to either develop new operating modes that are compatible with the old modes, or to upgrade the feeds and acquisition equipment at old sites to be compatible with new modes.
  - It must be possible to handle the occasional long delays in receiving data from Antarctic sites.

Here are three example observing strategies (with many others being possible):

- If VLBI2010 runs as a 16-station network continuously, it would be possible (with enough scheduling smarts, ideal station distribution, and sufficient sensitivity) to use a fixed or slowly changing list of 60 geodetic sources and also cycle through the 400 "stable" astrometric sources perhaps 20 per day. In this way daily EOP values as well as a time series of source positions can be estimated and there would be more than enough data to estimate the catalogue positions and TRF parameters. If the entire global network cannot run every day, then less frequent full-network sessions can connect the TRF while frequent smaller network sessions provide the high resolution EOP. CRF monitoring can occur as a small fraction of the time in all sessions.
- A 16-station network of less sensitive antennas could be run continuously for TRF and EOP. A smaller but more sensitive network with antennas uniformly distributed in the northern and southern hemisphere could then be reserved for CRF and occasionally for expansion of the TRF.
- A larger network with say 32 stations could be used for an optimized simultaneous determination of TRF, EOP and CRF. This could be done in a holistic fashion, with EOP determined continuously using all 32 stations, CRF candidate sources being slowly rotated into the schedule and extra TRF stations being slowly rotated into the network. It could also be done in a more segment fashion, e.g.:

- A geographically optimized 16-station network could be operated continuously for EOP.
- Of the 16-station EOP network, 3 stations (more if practical) could transmit data using eVLBI networks for low latency results.
- An optimized 32-station network (including the 16-station EOP network) could be operated once per week for TRF and EOP.
- A 32-station network (including the 16-station EOP network) could be operated once per week to incorporate legacy stations and Antarctic stations into the TRF and for EOP.
- Two separately optimized 16-station networks could be run once per week to test for systematic EOP biases between the networks.
- A 16-station network could be operated 4 days per week for CRF.

10 Network Structure

Currently, there are 27 IVS network stations. Of these, 9 are in Europe, 6 in Japan and 5 in North America, leaving 7 for the rest of the globe. Many of the antennas currently in use were acquired on an ``as-is where-is'' basis and hence their location, performance and availability were not optimized for geodesy. In addition to the 27 IVS network stations, others (also equipped with “geodesy compatible” receivers and recorders) are used on an *ad hoc* basis. Annually, the combined total is typically between 40 and 50. This includes the VLBA stations which are used 6 times per year in the RDV sessions.

10.1 Network Geometry

Important features of a network include:

- The total number of stations available to be used.
- The maximum number of stations that can be used in a single session.
- The maximum number of stations whose operations can be sustained on a continuous basis (excluding time for maintenance).
- The distribution of stations.

When considering these features, the requirements of TRF, CRF and EOP all need to be addressed. In general, TRF is a driver for the first two items, EOP for the third, and although not mentioned above, CRF is a driver for more sensitivity. Improving the distribution of stations will have a positive impact on all three.

10.1.1 Number of stations

There are a number of reasons to want to use a larger number of stations, e.g.:

- Since scale and orientation of reference frames are aggregate parameters, i.e. they are determined by making measurements at many stations, having more stations will in general improve the result.
- Results will be more robust against the loss or poor performance of an individual station.
- The connection between VLBI measurements and the ITRF will be improved.
- The negative impact of systematic effects on final results will be mitigated.

- Realistic performance studies will be enabled through intercomparison of separately optimized networks.
- More flexible use of antennas will be enabled with the result that the somewhat competing goals of TRF, CRF and EOP can be met without significant compromise.
- The expansion of the network to new sites (for the purpose of improving global distribution) will be enabled while at the same time enhancing VLBI's important legacy data sets by collocating as many new stations as practical at existing sites.

Having made the case for the beneficial effects of a large network, it is, unfortunately, difficult to use these arguments to define a specific number for network size. Below are some attempts to make more quantitative statements:

- **The total number of stations available to be used.** Typically, in any given year, 40-50 stations are used for geodetic observations. With the current constellation of stations, experience has shown that having at least this number is required for geodetic VLBI to be done properly, i.e. to carry out CRF, TRF, EOP and RD observations. However, these stations are of varying quality and only available a limited number of days per year. Since the dominant thrust of VLBI2010 appears to be the construction of a new "instrument" specifically for the establishment and maintenance of reference frames, we can anticipate the construction of a number of new identical high quality stations dedicated to geodetic VLBI. The question is "how many?" It is likely that fewer stations will be required to perform the same job that is being done today. However, in reality, a considerable amount more is being asked of the VLBI2010 system both in terms of performance and data frequency, e.g. submillimeter reference frame accuracy and high quality daily (or even sub-diurnal) EOP measurements. Some suggestions have been made in Section 9 for ways in which 16-32 stations might be used to effectively carry out the VLBI2010 requirements. However, these are merely straw-man examples and the final number will require a fine balance between perceived available funds and performance requirements. To this end, an extensive program of simulations and RD experiments are required to quantify the number of stations needed to achieve the expected performance levels. However, this approach has limitations since some parameters may be outside the scope of the studies, e.g. the number of stations required for a robust connection to the ITRF and the number of legacy stations that need to be continued into the future. In addition, in at least one case theoretical studies significantly underestimated the required number of stations. Recall that it was originally thought that 13 or so GPS stations would suffice for stable global solutions. Now few serious practitioners consider using fewer than 50 or even 100 stations in their analysis. It would be instructive to learn the reason for the significant shortfall in their initial estimates. In the case of GPS, it was reasonably painless to adapt to the larger number of stations. However, due to the highly integrated nature of VLBI and the higher cost of stations, this may be considerably more difficult for VLBI. Clearly, if performance is the dominant criterion, erring on the side of too many stations is safer than too few.
- **The maximum number of stations that can be used in a single session.** Currently, the maximum number of stations that can be used in a session is limited by correlator size. Consequently, geodetic sessions typically used 9 or

fewer stations, the exception being the 20-station RDV sessions which are correlated at the VLBA. Under the current circumstances, it is obvious that all VLBI stations cannot be observed simultaneously. The process of connecting them all involves using a few core stations in small networks and adding the rest of the stations on a cyclic basis. Although it is the best that can be done with current resources, it is, unfortunately, not particularly robust. Any increase in network size will have a beneficial effect. Some improvements can be expected in the near term. First, due to a recent excess in correlator capacity, network size will increase somewhat through the use of multi-pass processing at the correlator. Second, the number of station inputs at each correlator will be increased to 16 after the deployment of the comparatively low-cost Mk5B. If all the existing Mk4 correlation hardware could be brought together in one location, there would be enough resources for a 27-station correlator. Since 27 stations is already possible, it is recommended that the new VLBI2010 correlator be designed to handle at least 32 stations.

- **The maximum number of stations that can sustain continuous operations indefinitely**. This is currently limited by station availability. There is no easy solution with the current constellation of stations. However, it will be remedied when stations are built especially for IVS purposes and those stations are designed for unattended operation and minimal maintenance.

10.1.2 Distribution of Stations

Currently, there are 27 IVS network stations. IVS schedules other stations as well (e.g. the VLBA) for a total of 40-50 stations per year. This is a significant number of stations, however the distribution is not optimal. A better distribution of stations would have the following benefits:

- A more uniform global distribution would add to the geometric strength of adjustments.
- If at least three stations are located on each major plate, an independent VLBI TRF could be defined.
- Since one of VLBI's important contributions to space geodesy is long term stability, having more than three stations on some plates will enable the detection and monitoring of slow continuous and small episodic intra-plate movements.
- Since an important asset of VLBI is twenty years of uninterrupted data, as many of the current stations as is practical should be continued into the future.

There has been one suggestion for an interim improvement in distribution through the addition of the following stations:

- One in Greenland,
- One in North America (somewhere near Seattle, WA),
- Two in South America, one near the equator on the west coast and one near 50 degrees latitude on the east coast,
- Three in Africa, one each in the west, east and north,

- Two in Australia, say near Perth and Darwin and one in New Zealand.
- Four in southern Asia, e.g. two in Arabia and two in India, with maximum separation possible.
- One in Antarctica at McMurdo station.

The addition of these stations will undoubtedly improve the global distribution of geodetic VLBI sites. However, before network expansion is contemplated, IVS should encourage an extensive quantitative follow-up where Analysis Centers participate in a program of simulations for optimum station placement with respect to each of EOP, ITRF and ICRF.

10.2 Site Selection and Station Design Criteria

Achieving millimeter and submillimeter accuracy will require attention to detail. A thorough list of site selection and station design criteria will help minimize site related systematic errors and enhance operational efficiency.

With respect to site selection criteria, important examples might include:

- Benign troposphere conditions,
- Good horizon mask,
- Geological stability,
- Accessibility of bedrock,
- Lack of local interference,
- Proximity to other fundamental geodetic measurements
- Proximity to infrastructure such as power, transportation, communications and personnel,
- Proximity to advanced networks for eVLBI.

With respect to station design criteria, important examples might include:

- Ease and accuracy of site ties,
- Fast slew rates,
- Low elevation capability,
- Well understood thermal and gravity deformations,
- Interference tolerance,
- Adequate sensitivity,
- Stable and accurately calibrated electronics.

It is likely that significant performance and operating benefits will result also from using an identical station design at each site, e.g.:

- One large design effort can be expended to develop a high-quality low-cost station including antenna, receiver, data acquisition and transmission equipment, H maser, remote/automatic control, buildings, etc.
- Any performance issues learned about one station can be applied to all stations.
- Maintenance is more efficient.
- Spare parts and expertise can be shared by all stations.
- Site software development is more efficient and robust.

10.3 Site Ties

The integration of all space geodetic techniques is becoming increasingly important. Efficient determination and maintenance of accurate site ties is necessary for effective inter-technique integration. It also allows local movements of the antenna structure and pier to be separated from large scale geologic movements.

Recently, a novel approach has been proposed to improve local ties [Y. Koyama, unpublished]. The position of a small nearby antenna relative to the larger VLBI antenna can be accurately established using connected element interferometry. Since the antenna is small, if designed properly, very accurate ties could be established between it and the local monumentation. Perhaps the process can even be automated. The small antenna could also be used to verify thermal and gravitational deflection models of the large antenna.

11 Scheduling

Schedules have been made automatically for the past 15 years. Currently, a schedule can be generated based on interacting sets of rules that optimize the observing for desired characteristics. All the physical characteristics of the network (antenna locations, slew rates, drive limits, sensitivity, horizon mask) as well as the characteristics of the sources (positions, flux, and structure) are automatically taken into account so that idle time, slewing time, sky and elevation coverage, source distribution, etc. can all be optimized at the scheduler's discretion. The real issues for a newly designed system would be to determine the constraints to place on schedules, i.e. what should be optimized to reach the goals of the new system.

Current scheduling strategy optimizes schedules to have: the most possible observations (i.e. delay points) per 24 hours, approximately equal numbers of scans per network station, minimum time spent slewing or idle, and a full-sky distribution of sources for each hour of the schedule. The latter (sky coverage) is the major optimization goal of schedules, because analysis yields the best results if schedules have the widest distribution of points over the sky in the time for solving for atmospheric parameters. Another example is that sub-daily estimates of EOP require the schedules to have a good distribution of observations over the time interval of the estimates (usually one hour).

A single network and a single scheduling strategy could serve for EOP, CRF, and TRF. Today there are separate solutions made for each type of result, but the same data (i.e. the entire historical VLBI data) is used for all types of solutions. Until we can eliminate systematic errors, such as the atmosphere and instrumental effects, we will need to have all schedules with similar characteristics as today: as many observations as possible, widely distributed over the sky in the time interval of the parameters to be solved for.

We currently tend to schedule a "geodetic" subset of sources (about 110 sources) for routine sessions, because these sources have proven to have the least structure and the most stable fluxes. The list of such sources is ever evolving due to source changes, so that sources must be monitored to determine their continuing suitability for the geodetic catalog. The method used now for the monitoring is to include a set of about 10 sources in each 24-hour schedule, where the 10 are selected from an astrometric list that includes hundreds of sources from surveys and other studies. Over the course of a year with 100 geodetic sessions (with current antennas), we can monitor 1000 sources, with minimum flux density about 0.2-0.3 Jy. Observing this number of sources in a 24-hour schedule uses about 10% of the observations and should result in no significant change in the geodetic results. A similar approach could be used for the new VLBI2010 network.

Current geodetic sessions with existing networks observe about 50-60 sources in a 24-hour schedule. If more sources were available then the schedules could achieve a better sky distribution and therefore better geodetic results. Simulations of schedules with twice the usual number of sources (~100) gave improvements in formal errors of ~20%. This argues for better VLBI2010 network sensitivity than we have now, either through higher data rates, larger antennas, or better receivers.

In a typical 8-station network that we use today, with a 256 Mb/s data rate, we get 400-500 scans and 4000 observations. In this terminology, a "scan" is a subnetwork of stations observing a source at a given time, and an "observation" is a single delay point. So one scan may result in from 2 to 28 observations for an 8-station network. An individual station in such a network would participate in about 200-300 of the total number of scans in the 24-hour schedule, or about 8-12 scans per hour. The number of scans per hour at a station determines how well you can solve for the atmosphere parameters, in the way we are doing the analysis now. For each station in the network you probably want to aim for a minimum of 10-15 scans per hour per station, and even that might be too conservative, so maybe it should be say 20. Some scenarios that have been described in this report (see Section 8.1) result in more than 100 observations per hour per station. It is important to do simulations to see whether these added observations result in a significant improvement in performance.

There are several other scheduling issues that should be considered when the system is being implemented. With fully automated control of the new network we will be able to change schedules on a real time basis. For example if an antenna has an equipment problem the schedule could adapt to the changing situation and continue to be optimized for the actual network. If the network is observing full time schedules may be continuous, i.e. not divided into 24-hour periods. This would give another dimension to analysis strategies. The individual antennas of the network would need to have planned and scheduled maintenance periods, and the scheduling plans would have to take these into account also by dropping stations during maintenance or down periods. All of these issues are easily dealt with.

For the next phase of VLBI2010, simulations will play a critical role. In many cases in this report, lists of considerations, optimization criteria and options have been produced but no definite recommendations have been made. In order to make these decisions, easily accessible and convenient simulation tools will be required so that comparisons can be made based on objective criteria and so that a large number of groups can be engaged in this activity. To this end, it should be an important task within IVS to develop modern scheduling/simulation tools which are:

- **Easily accessible**, i.e. they can be easily ported to commonly available platforms so that many groups can participate in these studies.
- **Convenient to use**, so that numerous different scenarios can be evaluated with minimal effort.
- **Flexible**, so that novel optimization criteria and/or network scenarios (e.g. multi-beam observations) can be added as required with minimal effort.
- **Realistic**, i.e. all error sources including for example clocks and atmosphere, and all monitoring measurements such as cable cal and WVR are accounted for in a meaningful way.

12 Operations/Field System

The design of the control system should be driven by a requirement for unattended operation for routine observing. In addition it is important to provide interactive tools that assist technicians with troubleshooting and repairing equipment. A system that combines both provides the most capability and most flexibility for fixing and managing problems.

Unattended operation needs to be carefully defined. It is very unlikely that the hardware and software system will be so reliable that no operator will be required at all. A sensible model might be to have a operator, who must likely is a technician as well, who periodically visits the site for routine maintenance, but also is available "on-call" should a problem develop. There may be many possible strategies for handling this situation, but two are described here. The first is to provide a "call-out" mechanism in the control software, so that when any of a certain set of problems is detected, a technician can be contacted to correct the problem. The second is provide network connectivity so that a centralized "network operator" can keep tabs on how well the stations are performing, possibly taking corrective action himself or calling in a site technician if necessary. Both of these strategies can work reasonably well, either individually or in combination, as long as the system is reliable enough to keep the number of call-ins to a minimum. The reliability sets the level of unattended operation that is possible.

Uniformity in station design around the network will greatly simplify software design, development, and testing. The best situation of course is if all the systems can be identical. The next most desirable situation is that if the stations are not actually uniform that they be designed to be as modular and similar in operation as possible. The extent to which they are not identical will increase the effort required for the development of the control system and reduce its reliability as well.

It is possible to consider some adaptive operational issues for the overall network. In particular, if all the stations have reliable network connections, it is possible to consider adaptively changing the schedule if one or more observing stations breaks down. Allowances will of course have to be made for situations where the connection are not reliable. However, this has the potential to improve the overall result when stations fail, as they inevitably will.

13 Conclusions and Recommendations

- It will be difficult to meet the performance goals of VLBI2010 without **the development of a new "instrument" designed specifically for and dedicated to the establishment and maintenance of reference frames**. It is important that the IVS continues to move forward on this initiative on several fronts, e.g.:
    - **Technical.** An active program of simulations, etc. is required to better constrain specifications. Where appropriate prototyping can begin.
    - **Organization.** IVS members should come together as a consortium so that the new "instrument" can be funded internationally.
    - **Political.** Work should begin to promote the concept of a new international "instrument". A name should be found.
- **Modern scheduling/simulation tools are needed** which are easily accessible, convenient to use, flexible and realistic.
- A major effort is indicated to search for a method to **break through the 3mm barrier in the vertical component imposed by the clocks and troposphere**. Possible approaches using simulations, R&D experiments etc. include:
    - Differenced data, perhaps through multi-beam observations.
    - Many more observations per day, e.g. 3000-5000 observations per day per station.
    - Line-of-sight WVR.
- **A decision should be made whether either the 6m ATA antenna or the 12m LNSD antenna is appropriate for our purposes**. If so, closer ties should be established with the ATA and LNSD and the cost of upgrades to, for example, slew rate and elevation cut-off should be investigated (if required). Otherwise, a specification and cost estimate for a unique antenna for geodetic VLBI is required.
- **Required delay precision can be achieved at modest SNR using many combinations of frequency bands provided that absolute phase is used**. A final decision on frequency bands needs to be made so that the specification of the RF/IF system can begin. Remaining questions include:
    - Does Ka-band improve performance?
    - Is S-band interference tolerable assuming RFI-avoidance measures are applied?
    - Is 22 GHz required for line-of-sight WVR?

  - Are there any unforeseen complications resulting from the use of phase delay?

- **An RFI-tolerant system design is required.**
- **A minimum source strength of 0.15-0.2 Jy is required to avoid source structure corrections**.
- **Collaboration with the astronomical community will be required for ICRF densification below 0.15-0.2 Jy.** Formal agreements should be considered
- **A pair of antennas at each site can increase the number of observations per day significantly (>3000)**. Simulations are required to evaluate resulting benefits.
- **Low-maintenance automated stations are required** to minimize operating costs**.**
- **A large total number of stations (40-50) is required for connection with the ITRF and to maintain "legacy" data records.**
- **A decision on station locations will require intensive studies including detailed investigations into site conditions and simulation of performance.**
- **A modern 32-station correlator is required.**

Appendix A. Delay Uncertainty Goal for VLBI2010 System

In an attempt to determine the delay accuracy per observation that will be needed to obtain a vertical formal error of approximately 1 mm for a twenty-four hour global session, the R1 from 2003DEC29XA ver4 will be used as the basis. Dan MacMillan provided a *solve* output for this day in which only the position of Gilcreek was estimated, plus atmospheres and clocks for all stations.

For this day, the weighted RMS delay residual was 18.6 psec, and the additive noise for the stations ranged from 6 psec for Seshan to 29 psec for HartRAO. The median was 12 psec, which was also the value for Gilcreek and Westford. The largest number of observations appeared to be (in decreasing order) from Gilcreek, Westford, then Wettzell, for which the additive delay was only 8 psec. Subtracting quadratically an "average" additive delay of 12 psec from 18.6 psec says that the typical per-observation delay uncertainty is about 14 psec. It also says that the unmodelled delay uncertainty is about the same magnitude as the contribution from the total of the estimated parameters, which is not unusual.

The uncertainty for the Up component of Gilcreek in this solution is 3.66 mm. If the formal error is scaled by 1/3.66, the required delay uncertainty is 3.9 psec, suggesting a goal for the median delay uncertainty of four psec for a twenty-four hour session. This assumes that a comparable amount of delay noise will be added from unmodelled effects.

Of course with this uncertainty we cannot reach 1 mm vertical uncertainty in 24 hours because all of the other effects external to the observations, such as mapping function errors, antenna deformation, and loading effects, will add to this. Furthermore this assumes that the delay uncertainty due to SNR is the dominant contributor to the formal position uncertainty within a twenty-four hour session. The contribution of the atmosphere and clocks will be studied in the next Appendix.

Appendix B. Position uncertainties due to atmosphere and clock

The contributions of the stochastic properties of the wet atmosphere zenith delay and gradient, and of the clocks, will be evaluated using *solvk* and data from CONT94 [4]. To set the uncertainty of the observed delay to a small value, replace the sigma (*db_sigma* in *solvk*) with a fixed value for the baselines of the CONT94 940112 session. Initially use 0.001 ps for the delay uncertainty when evaluating the position uncertainty due to the atmosphere or clock.

In a typical solution for CONT94 an additive delay noise (*xtrnoise*) of approximately 10 psec is required for the group delays to achieve a reduced chi-square of 1. For these tests set this value to 0.0.

To assess the magnitude of each effect separately, set the markov process noise to a negligibly small value, then in turn set each to the nominal value for the CONT94 sessions.

For each contribution (atmosphere and clock) make three solutions using a) the nominal value of the variance/time, b) a value much larger than nominal, and c) a value much smaller than nominal.

Fix the positions of Gilcreek as the reference site, and set the clock to very small variation to serve as the reference clock.

During CONT94 the atmosphere random walk parameter for all sites except Kokee had a median value of approximately 0.1 ps^2/sec. This corresponds to *solvk* Markov input parameters of 11 psec at 20 minutes. The gradient variation is not easily assessed but is probably at least a factor of ten smaller than the zenith delay, which is what I will use here. The characteristic Markov value used for the clock in my *solvk* solutions has been $1*10^{-14}$ at 50 minutes. This was adopted in the HDS paper as a conservative value.

Solution index		ZWD markov psec @ minutes	clock markov psec @ minutes*	gradient markov psec @ minutes
0	tight	0.001 @ 1440	1.d-18 @ 1440	0.001 @ 1440
1	nominal	11 @ 20	1.d-14 @ 50	1.1 @ 20
2	<<	0.33 @ 20	1.d-16 @ 50	0.033 @ 20
3	>>	330 @ 20	1.d-12 @ 50	33ps @ 20
4			1.d-15 @ 50	

Denote solutions by vnjkl where

n = 0, 4, 16 ps for delay sigma

j,k,l = 0,1,2,3,4 for case in table above

Comparison parameters are WESTFORD NEU uncertainties (mm)

Solution	N	E	U

Reference	2.6	2.2	4.8
0000	0.2	0.2	0.3
0100	0.7	0.6	0.6
0010	0.5	0.4	1.0
0001	0.4	0.4	0.4
0111	1.4	1.2	1.9
0141	1.1	1.0	1.8
0222	0.3	0.3	0.5
0333	60	53	138
4111	1.4	1.3	2.9
4141	1.1	1.1	1.8
16111	1.6	1.6	3.6
16111x	1.8	1.7	3.8
16141	1.6	1.4	2.3

In conclusion, for the number of observations per hour of the CONT94 sessions, the stochastic properties of the atmosphere and clock-like errors limit the uncertainty in the vertical to about 3 mm, even with a per-observation delay uncertainty of 4 psec. For small fast moving antennas with high data rates, the number of atmosphere and clock samples per hour may be significantly higher. While it is tempting to speculate that this will reduce the correlations of the atmosphere, clocks, and positions, simulations must be done to determine to what extent this occurs.

Appendix C. A Phase Delay Scenario

The purpose of this appendix is to investigate the feasibility of using a broadband feed (e.g. 2.5-11 GHz) to make absolute phase ambiguity resolution possible at modest SNR and hence significantly improve geodetic VLBI delay precision. There are probably better ways to implement the delay calculation, but the present discussion should be adequate to show that ambiguity resolution is possible at an SNR of about 25 and to show roughly what precision can be achieved at that SNR. Although most of the available band (2.5-11 GHz) is useable, the frequencies allocated for commercial satellite broadcast and downlink should be avoided to mitigate degradation due to RFI. This leaves three broad bands at frequencies 2.69 to 3.4 GHz, 4.8 to 6.7 GHz, and 7.75 to 10.7 GHz that will be referred to here as S-band, C-band and X-band, e.g.

Band Designation	S	C	X
Band (GHz)	2.69-3.4	4.8-6.7	7.75-10.7
Centre Freq, υ (GHz)	3.045	5.75	9.225
Spanned bw, $\delta\upsilon$ (GHz)	0.71	1.9	2.95

The measured group delay in each band, i, can be written,

$$\hat{\tau}_i^G = \tau + \frac{K}{\upsilon_i^2},$$

where τ is the non-dispersive part of the group delay, $\frac{K}{\upsilon_i^{\,2}}$ is the dispersive part of the group delay and K is a term proportional to the integrated line-of-sight electron content. Assuming continuous frequency coverage across the band, the corresponding group delay precision can be written,

$$\delta\hat{\tau}_i^G = \frac{1}{2\pi \cdot SNR \cdot \delta\upsilon_i^{rms}} = \frac{\sqrt{12}}{2\pi \cdot SNR \cdot \delta\upsilon_i}$$

The measured group delay at S-band and X-band can then be used to solve for τ and K, i.e.

$$\hat{\tau}^{(G)} = \frac{\upsilon_X^{\,2} \cdot \hat{\tau}_X^G - \upsilon_S^{\,2} \cdot \hat{\tau}_S^G}{\upsilon_X^{\,2} - \upsilon_S^{\,2}}, \text{ with}$$

$$\delta\hat{\tau}^{(G)} = \frac{1}{\upsilon_X^{\,2} - \upsilon_S^{\,2}} \cdot \sqrt{(\upsilon_X^{\,2} \cdot \delta\hat{\tau}_X^G)^2 + (\upsilon_S^{\,2} \cdot \delta\hat{\tau}_S^G)^2}, \text{ and}$$

$$\hat{K}^{(G)} = \frac{\upsilon_X^{\,2} \cdot \upsilon_S^{\,2}}{\upsilon_X^{\,2} - \upsilon_S^{\,2}} \cdot (\hat{\tau}_S^G - \hat{\tau}_X^G), \text{ with}$$

$$\delta\hat{K}^{(G)} = \frac{\upsilon_X^{\,2} \cdot \upsilon_S^{\,2}}{\upsilon_X^{\,2} - \upsilon_S^{\,2}} \cdot \sqrt{(\delta\hat{\tau}_s^G)^2 + (\delta\hat{\tau}_X^G)^2}.$$

The measured phase (in cycles) in each band, i, can be written,

$$\hat{\phi}_i = \upsilon_i \cdot \tau - \frac{K}{\upsilon_i} + n_i, \text{ with}$$

$$\delta\hat{\phi}_i = \frac{1}{2\pi \cdot SNR}$$

where n_i is the integer cycle phase ambiguity.

At this point, it is possible to attempt to resolve the integer phase ambiguities using $\delta\hat{\tau}^{(G)}$ and $\delta\hat{K}^{(G)}$, i.e.

$$\hat{n}_i^{(G)} = \hat{\phi}_i - \upsilon_i \cdot \hat{\tau}^{(G)} + \frac{\hat{K}^{(G)}}{\upsilon_i}, \text{ and}$$

$$\delta\hat{n}_i^{(G)} = \sqrt{(\delta\hat{\phi}_i)^2 + (\upsilon_i \cdot \delta\hat{\tau}^{(G)})^2 + (\frac{\delta\hat{K}^{(G)}}{\upsilon_i})^2}.$$

Provided that $|\hat{n}_i - n_i| < 0.5$, the integer cycle ambiguity will be resolved properly. The ratio,

$$N\sigma_i^{(G)} = \frac{1}{2 \cdot \delta\hat{n}_i^{(G)}},$$

represents the number of sigma that $n_i^{(G)}$ would need to be in error before a cycle slip would occur. Using the broad S-band and X-band channels listed above, an SNR of 29 in each band or a combined SNR of 41 is required to achieve 5-sigma confidence in phase ambiguity resolution.

Although this is pretty good, it possible to decrease the per-band SNR requirement by more than a factor of two if a method is used that involves the C-band channel as well. The method begins the same way, but instead of resolving the S-band and X-band phase directly, it resolves the S-band/C-band and C-band/X-band phase differences to produce pseudo group delay observables, i.e.

$$\Delta\hat{\phi}_{i-j} = \hat{\phi}_i - \hat{\phi}_j = (\upsilon_i - \upsilon_j)\cdot\left(\tau + \frac{K}{\upsilon_i \cdot \upsilon_j}\right) + n_{i-j} \text{, with}$$

$$\delta\Delta\hat{\phi}_{i-j} = \sqrt{\left(\delta\hat{\phi}_i\right)^2 + \left(\delta\hat{\phi}_j\right)^2} \text{, and}$$

$$\hat{n}_{i-j} = \Delta\hat{\phi}_{i-j} - (\upsilon_i - \upsilon_j)\cdot\left(\hat{\tau}^{(G)} + \frac{\hat{K}^{(G)}}{\upsilon_i \cdot \upsilon_j}\right) \text{, with}$$

$$\delta\hat{n}_{i-j} = \sqrt{\left(\delta\Delta\hat{\phi}_{i-j}\right)^2 + (\upsilon_i - \upsilon_j)^2 \cdot \left(\left(\hat{\tau}^{(G)}\right)^2 + \left(\frac{\delta\hat{K}^{(G)}}{\upsilon_i^2 \cdot \upsilon_j^2}\right)\right)}$$

In this case, it turns out that the phase ambiguities for $\Delta\hat{\phi}_{C-S}$ and $\Delta\hat{\phi}_{X-C}$ can be resolved at 5-sigma confidence for SNR=14 per channel, or an overall SNR of 24. Assuming that the phase ambiguities have been properly resolved, these phase differences can be interpreted as pseudo group delay observables i.e.

$$\hat{\tau}_{i-j}^{(\Delta\phi)} = \frac{\Delta\hat{\phi}_{i-j}}{\upsilon_i - \upsilon_j} = \tau + \frac{K}{\upsilon_i \cdot \upsilon_j} \text{, and}$$

$$\delta\hat{\tau}_{i-j}^{(\Delta\phi)} = \sqrt{\left(\delta\hat{\phi}_i\right)^2 + \left(\delta\hat{\phi}_j\right)^2} \text{.}$$

Now, $\hat{\tau}_{C-S}^{(\Delta\phi)}$ and $\hat{\tau}_{X-C}^{(\Delta\phi)}$ can be used to get new more precise values of τ and K, i.e.

$$\hat{\tau}^{(\Delta\phi)} = \frac{\upsilon_X \cdot \hat{\tau}_{X-C}^{(\Delta\phi)} - \upsilon_S \cdot \hat{\tau}_{C-S}^{(\Delta\phi)}}{\upsilon_X - \upsilon_S} \text{, with}$$

$$\delta\hat{\tau}^{(\Delta\phi)} = \frac{1}{\upsilon_X - \upsilon_S} \cdot \sqrt{\left(\upsilon_X \cdot \hat{\tau}_{X-C}^{(\Delta\phi)}\right)^2 + \left(\upsilon_S \cdot \hat{\tau}_{C-S}^{(\Delta\phi)}\right)^2} \text{, and}$$

$$\hat{K}^{(\Delta\phi)} = \frac{\upsilon_S \cdot \upsilon_C \cdot \upsilon_X}{\upsilon_X - \upsilon_S} \cdot \left(\hat{\tau}_{C-S}^{(\Delta\phi)} - \hat{\tau}_{X-C}^{(\Delta\phi)}\right) \text{, with}$$

$$\delta\hat{K}^{(\Delta\phi)} = \frac{\upsilon_S \cdot \upsilon_C \cdot \upsilon_X}{\upsilon_X - \upsilon_S} \cdot \sqrt{\left(\delta\hat{\tau}_{C-S}^{(\Delta\phi)}\right)^2 + \left(\delta\hat{\tau}_{X-C}^{(\Delta\phi)}\right)^2} \text{.}$$

With $\hat{\tau}^{(\Delta\phi)}$ and $\hat{K}^{(\Delta\phi)}$, the phase ambiguities in $\hat{\phi}_S$ and $\hat{\phi}_X$ can easily be resolved (at 5-sigma confidence) with SNR=14 per channel. With the phase ambiguities resolved, $\hat{\phi}_S$ and $\hat{\phi}_X$ can be interpreted as phase delays, i.e.

$$\hat{\tau}_S^{\phi} = \frac{\hat{\phi}_S}{\upsilon_S} = \tau - \frac{K}{\upsilon_S^2} \text{, with}$$

$$\delta\hat{\tau}_S^{\phi} = \frac{\delta\hat{\phi}_S}{\upsilon_S}, \text{ and}$$

$$\hat{\tau}_X^{\phi} = \frac{\hat{\phi}_X}{\upsilon_X} = \tau - \frac{K}{\upsilon_X^2}, \text{ with}$$

$$\delta\hat{\tau}_X^{\phi} = \frac{\delta\hat{\phi}_X}{\upsilon_X}.$$

These can finally be used to get a highly precise ionospherically corrected estimate of τ, i.e.

$$\hat{\tau}^{\phi} = \frac{{\upsilon_X}^2 \cdot \hat{\tau}_X^{\phi} - {\upsilon_S}^2 \cdot \hat{\tau}_X^{\phi}}{{\upsilon_X}^2 - {\upsilon_S}^2}, \text{ with}$$

$$\delta\hat{\tau}^{\phi} = \frac{1}{{\upsilon_X}^2 - {\upsilon_X}^2} \cdot \sqrt{\left({\upsilon_X}^2 \cdot \delta\hat{\tau}_X^{\phi}\right)^2 + \left({\upsilon_S}^2 \cdot \delta\hat{\tau}_S^{\phi}\right)^2}$$

With SNR=14 per band, $\delta\hat{\tau}^{\phi}$ is about 1.5 ps.

Appendix D. Some Sensitivity Examples

Sensitivity in VLBI is governed by the equation,

$$SNR = \frac{\pi \cdot f \cdot S \cdot 1.e - 26 \cdot D_1 \cdot D_2}{8 \cdot k} \cdot \sqrt{\frac{e_1 \cdot e_2 \cdot BR \cdot t}{Ts_1 \cdot Ts_2}}$$

where SNR is the signal-to-noise ratio,

f is the VLBI processing factor (usually about 0.55 for single bit data),

S is the source flux (Jy),

D_i is the antenna diameter for station, i,

k is Boltzman's constant,

e_i is the aperture efficiency for antenna, i,

BR is the bit rate,

t is the integration time, and

Ts_i is the system temperature for station, i.

A number of factors have implications for the sensitivity equation and for the parameter values that are reasonable to be used in the equation, e.g.:

1. The science case for space geodesy justifies a need for long-term reference frame accuracy in the sub-millimeter range. Arthur Niell has shown that this implies a requirement for delay precision at sub-4ps level. Since delay precision and SNR are directly related, this should also constrain the SNR. The connection between delay precision and SNR is, however, also influenced by the detailed frequency structure of the observations. In a separate memo, I consider a frequency structure that includes three broad bands at S-band, C-band and X-band. With this frequency structure, it is shown that a fully resolved phased delay precision of 1.5ps can be achieved using an overall SNR of 24, i.e. SNR=14 in each of the three bands. Since 1.5ps is beyond the 4ps delay precision requirement, it might be tempting to consider the use of still lower SNR's. However, SNR=24 is

required to achieve phase ambiguity resolution at 5-sigma confidence. For the remainder of this discussion, SNR=24 will be considered the minimum SNR requirement.

2. With the introduction of disk-based record systems, sustained bit-rates of 1-2 Gbps are becoming feasible. Since commercial disk technology is advancing rapidly, it is conceivable that significantly higher sustained bit rates will be possible by 2010. However, it should be noted that the advance might not be as rapid as expected since record rate is increasing at a slower rate than the more often quoted disk capacity. The potential for eVLBI may be even greater than for disks but it is also more difficult to predict 6 years into the future. Bit-rates of 1, 2, 4 and 8 Gbps will be considered in the following discussion.
3. Scheduling has been shown to be a powerful tool for improving geodetic VLBI performance. One of the most important figures of merit with respect to scheduling is the number of scans per day. The number of scans per day can be increased by decreasing slew time and/or integration time. If either slew time or integration time dominates, significant improvement can only be achieved by reducing the one that dominates. It will be assumed that a slew time of 60s (which would imply about 180 degrees/min slew rate) is typical and integration times of 30s, 60s, 120s and 240s will be considered. These integration times would correspond to 960, 720, 480 and 288 observations per day respectively on a particular baseline.
4. There are a number of reasons to want to increase the number of stations in a network significantly. However, this will only become practical if the capital and operating costs of stations can be reduced. VLBI2010 comes at a very fortunate time in this regard because of concurrent efforts in the radio astronomy community to produce high performance low cost 6m and 12m antenna systems. The 6m antennas (e=60%, Ts=45K, f=0.5-11 GHz) are already being produced for the ATA. There is also a proposal for the US contender for the SKA which includes high performance cost effective 12m antennas (e=60-75%, Ts=18-45K and f=0.15-35 GHz). As a result, antenna diameters of 6m and 12m will be considered in the discussion below.
5. The number of available sources increases quickly as the source strength cut-off decreases. Having more sources available is important because it allows more efficient scheduling and better selection with respect to lack of structure and positional stability. It also enhances capabilities with respect to IVS's mandate to maintain the ICRF.
6. Antenna efficiency (e) of 60% and system temperature (Ts) of 45K have been achieved for the ATA. For the SKA proposal, the most optimistic projections for e and Ts are 75% and 18K. Although these latter values are still highly speculative, especially in a cost-effective form, we will consider two cases, one with e=60% and Ts=45K and the other with e=75% and Ts=18. This will bracket the entire range between what is currently achievable at low cost and what might, under an optimistic projection, be available by 2010.

Four tables are presented below, the first pair is for a 6m antenna at each end of the baseline and the second pair is for a 12m antenna at each end of the baseline. In both cases, one table will be produced for e=60% and Ts=45K and one for e=75% and Ts=18K. The tables present the minimum correlated flux required to achieve SNR=24 for t=30, 60, 120 and 240 seconds and for BR=1, 2, 4 and 8 Gbps.

	1 Gbps	2 Gbps	4 Gbps	8 Gbps
30s	1.85	1.30	0.92	0.65
60s	1.30	0.92	0.65	0.46
120s	0.92	0.65	0.46	0.33
240s	0.65	0.46	0.33	0.23

Table 1. Minimum correlated fluxes(j) for a pair of 6m antennas with e=60% and Ts=45K

	1 Gbps	2 Gbps	4 Gbps	8 Gbps
30s	0.59	0.42	0.30	0.21
60s	0.42	0.30	0.21	0.15
120s	0.30	0.21	0.15	0.10
240s	0.21	0.15	0.10	0.07

Table 2. Minimum correlated fluxes(j) for a pair of 6m antennas with e=75% and Ts=18K

	1 Gbps	2 Gbps	4 Gbps	8 Gbps
30s	0.46	0.33	0.23	0.16
60s	0.33	0.23	0.16	0.12
120s	0.23	0.16	0.12	0.08
240s	0.16	0.12	0.08	0.06

Table 3. Minimum correlated fluxes(j) for a pair of 12m antennas with e=60% and Ts=45K

	1 Gbps	2 Gbps	4 Gbps	8 Gbps
30s	0.15	0.10	0.07	0.05
60s	0.10	0.07	0.05	0.04
120s	0.07	0.05	0.04	0.03
240s	0.05	0.04	0.03	0.02

Table 4. Minimum correlated fluxes(j) for a pair of 12m antennas with e=75% and Ts=18K

For reference, in a list of 92 commonly used geodetic sources, 10 are below 0.5j, 38 are between 0.5j and 1.0j and 44 are above 1.0j. It should be noted that these are total fluxes. Correlated fluxes on long baselines can be considerably lower. However, the drive to get a better distribution and selection (with respect to structure and positional stability) of sources may drive down the typical source strength, especially if it can be shown that observation of these sources is feasible.

Appendix E. Examples with Two Antennas at Each Site

First, consider two examples: one involving a pair of 6m antennas at each site and the other a pair of 12m antennas at each site. In the table below, it is assumed that SNR=24, e=60%, Ts=45K and BR=2 Gbps (i.e. this option can already be achieved today). The table presents the minimum correlated flux required to achieve SNR=24 for t=15, 30, 60, 120 and 240 seconds assuming the antennas are observing the same source and are phased together.

	2-6m antennas	2-12m antennas
15s	0.92	0.23
30s	0.65	0.16
60s	0.46	0.12
120s	0.33	0.08
240s	0.23	0.06

Table 1. Minimum correlated fluxes for pairs of phased antennas at each station.

The most obvious feature of Table 1 (relative to Tables 1 and 3 of Appendix D) is that, for a particular integration time, the minimum flux has decreased because the effective collecting area of the pair of phased antennas is double that of a single antenna. Consequently, the number of observations per day will increase simply because the integration time is smaller. But is this the best use of a pair of antennas if your goal is to achieve the greatest number of observations per day? Another option would be to use the two antennas to observe two different sources at the same time. This will obviously be more efficient when observations are slew time dominated. In order to see when a schedule becomes slew time dominated, begin by expressing the length of time per scan for the two scenarios. For the case of the phased antennas, the time per scan can be written,

$$T_{phased} = t + s$$

where t is the integration time from Table 1 and s is a typical slew time. For the case of the two antennas observing different sources, t needs to increase by a factor of 8 per antenna to compensate for the fact that both the collecting area and BR have been split equally between the two antennas. In addition, it can probably be argued that s should be different as well. In a typical geodetic schedule, geometry is varied radically from observation to observation so slew distances are typically of the order of 180 degrees. However, with the two-antenna scenario, the required source separation can be attained by having the two antennas always observe widely separated sources. This will greatly reduce slew distance requirements for the individual antennas and it should be reasonable, for the sake of this discussion, to assume that average slew times decrease by about a factor of two. Taking these two factors into consideration, the length of time per observation for one of the two antennas can be written,

$$T_{antenna} = 8t + \frac{s}{2}.$$

Since two antennas are observing simultaneously, the time per observation for this scenario becomes,

$$T_{pair} = \frac{T_{antenna}}{2} = 4t + \frac{s}{4}$$

The point where the transition is made from integration-time dominated to slew-time dominated is obviously when

$$T_{phased} = T_{pair}$$

i.e. when $t = \frac{s}{4}$.

The value for the average slew time, s, is dependent on antenna slew rates. Ignoring the complications resulting from the cable wrap, if the slew rate is 90 degrees per minute, $s \le 120$ s. If the slew rate is 180 degrees per minute, $s \le 60$ s. Assuming $S = 60$ s, slew-dominated observations begin when t is 15s. From Table 5, sources stronger than 0.92j are then slew dominated for 6m antennas and sources stronger than 0.23j are slew dominated for 12m antennas. As a result, phased antennas will be the dominant strategy for 6m antennas and separate antennas will be the dominant strategy for 12m antennas. Conclusions will obviously change for different values of e, Ts, BR and s.

There is one further refinement that can be made to increase efficiency in the slew-dominated case. Instead of splitting BR between the two antennas, it can all be focused on one antenna at a time so that when one antenna is observing, the other can be slewing. In this way, the down time with respect to gathering data is minimized. From Table 3 (i.e. for 12m antennas), it can be seen that for a schedule including sources stronger than .33j and using $BR = 2.e9$, the duration of a typical observation will be less than 30 seconds as will each slew time (if slew rates are assumed to be 180 degrees per minute). This translates to about 2880 scans per day, and perhaps significantly more if creative scheduling strategies are employed. This represents an important advance over performance of today.

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