IVS Memorandum 2006-019v01

1 September 2006

“The Case For and Against Multiple Antennas at a Site”

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Memo#: 2006-019v01
Title: The Case For and Against Multiple Antennas at a Site
Date: Aug. 30, 2006
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Purpose

There are a number of reasons to consider using multiple antennas at a geodetic VLBI site, e.g.:

- To increase the total collecting area.
- To increase the total number of sources observed in a day.
- To remove the corrupting effect of the reference oscillators through differencing.
- To increase redundancy.

The purpose of this memo is to investigate each of these reasons in more detail to determine under which conditions multiple antennas provide an advantage over a single larger antenna.

Assumptions

1. The total cost of the site will be the same, regardless of the number of antennas.
2. The total data rate for the site will be the same, regardless of the number of antennas.
3. The cost of an antenna, including foundations, pedestal, drive system, reflector, shipping to the site and assembly, scale according to the formula,
$$\frac{Ca_2}{Ca_1} = \left(\frac{D_2}{D_1}\right)^{\alpha},$$
where $\alpha = 2.7$, and
Ca_i represents the cost of antenna i.
4. The cost of a fully assembled 12 m antenna is about $500k. Patriot has quoted the cost of a 12 m antenna with 6 deg/s slew rate and 180 deg elevation motion at $375k. The quote does not include the cost of shipping, assembly or footings. I have assumed that these additional costs are about $125k.
5. Regardless of the diameter, there will be fixed costs (Cf) associated with each antenna, e.g.

Feed (Kildal?)	$40k
Receiver (LNA, cooler, etc)	$20k
PCAL and Cable cal	$20k
Cables and trenching	$10k
DAS	$100k
TOTAL	$190k

6. A typical slew time for the antenna will be 32 s. [Reasoning: 1. Assuming a max slew rate of 6 deg/s, an elevation drive with 180 deg of motion (i.e. from horizon to horizon) and 5 s each for acceleration and deceleration, the max slew time will be 35 s. 2. For a typical geodetic schedule using a large number of antennas, at least one of the antennas in the network will have to slew near the maximum

distance at every source change. E.g. 32 s represents 90 % of the max slew distance.]

7. A typical integration time for a 12 m antenna will be 18 s. [Reasoning: If it is assumed that the VLBI2010 data rate will be 8 Gbps, then a pair of 12 m antennas will achieve the same sensitivity in 36 s as a pair of VLBA antennas achieves in 120 s at 128 Mbps. If this represents the maximum sensitivity of the interferometer, stronger sources will require shorter integrations. The typical integration time will depend on the distribution of source strengths and the details of the schedule, but 18 s is assumed for this study.]
8. A pair of VLBI antennas of diameter D1 can achieve the same sensitivity as an antenna of diameter D2 if the integration times are properly compensated. The governing equation is

$$T_2 = T_1\left(\frac{D_1}{D_2}\right)^4$$

Collecting Area

The question to answer is under which conditions will a group of phased antennas have more collecting area than a single antenna. Applying assumption 1, 3, 4 and 5, the governing equation is,

$$Ca_1 + Cf = N(Ca_2 + Cf) = N\left(Ca_1\left(\frac{D_2}{D_1}\right)^{2.7} + Cf\right)$$

Results for single antennas with diameters in the range 1 to 30 m are displayed in Fig. 1.

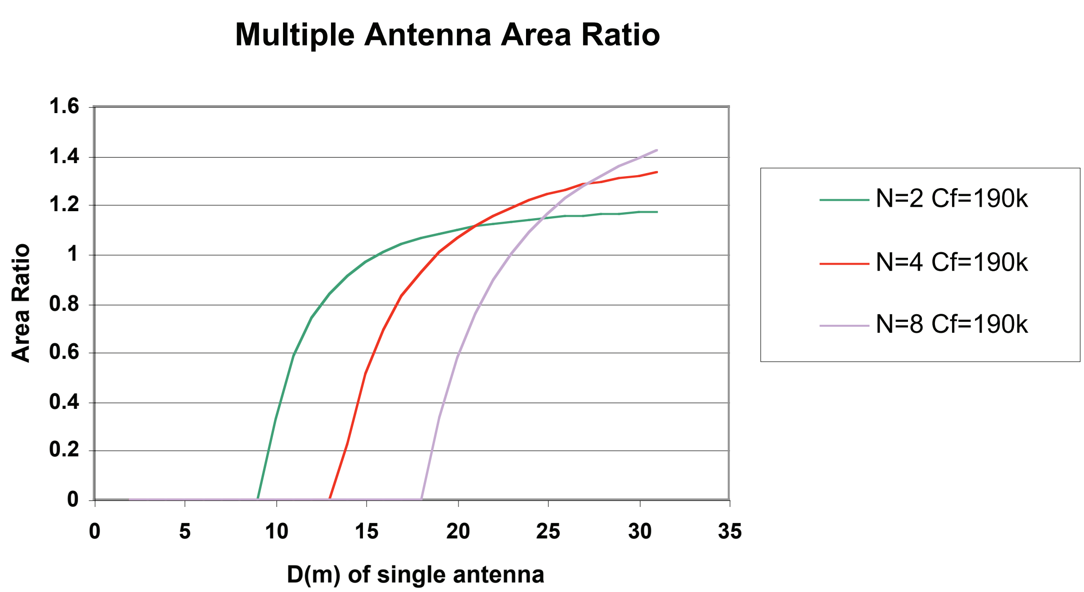

Fig.1. This shows the collecting area ratio between a group of phased antennas and a single antenna of equal cost.

The area ratios are displayed for groups of 2, 4 and 8 antennas. For single antennas above 15 m diameter, a pair of antennas has more collecting area than the equal cost single antenna; for single antennas above 18 m, 4 antennas have more collecting area; and, for antennas above 22 m, 8 antennas have more collecting area.

Number of Observations per Day

It is generally believed that performance improves as the number of observations per day increases. Simulation studies are currently being performed to verify this. The question to answer here is under which conditions will a group of antennas acquire more observations per day than a single antenna of the same cost. Three approached will be considered.

i) **No Burst Mode**. This is the simplest mode of operation. In this mode, an antenna is either on source and recording data, or it is slewing. For a multiple antenna site, the 8 Gbps record capability is split between the antennas. For a single antenna, the total time for an observation is $Tobs_1 = T\text{int}_1 + Tslew$ and the number of observations per day is $Nobs_1 = 86400 / Tobs_1$. For an antenna at a multiple antenna site, the total time for an observation is $Tobs_i = T\text{int}_i + Tslew$, where $T\text{int}_i = Nant \cdot \left(\frac{D_1}{D_i}\right)^4 \cdot T\text{int}_1$, and the number of observations per day is $Nobs_n = Nant \cdot 86400 / Tobs_i$. See Fig's 2, 3 and 4 for performance of stations with 2, 3 and 4 antennas respectively.

ii) **With Burst Mode**. This mode of operation is somewhat more complicated. While an antenna is on source, data is being acquired at a very high rate and placed into RAM. Data is then taken from RAM and written to media at the max record rate. Writing from RAM to media can be done not only during the on source period but also while the antenna is slewing. This allows for shorter on source periods, which is particularly important for smaller antennas. The record time relative to the acquisition rate into RAM can be written $Trec = BF \cdot T\text{int}$, where, for the same sensitivity, $Trec$ needs to be the same as $T\text{int}$ from the "no burst" mode of operation described in the section above. In all cases considered here, a burst factor of 4 will be used, i.e. the acquisition rate is 32 Gbps and the record rate is 8 Gbps. Two regimes of operation need to be considered. The first occurs when $Trec > T\text{int} + Tslew$, which is the record dominated case. In this case, $Tobs = Trec$. Otherwise, $Tobs = T\text{int} + Tslew$. As in the "no burst" case, $T\text{int}_i = Nant \cdot \left(\frac{D_1}{D_i}\right)^4 \cdot T\text{int}_1$, $Nobs_1 = 86400 / Tobs_1$, and $Nobs_n = Nant \cdot 86400 / Tobs_i$. See Fig's 2, 3 and 4 for performance of stations with 2, 3 and 4 antennas respectively.

iii) **Switching Antennas**. In this mode, only one antenna is observing at a time, and the entire record system is dedicated to that antenna. While it observes, the other antennas are slewing. Two regimes of operation need to be considered. The first occurs when $T\text{int} > Tslew / (Nant - 1)$, which is the integration-dominated case. In this case, $Tobs = Nant \cdot T\text{int}$. Otherwise, $Tobs = T\text{int} + Tslew$. Since the record system is not shared, $T\text{int}_i = \left(\frac{D_1}{D_i}\right)^4 \cdot T\text{int}_1$. As in the other cases though $Nobs_1 = 86400 / Tobs_1$, and $Nobs_n = Nant \cdot 86400 / Tobs_i$. See Fig's 2, 3 and 4 for performance of stations with 2, 3 and 4 antennas respectively.

The performance of the three operating modes is displayed in the plots below. In Fig. 2, the number of observations per day for a 2-antenna site is compared to that of a 1-antenna site. All three operating modes are considered. At about 15 m, the 2-antenna site becomes more efficient with respect to number of observations per day compared to a 1-antenna site. At 17m, two 12 m antennas can replace a single larger antenna at the same cost, but the 2-antenna site will be able to make 65% more observations in a day, for a total of about 4300 observations.

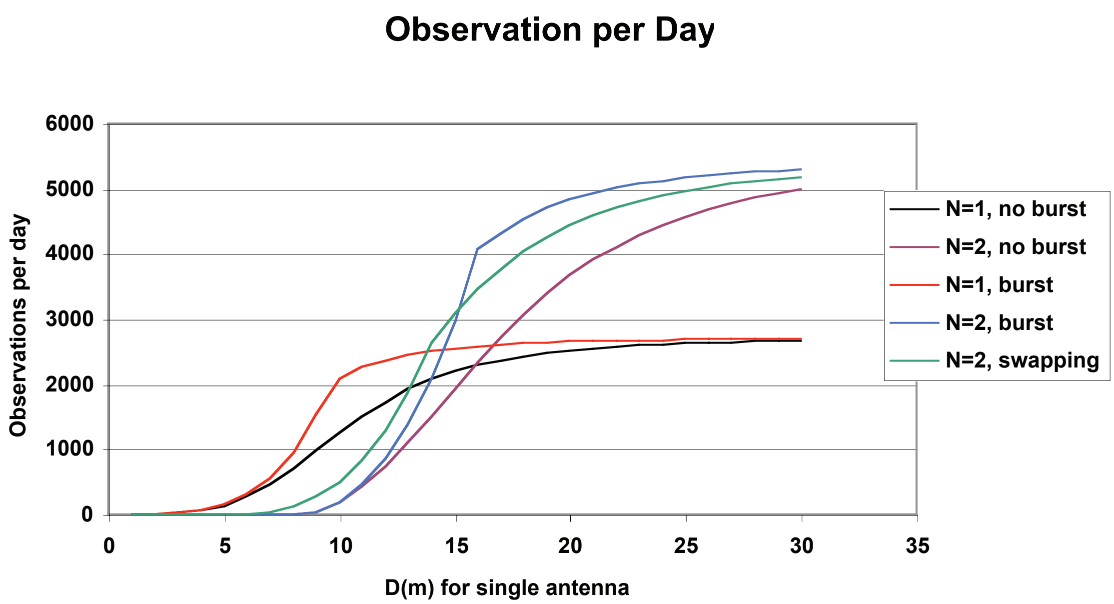

Fig. 2. This is a comparison of a 2-station site with a 1-station site with respect to the number of observations per day. All three operating modes are considered.

In Fig. 3, the number of observations per day for a 3-antenna site is compared to that of a 1-antenna site. All three operating modes are considered. At about 17 m, the 3-antenna site becomes more efficient with respect to number of observations per day. At 19m, three 12 m antennas can replace a single larger antenna at the same cost, but the 3-antenna site will be able to make about 2 times as many observations in a day, for a total of about 5000 observations.

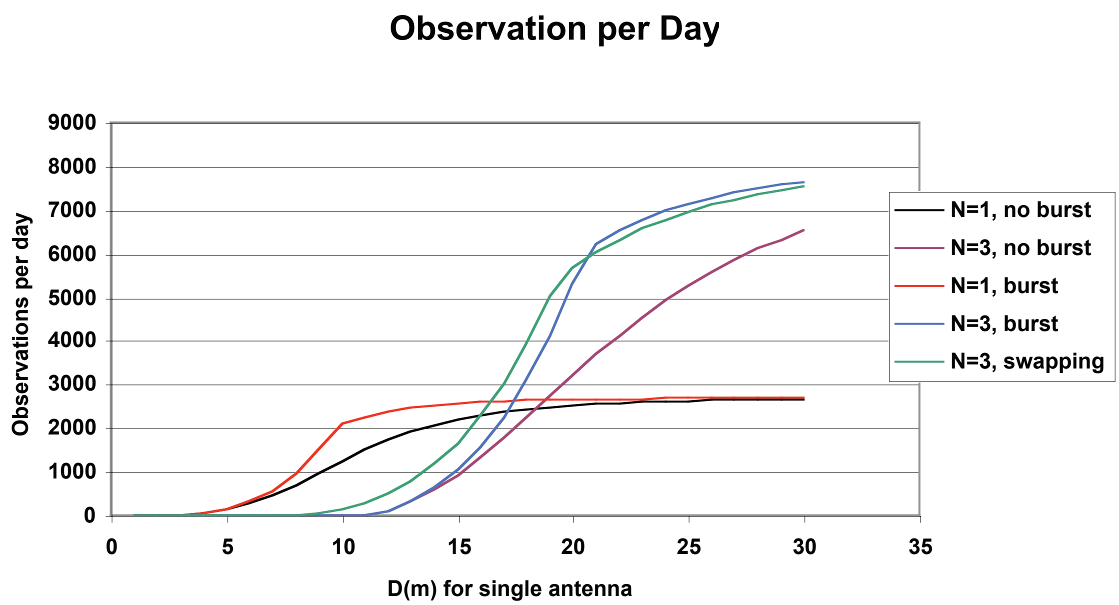

Fig. 3. This is a comparison of a 3-station site with a 1-station site with respect to the number of observations per day. All three operating modes are considered.

In Fig. 4, the number of observations per day for a 4-antenna site is compared to that of a 1-antenna site. All three operating modes are considered. At about 19 m, the 4-antenna site becomes more efficient with respect to number of observations per day. At 24m, four 14 m antennas can replace the single larger antenna at the same cost, but the 4-antenna site will be able to make 3 times as many observations in a day, for a total of about 8200 observations.

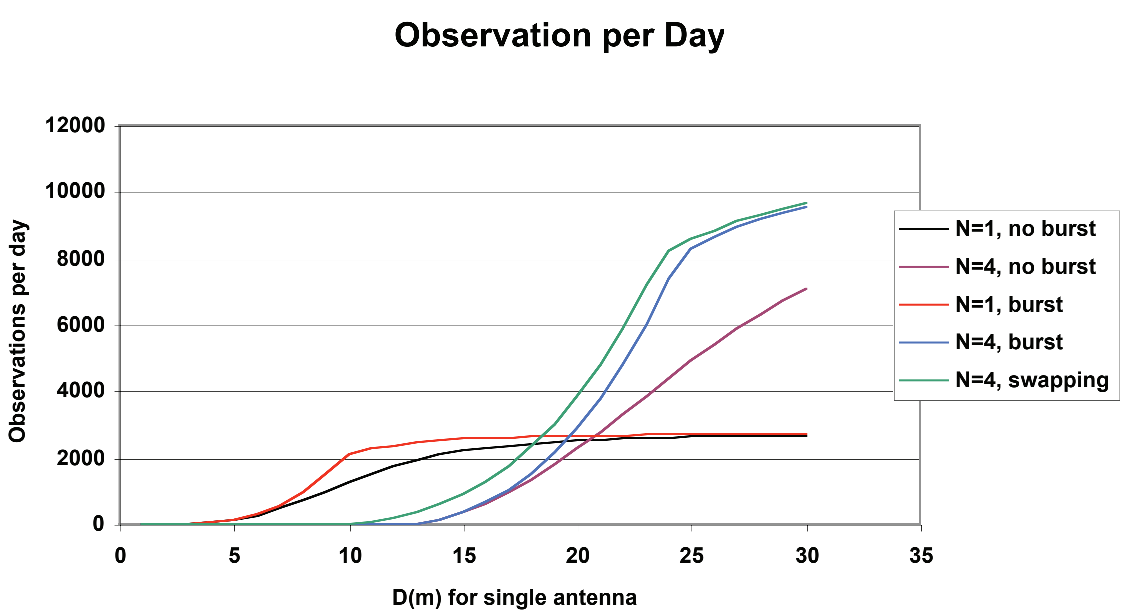

Fig. 4. This is a comparison of a 4-station site with a 1-station site with respect to the number of observations per day. All three operating modes are considered.

Differencing to Removing the Effect of the Reference Oscillators

During parameter estimation, there is a strong correlation between the vertical component of the baseline and the constant terms of the clock and atmosphere. This correlation degrades the estimate of the vertical component significantly. With a multiple antenna site, it is possible to remove the effect of the clock entirely by differencing simultaneous observations on the same baseline. Although there is some hope that this approach might improve the estimation of the vertical component of the baseline because of the disappearance of the clocks, there is no evidence (that I know of) to indicate that this is true. Before attaching any importance to this as a criterion for deciding between a single and multiple antenna sites, further studies are required. However, even if it were known that this is a valid approach, it is possible to do something similar with a single antenna by differencing observations that are nearby in time. If there is an observation every 50 s and the clock stability is 1 part in 10^{14}, then the clocks can be expected to make a contribution to each differenced delay observation as small as about 0.5 ps of random error. Longer-term trends in the clocks can be removed if the differencing is done in conjunction with a more traditional parameter inversion to estimate the clock behavior.

Redundancy

By having two antennas at a site, there is redundancy for many system failures. This may be a significant benefit in an operational program. However, this redundancy needs to be considered against two other factors. First, if the performance of the station is improved significantly by the use of multiple antennas, can the loss of one of the antennas still be tolerated? Second, with respect to the quality and reliability of final products for the whole network, what is the better distribution of resources – a greater number of single antenna sites, or fewer multi-antenna sites?

Unfortunately, these questions require more study and will not be considered further here.

Conclusion

Based on the initial assumptions of this study, it appears that there are significant benefits to a (same cost) multiple antenna site when the comparable single antenna diameter is greater than about 16 m. Examples of factors that have not been considered are:

- The additional maintenance costs of a multiple antenna site,
- The need to tie the additional antennas to a reference point,
- The cost of a drive system capable of 6 deg/s sustained slew rate, which may not scale as $\left(\frac{D_2}{D_1}\right)^{\alpha}$, where $\alpha = 2.7$.