MMA Memo No. 265
Cost-Benefit Analysis of ALMA Configurations

M. S. Yun & L. Kogan
National Radio Astronomy Observatory

May 10, 1999

Abstract

A cost-benefit analysis for ALMA configurations is conducted based on the previous analysis of the MMA configurations by Holdaway (1998). In particular, the impacts of having a larger number of antennas and longer baselines on the overall array efficiency are addressed along with several practical concerns that may affect the configuration plan.

1 Introduction

A cost-benefit analysis for MMA configurations was previously conducted by M. Holdaway for a 36×10m antenna array with a maximum baseline of 3 km (see Holdaway 1998). The combined NRAO plus European project now calls for a 64×12m antenna array with a maximum baseline of up to 20 km, and these new requirements have significant new demands on the configuration design. In this memo, we report the cost-benefit analysis for the number of ALMA configurations as part of the ongoing configuration study. In addition to addressing a larger number of antennas and longer baselines, we also evaluate some of the assumptions included in the earlier analysis by Holdaway and address several related practical concerns. See Holdaway (1998) for the description of the basic method and detailed discussions of nomenclatures and symbols used here.

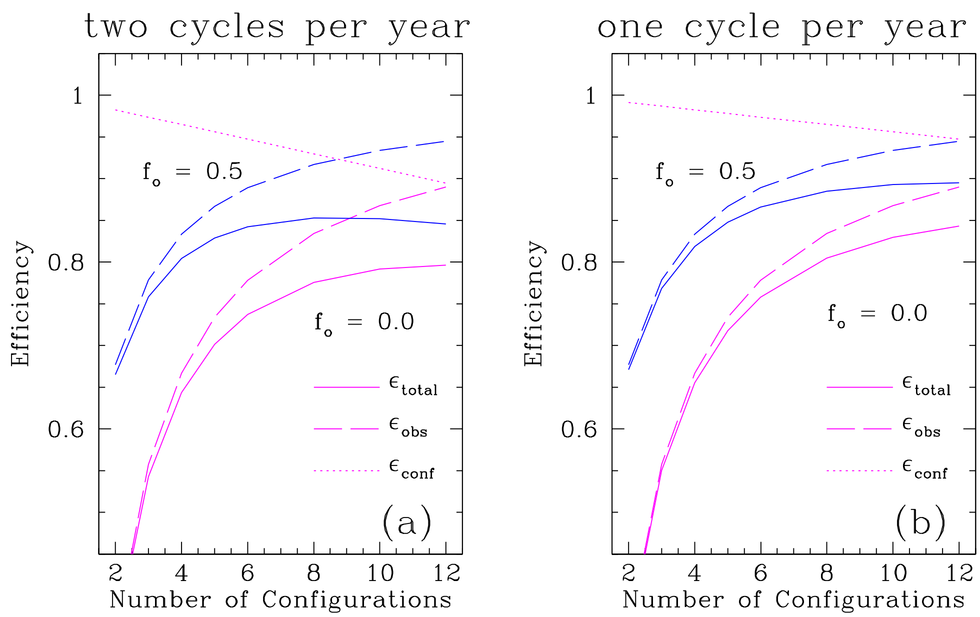

Figure 1: A comparison of the array efficiency between one full configuration cycle per year and two configuration cycles per year. The cases considered here are essentially the same as in Figures 1&2 of Holdaway (1998). The main difference is in the reconfiguration efficiency (dotted line), and the monetary cost comparison is given in Table 1.

2 Frequency of Reconfiguration

In his initial analysis, Holdaway (1998) assumed that the array will cycle through all configurations every 6 months. The motivation for such rapid reconfiguration was to achieve a faster, more efficient scientific turnaround and to get around the strong seasonal and diurnal effects on observing conditions (Holdaway, priv. comm.). The archival site test data at Chajnantor suggest a strong seasonal variation in atmospheric opacity and a strong diurnal variation in atmospheric phase stability. Therefore, projects requiring the best observing condition and a particular configuration may have to wait through several configuration cycles – a situation familiar to many VLA users. A reconfiguration of the ALMA could take a much less time than that of the VLA, and more frequent reconfiguration may be feasible (see Holdaway & Owen 1995; but also see below).

Balancing these arguments, there are several practical concerns for a rapid reconfiguration plan (e.g. once per month). There is a significant cost to reconfiguring, particularly in the time lost for science and demands on man power and equipment. These cost are illustrated in Figure 1 and Table 1, where the loss in efficiency and reconfiguration costs for one full configuration cycle per year versus two full cycles are compared. Estimated reconfiguration cost for cycling through a full 6 configuration cycle is about \$200K per year (see Table 1 and Holdway 1998). The configuration cost alone is expected to exceed \$35M if more than 8 configurations are considered ($N_c \geq 8$).

A practical rule of thumb such as requiring the reconfiguration time not to exceed 10% of the total duration of a particular configuration (e.g. the VLA) is considered next. For a plan with 6 total configurations ($N_c = 6$), this translates to a reconfiguration every 2 months, which is a reasonable compromise between the Holdaway scenario and the VLA. The entire configuration set can be cycled through in one calendar year, but a built-in offset between the seasonal cycle and configuration cycle would be highly desirable (*a la* the VLA). A more detailed configuration plan including such details as non-uniform duration or staggered scheduling should be drafted at a later time. In the spirit of allowing a maximum flexibility in designing the configurations, the original assumption of two configuration cycles per year by Holdaway (1998) is maintained for the moment as an upper bound for a reasonable reconfiguration plan.

3 Sensitivity Loss by Tapering

A significant fraction of the ALMA projects are expected to require tapering of data either to improve surface brightness sensitivity or to achieve the desired angular resolution (e.g. Holdaway 1996). Resulting loss of sensitivity can be avoided if the observation is conducted in a configuration better matching the desired resolution. Therefore a clear cost trade-off exists between tapering of the data and time loss during reconfiguration. The cost-benefit analysis presented here is simply a comparison of the array efficiency with respect to the maximum efficiency case of no tapering and no loss of observing time due to reconfiguration.

In computing observing efficiency ϵ_{obs}, Holdaway (1998) used a sensitivity function of the form $\psi(\theta) = \theta^{-1}$ based on a model analysis in Holdaway (1996). Since the actual sensitivity function depends critically on the uv distribution, we examine this sensitivity function further by analyzing the behavior of several types of 64 antenna configurations currently being stud-

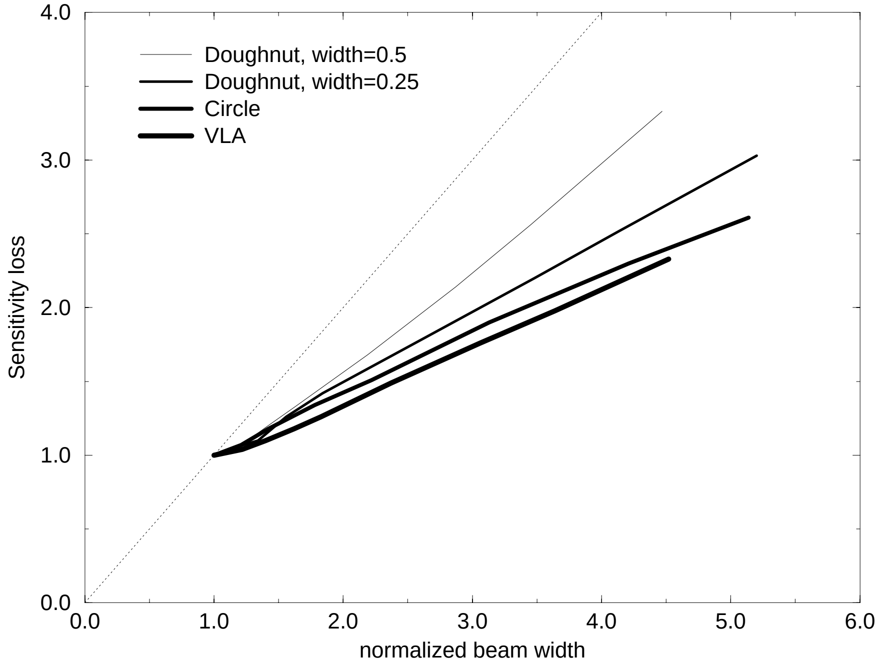

Figure 2: Sensitivity loss for various configuration designs with increasing tapering. A "circle" and thin "doughnut" array show a rather gradual sensitivity loss, similar to the VLA, because their uv coverage is centrally concentrated. Even the thick doughnut array shows a much flatter sensitivity loss than θ^{-1} function assumed by Holdaway (1998; dotted line). The slope K for the general sensitivity function (Eq. 1) is $+0.4$ for the circle array, $+0.5$ for the doughnut array with a width of 0.25, and $+0.75$ for the doughnut array with a width of 0.5.

ied by one of us (see Kogan 1998abc). The model uv distributions are constructed using UVCON in AIPS, and the synthesized beams and sensitivity losses are computed using IMAGR with natural weighting. Both the "circle" and thin "doughnut" arrays are fairly robust against tapering, similar to the VLA, which has a highly concentrated uv distribution (see Figure 2). A doughnut array with a width of $0.5R$ produces a more uniform uv distribution and thus results in a more rapid sensitivity loss with tapering.

While the sensitivity loss grows linearly with tapering in all cases as postulated by Holdaway (1998), the observed slope is significantly flatter than unity. This in turn means that the ϵ_{obs} computed using Eq. 10 of Holdaway (1998) may be overly pessimistic. We adopt instead a general

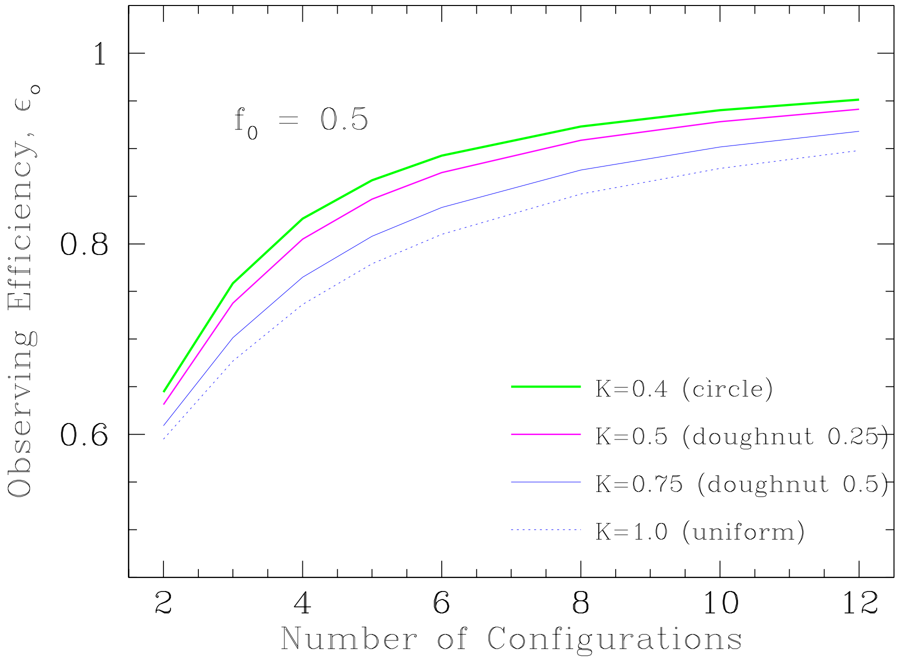

Figure 3: Observing efficiency ϵ_{obs} for various configuration designs considered in Figure 2. The observing efficiency for the more concentrated circle and thin doughnut arrays are higher because they are more robust against tapering and offer up to 10% gain in observing efficiency over a uniform array.

sensitivity function of the form,

$$\psi(\theta) = \frac{1}{K(\theta - 1) + 1} \tag{1}$$

(where K is the constant slope in Figure 2) and derive a more general expression,

$$\epsilon_{obs} = f_o + \frac{(1 - f_o)}{\alpha(1 - K)}[ln\frac{e^\alpha}{e^\alpha + (1 - K)/K} - ln(K)] \tag{2}$$

where $\alpha \equiv (lnR^p)/(N_c - 1)$. The array efficiency derived using this new sensitivity function is compared with the θ^{-1} sensitivity function in Figures 4a&b for $K = 0.5$ case (thin doughnut array). An analysis incorporating the new sensitivity function shows 5 to 10% improvement in the observing efficiency for $N_c < 4$ but only a few per cent increase for $N_c > 4$, despite a much slower decline in sensitivity loss.

This less than expected improvement is the result of two contributing factors. First of all, the observing efficiency is an integral of the product of a tapering sensitivity function $\psi(\theta)$ and a "required resolution distribution" $\rho_i(\theta)$ (see Eq. 7 of Holdaway 1998). The resolution distribution function of the form adopted by Holdaway, $\rho_i(\theta) = ((N_c - 1)\ lnS)^{-1}\theta^{-1}$, gives the most weight to little or no tapering cases and thus minimizes the impact of tapering. Second, Holdaway integrates the resolution distribution over only a truncated range of $\theta = 1$ to $\theta = S^{0.5}$ rather than a full range out to $\theta = S$ (point where the next compact configuration should be used instead), assuming the most extreme tapering cases can be reasonably excluded. However, this practical concern is already address to the first order in $\rho_i(\theta)$. Furthermore, some science experiments such as monitoring of a temporal event (e.g. a comet) may require even more extreme tapering. When we extend the integration out to $\theta = S$, the observing efficiency decreases significantly across the entire range of N_c, and total array efficiency now reaches the plateau value at a larger N_c (see Figs. 4c&d).

4 Science during Reconfiguration

An important consequence of having 64 antennas (versus 36) is that detection experiments requiring only integration times can be be conducted during reconfigurations, and this should increase the scientific output of the array significantly. In any given reconfiguration day, some 9-12 antennas are moved and become unavailable for scientific observations. A partial array with the remaining antennas still retain about 80% of the sensitivity in the 64 element case, compared with a sensitivity loss of $\sim 1/3$ (and poor uv coverage) for the 36 element case. The assumption on the fraction of reconfiguration time not available for science, f_r, strongly impacts the computation of reconfiguration efficiency ϵ_{conf} as demonstrated in Figure 5. For the 64 element array, f_r may be as small as 0.1, and this represents a significant change over the assumption of $f_r = 0.5$ used by Holdaway (1998). Comparing Figures 4 & 5 clearly demonstrates that the array efficiency loss due to reconfiguration may be reduced by a factor of two or more, and a larger N_c is now favored for maximizing the total array efficiency.

5 Number of Transporters

A larger number of array elements directly translates to a proportionally greater man-hours for each reconfiguration. Twice as many calendar days are needed to reconfigure a 64 element array (compared with 36 element array) if the number of transporters and crews are kept unchanged ($N_t = 3$ in Holdaway 1998).

An important concern here is whether a 2 hrs per antenna move time assumed in the earlier analysis would be sufficient given the larger, heavier antennas and significantly longer baselines. The specs for the transporter found in the May 1999 version of the Project Book include a top speed of 10 km/hr on a flat road and 5 km/hr on a 10% incline while carrying an antenna and 20 km/hr unloaded. These specs translate to the travel time dominating the move time for the larger configurations, perhaps well in excess of 2 hrs, especially if the paths between the pads are not straight in order to negotiate around quebradas. For the most compact configuration, the move time is dominated by the pick-up and drop-off times of an antenna, which are estimated to be about 20 and 30 minutes, respectively. Therefore, we adopt an average move time of 3 hours per antenna here, but the actual move time must depend on the configurations involved. It may be worth reconsidering the specs for the transporter if the duration of reconfiguration is dominated by the transporter speed in a large fraction of time.

The impact of increasing the number of transporters and move crew is shown in Figure 6 and tabulated in Table 2. The main effect of doubling the number of transporters and move crew is increased configuration efficiency, ϵ_{conf}. (The "0.5" power at the end of Eq. 12 in Holdaway 1998 is an error.) The gain in total array efficiency achieved by doubling the number of transporters and crews is relatively minor, however, only about 2% for $f_r = 0.3$ and $f_o = 0.5$ cases. The gain from having a larger number of transporters and crews becomes more important only if little or no science can be done during reconfiguration, but this is not likely in most cases. One very important consideration is that *increasing the number of transporters and move crew is the only direct way of reducing the number of reconfiguration days*, which may dictate how frequently the array may cycle through the configurations (see § 2).

The monetary impact of increasing the number of transporters and move crews as formulated by Holdaway (1998) is minimal as "move cost per antenna" does not change. The cost of a transporter is estimated to be $1M each, and this is added to the total cost in Table 2. Increasing the number of move crew arbitrarily is not practical since they are needed for only 5 days in a month for a reconfiguration in $N_c = 6$ and $N_t = 4$ case. Table 1 in Chapter 18 of the MMA Project Book gives a total number for the US and Chilean personnel to be 102, including 44 technicians and 15 maintenance personnel. The latter numbers should scale up approximately with the increased number of array elements. Thus the maximum number of the move crew is set by the size of this site crew. Scheduling the reconfigurations during the site crew changes should help maximizing the man power resource.

6 Trading Configuration and Antenna Costs

The cost-benefit analysis by Holdaway (1998) included an explicit concern for the overall budget, and any extra cost for having an additional configuration had to be balanced by reducing the number of antennas. We have relaxed this particular constrain in our analysis because the cost of additional configuration (about $5M) is only about the cost of a single 12-m antenna out of the 64 total. While this additional configuration cost is not negligible, trading in one array element has a far less impact now compared with the 36 element array case Holdaway considered.

7 Reconfiguration Overheads (Post-move Calibrations)

A monotonic rise in the observing efficiency ϵ_{obs} with the number of configurations N_c in Figures 4-6 raises an interesting theoretical possibility of having as many configurations as there are calendar days in a year. Holdaway (1998) would have rejected such a scenario based on the fact that the configuration budget has to be balanced by the antenna budget. The man power and equipment requirements may also make such a scenario unacceptable. Here we address several practical concerns over reconfiguration overheads such as pointing, baselines, and delay determinations that will also impact the reconfiguration plan.

Staying with the idea of having N_c configurations for the moment, the maximum number for N_c is set by the number of transporters and move crew. If we were to cycle through all N_c configurations twice in each year, the upper limit on N_c is between 15 and 20 if between 9 and 12 antennas are moved each day to a new pad position. The overhead for determining pointing, baseline solutions, delays, etc. will require several hours after each move – see Holdaway & Owen (1995) for an earlier estimate. Pointing and delay determinations should proceed quickly with the excellent continuum sensitivity expected, requiring about an hour of calibration time. Determining a good baseline solution may take significantly longer, however. Holdaway & Owen (1995) estimated only about one hour for the baseline determination assuming only a 30 second integration per source and a mean slew time between sources of 10-15 seconds. To reduce correlated systematic effects, the sampling of the AZ-EL plane also requires large changes in position ($\geq 40°$) between sources, and the actual slew time should be at least 2-3 times larger. Also the baseline determination is limited by atmospheric phase noise rather than by thermal detector noise, and longer integration times may be needed (unless the radiometric phase correction can offer some help). Therefore, baseline calibration may still take up to 2-3 hrs total (40-80 integrations of 3-5 minutes each, see Lay 1997).

As argued by Holdaway & Owen (1995), these calibration measurements may be best made at 30 GHz, and this by itself could be a sufficiently important reason to design this frequency band into the receiver system. If the receiver noise scales strictly as ν, then the gain is offset by the correction factors that are also scaling by ν. The overall system noise is likely to rise faster than $\nu^{1.0}$, however, and a strong case can be made for a lower frequency calibration system. A lower frequency system also offers less ambiguity in baseline determination (see Holdaway & Owen 1995). See Holdaway & Owen (1995) for other concerns such as the windy conditions.

These calibration measurements can be made using only a subset of the array elements directly involved. These post-move overheads nevertheless effectively reduce the sensitivity of the array by 20% during each post-move calibration period when 12 antennas are moved. And this adds up to about 4% net loss in the overall efficiency.

Given the large number of array elements, it has been suggested in some circles that just one or a few antennas may be moved each day so that the reconfiguration would proceed gradually and continuously (e.g. Conway 1998). While such a scheme can maximize the reconfiguration efficiency, this will in turn degrade the overall array efficiency dramatically since the situation becomes analogous to having just a single configuration, possibly requiring a large number of projects to sacrifice sensitivity by tapering. Also, even when only one antenna is moved each day, the post-move calibrations require up to 5 additional "good" antennas to be taken out of the normal observations. For this reason *any move involving less than 3 antennas at a time should be avoided*.

Another important practical concern is the real time data pipeline philosophy adopted into the routine operation of the array (e.g. to coupe with the high data rate). In that case, post-move calibrations such as deriving baseline solutions and pointing should also be performed in real time as well. Some post-corrections such as the baseline errors should be possible in principle, but this is neither compatible nor consistent with real time data pipeline philosophy. Sensitivity loss due to the delay and pointing errors are not recoverable.

8 Summary

We have computed the array efficiencies for the ALMA based on the previous analysis of the MMA by Holdaway (1998). In general, observing efficiency ϵ_{obs} dominates the overall array efficiency for the small N_c cases while reconfiguration efficiency ϵ_{conf} becomes important once the number of configurations grows to more than a few. We identify strong dependence of these calculations on the assumptions for $\rho_i(\theta)$ ("required resolution distribution function"), f_o (fraction of projects requiring tapering), and $1 - f_r$ (the fraction of reconfiguration time useable for scientific observing). Unfortunately, these quantities are neither well determined nor easy to predict. Nevertheless, there is a clear trend of favoring a larger number of configurations (N_c) as the ranges of $\rho_i(\theta)$ (i.e. $p = 1$), N_t (number of transporters), and $1 - f_r$ (fraction of reconfiguration time available for science) are increased. The number of configurations that can achieve within 5% of the maximum overall efficiency is between 4 and 6 for $f_o = 0.5$ (50% of projects requiring data tapering) and between 6 and 8 for $f_o = 0.0$ (all of the projects requiring data tapering).

Table 1: Array Efficiency and Configuration Costs† on Reconfiguration Frequency

N_c	S	ϵ_{obs}	ϵ_{conf}	ϵ_{total}	C_{conf} (M$)	C_{move} (M$)	C_{total} (M$)
one array cycle per year							
2	188.2	0.677	0.991	0.671	9.0	1.1	13.1
3	13.72	0.779	0.987	0.769	13.4	1.7	18.1
4	5.731	0.834	0.983	0.819	17.9	2.3	23.2
5	3.704	0.867	0.978	0.848	22.4	2.8	28.2
6	2.851	0.889	0.974	0.866	26.9	3.4	33.3
8	2.113	0.917	0.965	0.885	35.8	4.5	43.4
10	1.79	0.934	0.956	0.893	44.8	5.6	53.4
12	1.61	0.945	0.947	0.895	53.8	6.8	63.5
two array cycles per year							
2	188.2	0.677	0.983	0.665	9.0	2.3	14.1
3	13.72	0.779	0.974	0.758	13.4	3.4	19.8
4	5.731	0.834	0.965	0.804	17.9	4.5	25.4
5	3.704	0.867	0.956	0.829	22.4	5.6	31.0
6	2.851	0.889	0.947	0.842	26.9	6.8	36.6
8	2.113	0.917	0.930	0.853	35.8	9.0	47.9
10	1.79	0.934	0.912	0.852	44.8	11.3	59.1
12	1.61	0.945	0.895	0.846	53.8	13.5	70.3

† Reconfiguration cost is computed for a 20 year operation as in Holdaway (1998).

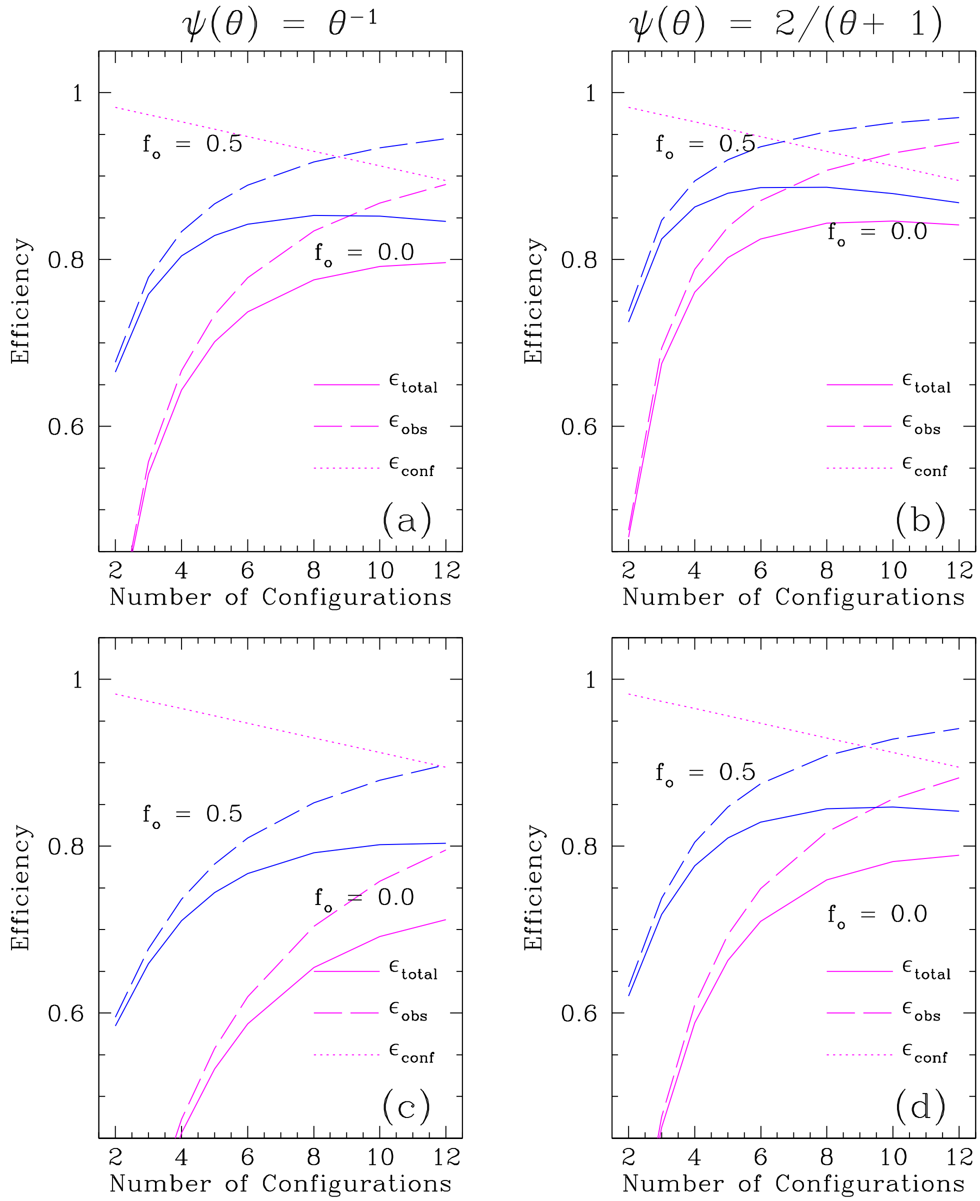

Figure 4: Array efficiencies computed using (a) a linear sensitivity function of Holdaway (1998) versus (b) a flatter sensitivity function derived from simulated 64 element configurations ($K = 0.5$, see Fig. 2). These calculations are performed for $N_t = 3$ and assuming science can be done only for 50% of time during the reconfiguration (same as in Holdaway 1998). The same calculations using a broader range of integrand for the "required resolution distribution" $\rho_i(\theta)$, from $\theta = 1$ to $\theta = S$ (rather than $S^{0.5}$), are shown in (c)&(d).

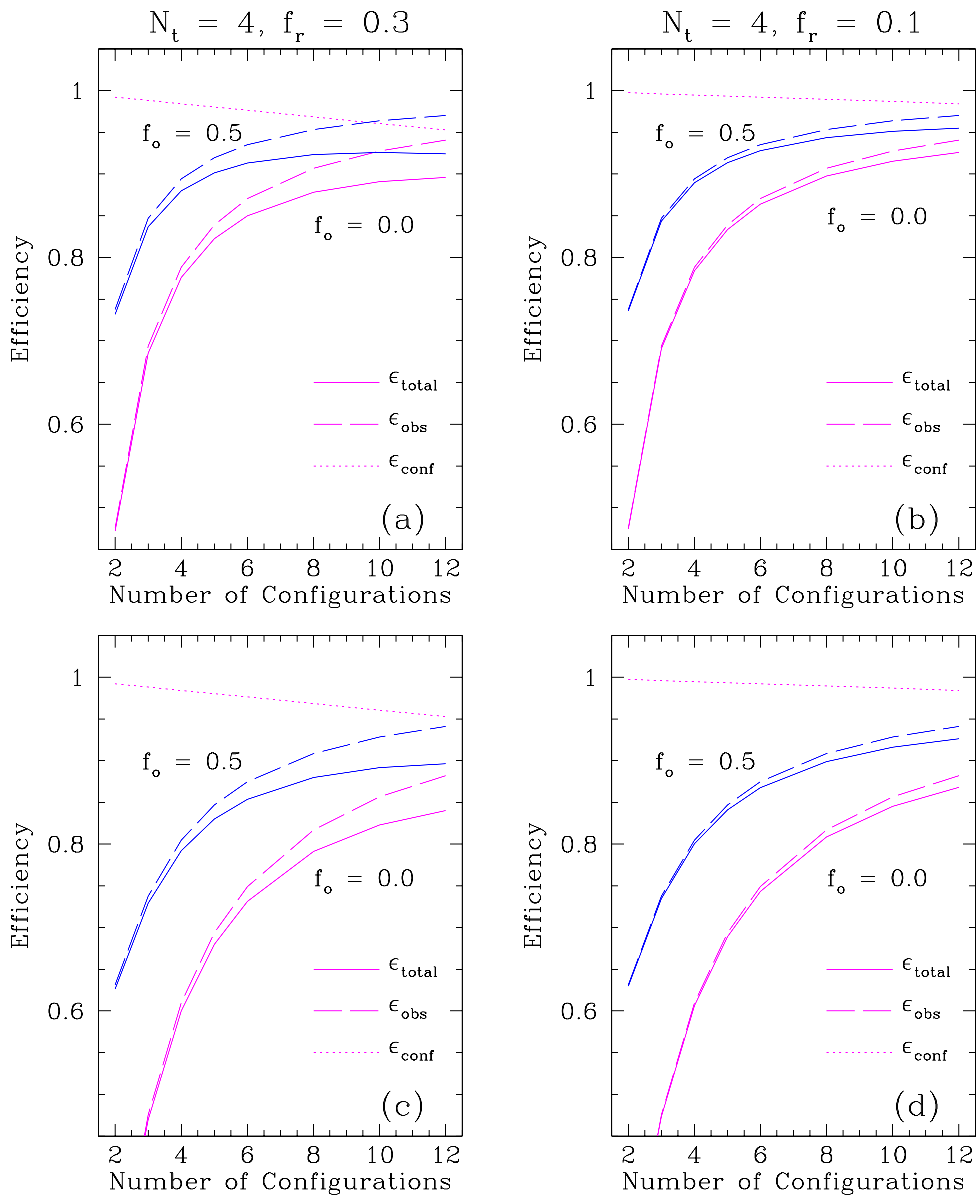

Figure 5: The array efficiencies are computed for (a) assuming science projects can be carried out during 70% of reconfiguration time ($f_r = 0.3$); and (b) during 90% of time ($f_r = 0.1$) assuming $N_t = 4$ and $p = 0.5$. These calculations can be compared with the $f_r = 0.5$ case previously considered by Holdaway (e.g. Fig. 4a). The corresponding calculations for $p = 1$ cases are shown in (c)&(d).

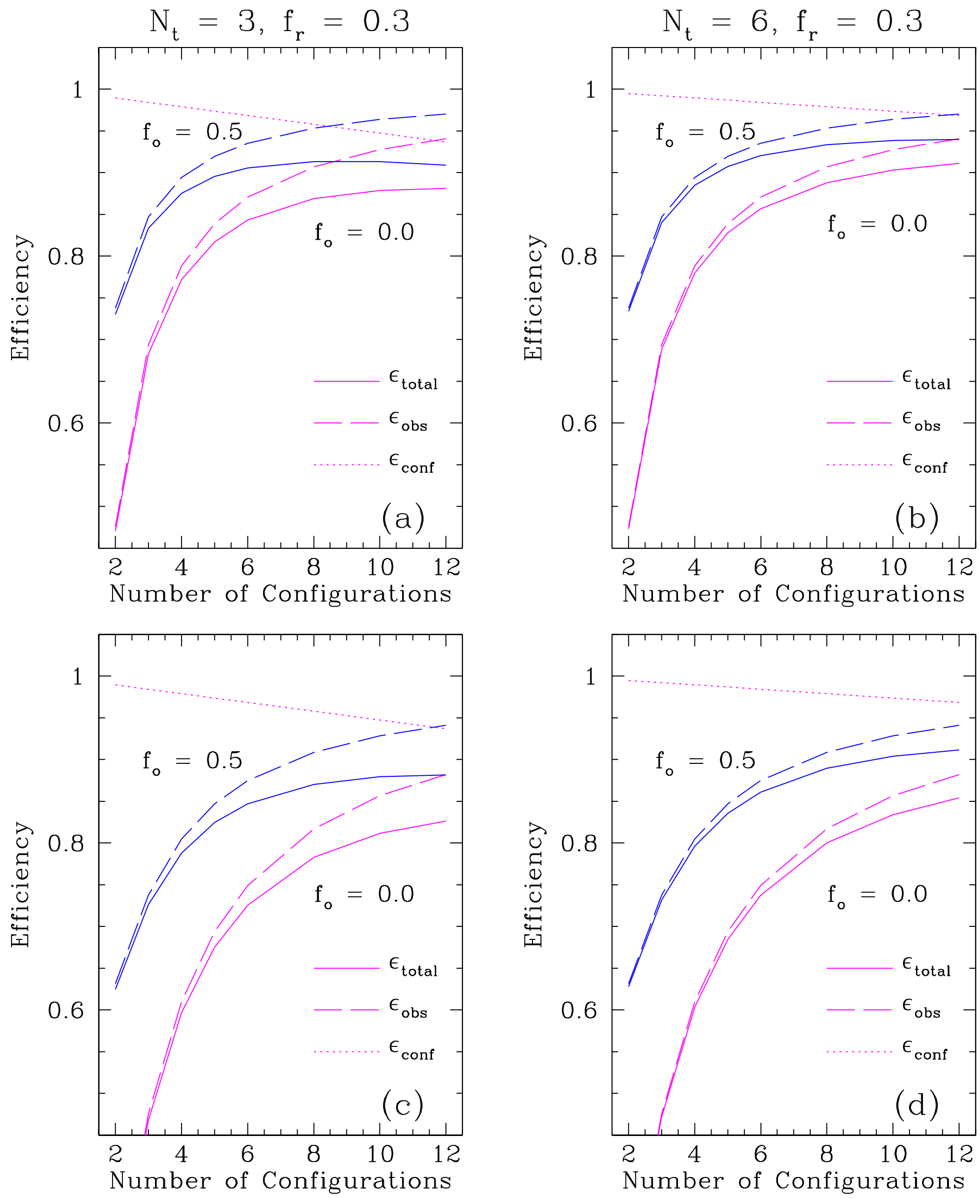

Figure 6: Effects of increasing the number of transporters and move crew for $N_t = 3$ and $N_t = 6$ with $f_r = 0.3$. The main difference is in the configuration efficiency, ϵ_{conf}, which scales as $1/N_t$. As in Figures 4 & 5, (a) & (b) are for $p = 0.5$ and (c) & (d) are for $p = 1$.

Table 2: Array Efficiency and Configuration Cost for Different N_t

N_c	S	ϵ_{obs}	ϵ_{conf}	ϵ_{total}	C_{conf} (M$)	C_{move} (M$)	C_{total} (M$)
$N_t = 3$							
2	188.2	0.738	0.990	0.730	9.0	2.3	14.2
3	13.72	0.847	0.984	0.834	13.4	3.4	19.8
4	5.731	0.894	0.979	0.875	17.9	4.5	25.4
5	3.704	0.920	0.974	0.895	22.4	5.6	31.0
6	2.851	0.935	0.968	0.906	26.9	6.7	36.6
8	2.113	0.954	0.958	0.913	35.8	9.0	47.9
10	1.79	0.964	0.947	0.913	44.8	11.3	59.1
12	1.61	0.970	0.937	0.909	53.8	13.5	70.3
$N_t = 4$							
2	188.2	0.738	0.992	0.732	9.0	2.3	15.2
3	13.72	0.847	0.988	0.837	13.4	3.4	20.8
4	5.731	0.894	0.984	0.880	17.9	4.5	26.4
5	3.704	0.920	0.980	0.901	22.4	5.6	32.0
6	2.851	0.935	0.976	0.913	26.9	6.7	37.7
8	2.113	0.954	0.968	0.923	35.8	9.0	48.9
10	1.79	0.964	0.960	0.925	44.8	11.3	60.1
12	1.61	0.970	0.952	0.923	53.8	13.5	71.3
$N_t = 6$							
2	188.2	0.738	0.995	0.734	9.0	2.3	17.2
3	13.72	0.847	0.992	0.840	13.4	3.4	22.8
4	5.731	0.894	0.990	0.885	17.9	4.5	28.4
5	3.704	0.920	0.987	0.908	22.4	5.6	34.0
6	2.851	0.935	0.984	0.921	26.9	6.7	39.6
8	2.113	0.954	0.979	0.933	35.8	9.0	50.9
10	1.79	0.964	0.974	0.938	44.8	11.3	62.1
12	1.61	0.970	0.968	0.940	53.8	13.5	73.3

REFERENCES

Conway, J. 1998, "Self-Similar Spiral Geometries for the LSA/MMA," MMA Memo No. 216

Holdaway, M. 1996, "What Fourier Plane Coverage is Right for the MMA?," MMA Memo No. 156

Holdaway, M. 1998, "Cost-Benefit Analysis for the Number of MMA Configurations," MMA Memo No. 199

Holdaway, M.A., & Owen, F.N. 1995, "How Quickly Can the MMA Reconfigure?," MMA Memo No. 147

Kogan, L. 1998a, "Optimization of an Array Configuration with a Donut Constraint", MMA Memo No. 212

Kogan, L. 1998b, "A, B, C, and D configurations in the shape of concentric circles with fixed pads at the common circumferences", MMA Memo No. 226

Kogan, L. 1998c, "The Imaging Characteristics of an Array with Minimum Side Lobes, I.", MMA Memo No. 247

Lay, O. 1997, "The Temporal Power Spectrum of Atmospheric Fluctuations Due to Water Vapor," A&AS, 122, 535