MMA Memo No. XXX
A Cost-Benefit Analysis of MMA Configurations Revisited

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Abstract

1 Introduction

A cost-benefit analysis for MMA configurations was previously conducted by M. Holdaway for a 36 $\times$ 10m antenna array with a maximum baseline of 3 km (see Holdaway 1998). The combined NRAO plus European project now calls for a 64 $\times$ 12m antenna array with a maximum baseline of 20 km, and these new requirements have significant new demands on the configuration design. In this memo, we re-visit the cost-benefit analysis for the number of MMA 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 related practical concerns.

See Holdaway (1998) for the description of the basic method and detailed discussions of nomenclatures and symbols used here. We adopt the same assumption that the array will cycle through all configurations every 6 months.

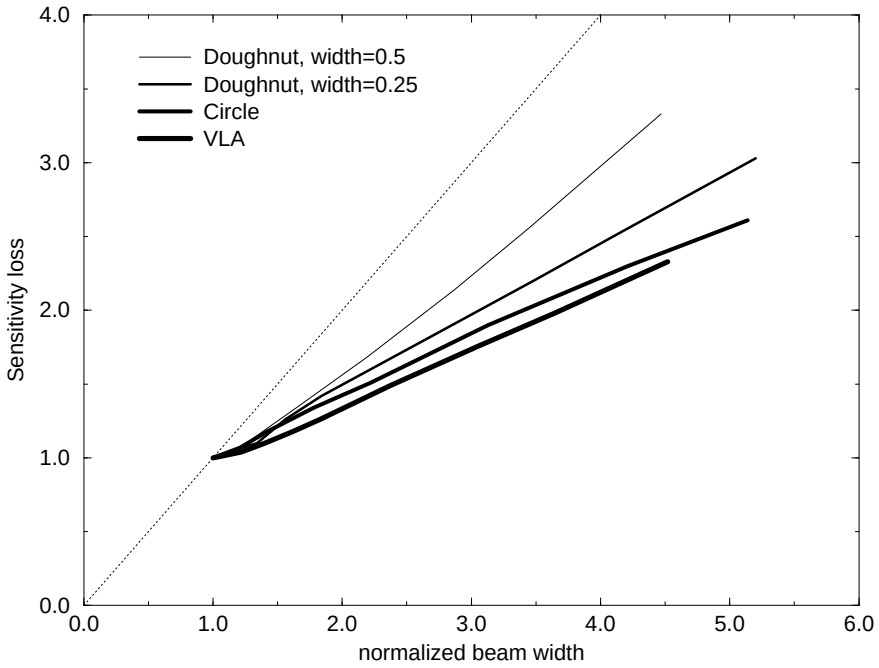

Figure 1: Sensitivity loss for various configuration designs with increasing tapering. "Circle" and thin "doughnut" arrays have a rather gradual sensitivity loss, similar to the VLA because their uv coverage is highly centrally concentrated. Even the thick doughnut array has much flatter sensitivity loss than θ^{-1} function assumed by Holdaway (1998; diagonal dotted line). The new sensitivity function we consider here, $\psi(\theta) = \frac{2}{\theta+1}$, corresponds to that of the doughnut array with width of 0.25.

2 Sensitivity Loss by Tapering

A significant fraction of the MMA projects are expected to require tapering 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 discussed here is simply a comparison of the array efficiency with respect to the maximum efficiency case with no tapering and no reconfiguration.

In computing observing efficiency ϵ_o, Holdaway (1998) uses a sensitivity function of the form $\psi(\theta) = \theta^{-1}$ based on a model analysis in Holdaway

(1996). Since sensitivity function depends critically on actual uv distribution (thus array design), we examine this sensitivity function further by analyzing the behavior of a wide range of 64 antenna configurations currently being studied by one of us (L. Kogan), and the results are summarized in Figure 1. 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. A doughnut array with a width of $0.5R$ produces a more uniform uv distribution, and the sensitivity loss due to tapering is more pronounced.

While the derived sensitivity functions show a nearly linear dependence on the synthesized beam size as postulated by Holdaway (1998), the slope is significantly flatter than unity because none of these configurations produce a completely uniform uv distribution. This in turn means that the ϵ_o computed using Eq. 10 of Holdaway (1998) may be overly pessimistic. We adopt instead a shallower sensitivity function of the form:

$$\psi(\theta) = \frac{2}{\theta + 1}$$

and derive a new analytical form for ϵ_o as:

$$\epsilon_o = f_o + 2(1 - f_o)(ln\, S^p)^{-1}(ln\frac{S^p}{S^p + 1} - ln(1/2))$$

The array efficiency derived using this new sensitivity function is compared with the θ^{-1} sensitivity function in Figure 2a&b. The analysis using the new sensitivity function has produced only a marginal increase (a few %) in the observing efficiency, however, despite a much slower decline in sensitivity due to tapering.

This puzzling outcome has a dual explanation, and it also highlights another important assumption that goes into this calculation. 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 reduces 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 $\rho_i(\theta)$. If we extend the integration out to $\theta = S$, the observing efficiency decreases significantly across the entire range of N_c, and the observing and total array efficiency reaches the plateau value at a larger N_c (see Fig. 2c&d). The exact fraction of MMA science projects requiring tapering is unknown, and it is not obvious which assumption is more appropriate. Nevertheless, this analysis demonstrates the importance of the assumption on the required resolution distribution.

3 Science during Reconfiguration

An important consequence of having 64 antennas (versus 36) is that detection experiments requiring only integration times may 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 may be 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 more than 30% loss in sensitivity (and much poorer uv coverage) for the 36 element case. The assumption on the fraction of reconfiguration time not available for science, f_r, directly impacts the computation of reconfiguration efficiency ϵ_{conf}, and its impact is demonstrated in Figure 3. This represents a significant change over the assumption of $f_r = 0.5$ used by Holdaway (1998), and comparing Figures 2 & 3 clearly demonstrates that the array efficiency loss due to reconfiguration may be reduced by a factor of two or more, favoring a larger N_c in maximizing the total array efficiency.

4 Number of Transporters

A larger number of array elements directly translates to a proportionally greater man-hours for each reconfiguration. Roughly twice as many calendar days will be 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).

Another important concern 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 February 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. Times estimated for a pick-up and drop-off of an antenna are 20 and 30 minutes, respectively. On average, the travel distance between pads should be ≤ 10 km in most reasonable configuration designs. Therefore, we estimate that a move time of 3 hours per antenna is probably appropriate.

The effects of increasing the number of transporters and crew are shown in Figure 4 and tabulated in Table 1. The main effect of doubling the number of transporters and moving crew is the increase in the configuration efficiency, ϵ_{conf}, primarily by reducing the calendar days needed for reconfiguration. The loss in array efficiency due to telescope move is nevertheless minor, only 10% even in $N_t = 3$ case with 12 configurations, and the gain in the total efficiency by doubling the transporters and crews is only about 2% for $f_r = 0.3$ and $f_o = 0.5$ case. The gain from having a larger number of transporters and crews becomes more important only if little science can be done during reconfiguration (which is not likely).

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 should enter into the configuration cost. Increasing the number of moving 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.

5 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 a total of 64 (see Table 1). While this additional configuration cost is not negligible, trading in one element has far less real impact on the overall array performance in this case compared with the 36 element array case Holdaway considered.

6 Reconfiguration Overheads (Post-move Calibrations)

A monotonic rise in the observing efficiency ϵ_o with the number of configurations N_c in Figures 2-4 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. We also want to address a practical concern over reconfiguration overheads such as pointing, baselines, and delay determinations.

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 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 add up to several hours per move – determining a good baseline solution alone may take up to 2-3 hrs because sufficiently large sampling of the AZ-EL space is needed with a sufficiently long integration time to average out the atmospheric phase fluctuation (40-80 integrations of 3-5 minutes each, see Lay 1997). Pointing and delay determinations may proceed much faster with excellent continuum sensitivity expected, but these will also require a non-zero sum of telescope time. These calibration measurements can be made using only a subset of the array elements directly involved. Nevertheless, these overheads effectively reduce the sensitivity of the array by 20% during the post-move calibration period when 12 antennas are moved and can add 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 can be gradual and continuous. While such a scheme can maximize the reconfiguration efficiency, this will also degrade overall array efficiency dramatically since the situation becomes analogous to having just a single configuration where a large number of projects may be forced to sacrifice sensitivity by requiring tapering. Also, even when only one antenna is moved each day, the post-move calibrations will require at least 2 to 5 additional "good" antennas to be taken out of the normal observations. For this reason a minimum move should involve at least 3 to 6 antennas.

Another related practical conern is the real time data pipeline philosophy. If we were to adopt a real time data process pipeline (e.g. to coupe

with the high data rate), then the reconfiguration overheads such as deriving baseline solutions and pointing should also be obtained in real time as well. For example, a post-correction of baseline errors should always be possible, but this is neither compatible nor consistent with real time data pipeline philosophy.

7 Summary

We have examined the derivation of array efficiencies previously conducted by Holdaway (1998). In general, observing efficiency ϵ_o dominates the overall array efficiency for the low 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 not well determined and are difficult to predict. On the positive side, there is a clear general trend of favoring a larger number of configurations (N_c) as the range of $\rho_i(\theta)$ (i.e. $p = 1.0$), 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).

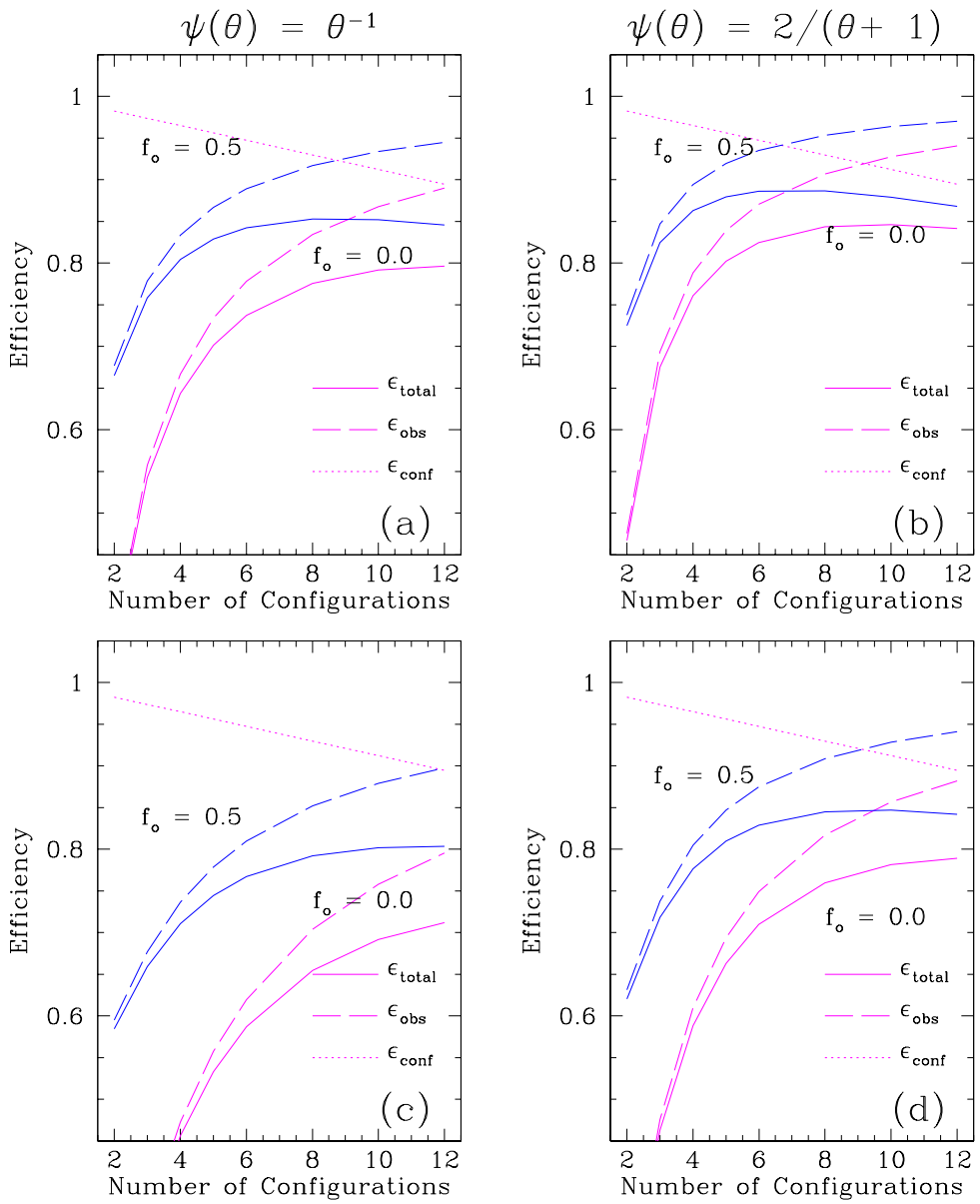

Figure 2: The array efficiencies computed using (a) a linear relation of Holdaway (1998) versus (b) a flatter sensitivity function derived from simulated 64 element configurations. These calculations are performed for $N_t = 3$ and assuming science can be done only for 50% of time during the reconfiguration (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).

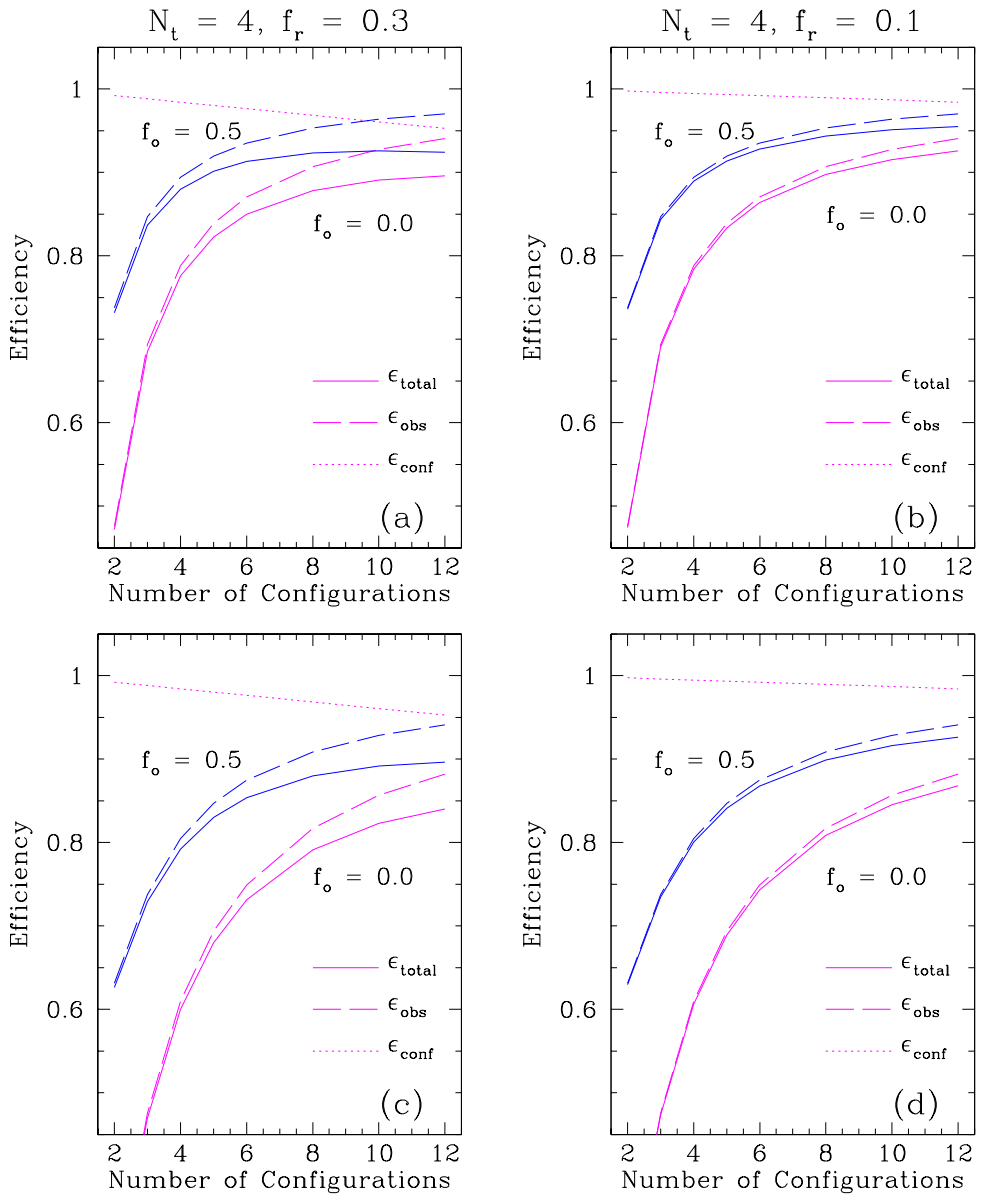

Figure 3: The array efficiencies are computed for (a) assuming science project can be carried out during 70% of reconfiguration time ($f_r = 0.3$); and (b) during 90% of time ($f_r = 0.1$) assuming $N_t = 4$ and $p = 0.5$. These calculations can be compared with the $f_r = 0.5$ case previously considered by Holdaway (e.g. Fig. 2a). The corresponding calculations for $p = 1.0$ cases are shown in (c)&(d).

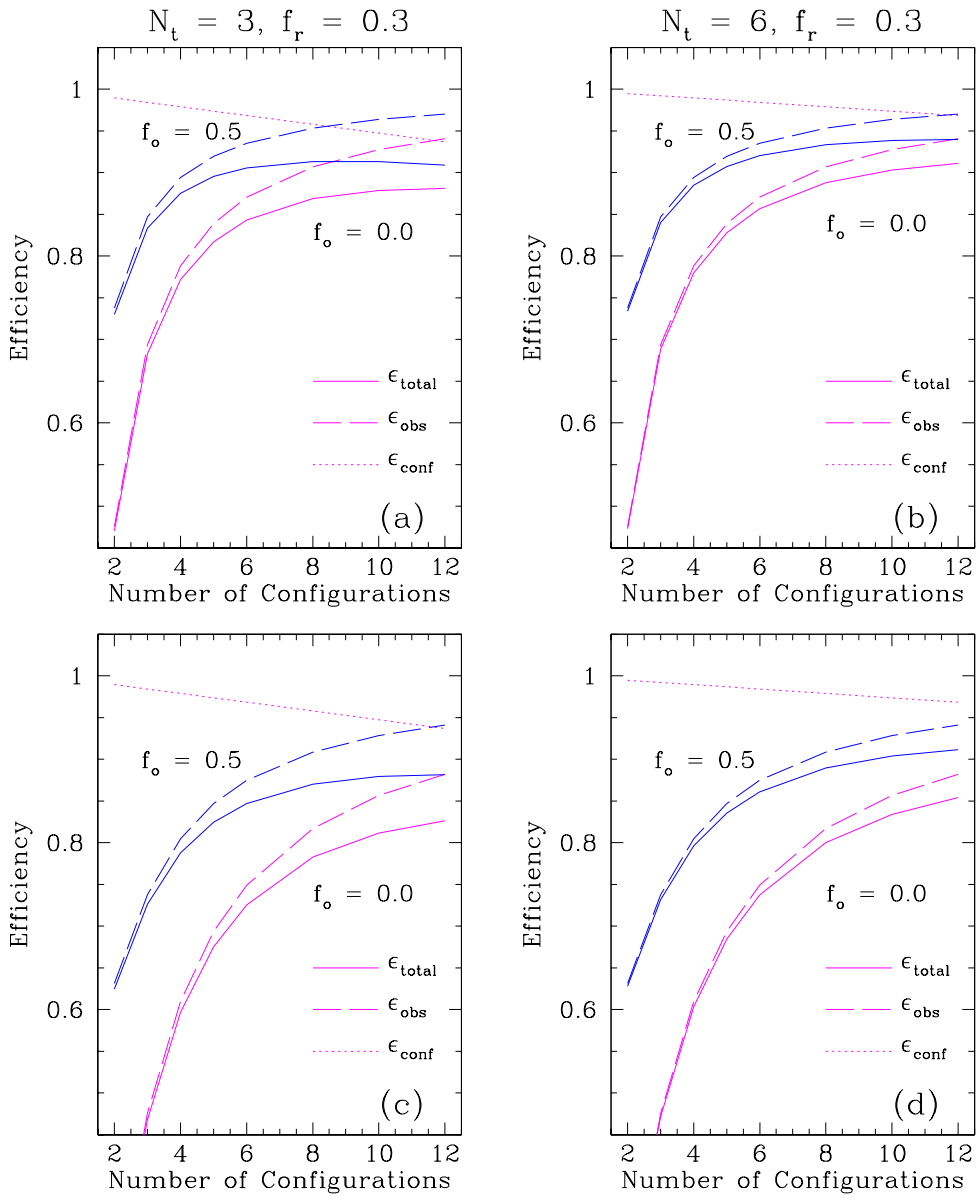

Figure 4: The effects of increasing the number of transporters and crew are examined by comparing the case for $N_t = 3$ and $N_t = 6$ with $f_r = 0.3$. The main difference is in the configuration efficiency, ϵ_{conf}, which scales as $1/N_t$. Same as in Figures 2 & 3, (a) & (b) are for $p = 0.5$ while (c) & (d) are for $p = 1$.

Table 1: Array Efficiency and Configuration Cost for Different N_t

N_c	S	ϵ_o	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	1.1	14.1
3	13.72	0.847	0.984	0.834	13.4	1.7	19.1
4	5.731	0.894	0.979	0.875	17.9	2.3	24.2
5	3.704	0.920	0.974	0.895	22.4	2.8	29.2
6	2.851	0.935	0.968	0.906	26.9	3.4	34.3
8	2.113	0.954	0.958	0.913	35.8	4.5	44.4
10	1.79	0.964	0.947	0.913	44.8	5.6	54.4
12	1.61	0.970	0.937	0.909	53.8	6.8	64.5
$N_t = 4$							
2	188.2	0.738	0.992	0.732	9.0	1.1	14.1
3	13.72	0.847	0.988	0.837	13.4	1.7	19.1
4	5.731	0.894	0.984	0.880	17.9	2.3	24.2
5	3.704	0.920	0.980	0.901	22.4	2.8	29.2
6	2.851	0.935	0.976	0.913	26.9	3.4	34.3
8	2.113	0.954	0.968	0.923	35.8	4.5	44.4
10	1.79	0.964	0.961	0.926	44.8	5.6	54.4
12	1.61	0.970	0.953	0.924	53.8	6.8	64.5
$N_t = 6$							
2	188.2	0.738	0.995	0.734	9.0	1.1	14.1
3	13.72	0.847	0.992	0.840	13.4	1.7	19.1
4	5.731	0.894	0.990	0.885	17.9	2.3	24.2
5	3.704	0.920	0.987	0.908	22.4	2.8	29.2
6	2.851	0.935	0.984	0.921	26.9	3.4	34.3
8	2.113	0.954	0.979	0.933	35.8	4.5	44.4
10	1.79	0.964	0.974	0.938	44.8	5.6	54.4
12	1.61	0.970	0.968	0.940	53.8	6.8	64.5

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