The Gain of Multibeaming

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Introduction

When comparing a multibeam radiotelescope with a single beam radiotelescope there is a major problem because the improvement due to the increased observing time on multibeam telescope depends on whether the observations are sensitivity limited or not. True multibeaming, where the beams can be used independently at the same time, increases the total observing time by a factor equal to the number of beams. For sensitivity limited observations of point sources, the improvement in Ae/Tsys is proportional to the square root of the number of beams. For other observations, the improvement is directly proportional to the number of beams. A true comparison can be made by assuming a single beam telescope performance and calculating the performance needed in a multibeam telescope to equal this performance. This gives the equivalent single dish performance of a multibeam telescope

True Multibeaming

For the total observing time to be directly proportional to the number of beams:

1. The primary field of view of the antenna must be large enough that all beams can be used at independent pointings within the field-of-view at any one time.
2. There is sufficient backend processing resources for these independent astronomy programs. Although, future expected decreases in backend costs probably make this factor irrelevant.

The first condition for true multibeaming, a large field of view, is set by the design of the antennas and is very hard to change later in the life of the telescope. This parameter must be considered very carefully at the time the telescope is designed. The second condition is a feature that will evolve with time. To what extent backend processing power will grow in the next 20 to 50 years is not known. Assuming Moore's Law continues to hold for 20 years after the completion of the telescope then in the future we may expect a telescope with 1000 times the capability if the initial design. This growth in backend processing can be used to drive the improvement in telescope performance that was previously obtained by an ever-decreasing Tsys.

Comparison

Assume the single beam instrument is more sensitive per beam by a factor of G than one beam of the multibeam instrument and for a fraction k of the time the observations are sensitivity limited on the single beam instruement. The multibeam instrument needs $k.G^2$ beams to equal the performance of the single beam instrument on these observation. For example, using one hour observations a single beams instrument takes $k.G^2$ hours to observe $k.G^2$ "sources". In the same time the multibeam instrument can observe all the sources for the whole time. The multiple beams have been used to increase the observing time so that the same sensitivity is reached as the one hour observation on the single beam instrument. For the observations, that are not sensitivity limited on the single beam telescope and assuming that these are also not sensitivity limited on the multibeam instrument, an extra (1-k) of a beam is needed. Thus if there are no backend processing limitations then the total number of beams need for equal sensitivity is:

Number of beams n needed = $k.G^2 + 1\text{-}k$

Solving for G gives the sensitivity difference per beam needed to provide equal astronomy throughput as the single beam telescope:

$$G = \sqrt{\frac{n-1+k}{k}} \approx \sqrt{\frac{\text{n - 1}}{\text{k}}}$$

The simplification on the right does not overestimate the gain improvement due to multibeaming and provides a simple insight into the comparison:

> Use all beams but one to cater for observations that need the same sensitivity as the nominal sensitivity of the single beam instrument.

Or a multibeam telescope has:

$$\text{Equivalent single beam sensitivity} \approx \sqrt{\frac{\text{number of beams - 1}}{\text{fraction of observing sensitivity limited}}} \cdot \frac{A_e}{T_{sys}}$$

where Ae/Tsys is the sensitivity of one beam of the multibeam telescope. The table below gives some example the effective increase in sensitivity due to multibeaming

n No. Beams	*k* - Fraction Sensitivity Limited	*G* – Operational Increase in Ae/Tsys
4	0.5	2.6 (~2.4)
9	0.5	4.1 (~4.0)
25	0.5	7.0 (~6.9)
100	0.5	14.1 (~14.1)
4	0.9	2.1 (~1.8)
9	0.9	3.1 (~3.0)
100	0.9	10.5 (~10.5)

Table 1 Increase in sensitivity due to multibeaming.

With this model, almost all the time on the telescope is used to achieve the high sensitivity of the equivalent single-beam telescope. In practice, more active astronomy is processed if observations with a greater range of sensitivities are undertaken on a multibeam instrument.

Application to Surface Brightness Sensitivity

The SKA will almost certainly include a compact component that will provide observations with high surface brightness sensitivity. Surface brightness sensitivity also improves with multibeaming, in the same way as point source sensitivity, but the difference between different technologies is less clear cut. Both large dishes and phased arrays can achieve high filling factors which give high surface brightness sensitivities.

To avoid shadowing small parabolic dishes and Luneburg lens have low filling factors resulting in reduced surface brightness sensitivities. Cylindrical reflectors can achieve filling factors intermediate between those of large and small parabolic reflectors. Thus, it is possible for a high Tsys phased array to have a higher surface brightness sensitivity than a low Tsys array of small parabolic dishes, and this is before the advantages of multibeaming are considered.

Discussion

The first requirement of true multibeaming is a sufficiently large field-of-view to allow all the available beams to target independent sources. Each source needs to be a target of interest to an observing program in the current observing session. If complete surveys are exclude then any randomly chosen square degree would probably not include a target of interest at any one time. Just how many targets there are is hard to estimate but the increased sensitivity of the telescope will certainly increase the number when compared to present day instruments. Considering that a telescope such as the Australia Telescope hosts over 100 programs every 6 months and most programs target multiple sources or pointings then the number of targets of interest should number in the thousands or even tens of thousands. With this number of targets a 100 beam instrument needs a field-of-view of up to 1000 square degrees to fully utilise all its capabilities. It is seen that a great increase in astronomy throughput can be achieved with a multibeam instrument that has a large but not full sky field-of-view.

Limitations

It is known that full instantaneous sky coverage is not possible at high frequency. Thus, for most antenna technologies, it is not possible to arbitrarily target sources, a highly desirable but in general not achievable objective. The best that can be done is to choose the largest field-of-view possible within budgetary constraints. Technologies such as the Luneburg lens allow do allow arbitrary targeting of sources but as yet their cost effectiveness is unknown.

A large field-of-view comes at the cost of larger numbers of feeds, low noise amplifiers and backend electronics. (Note , a Luneburg lens minimises this increase). In general, to accommodate the increased numbers the Tsys of the system will increase. The major difference in this area is usually a change form cooled (80^0K, costs will probably preclude a temperatures lower than this) amplifiers to uncooled amplifiers which roughly doubles Tsys at higher frequencies. At frequencies below 1GHz the sky temperature starts to predominate and there is no advantage in using cooled receivers.

It is estimated that the large field-of-view multibeam instrument will have an Ae/Tsys that is two to three times lower at high frequencies than a single beam instrument, assuming similar reflectors or lens costs. This loss of sensitivity is recovered when 3 to 9 independent beams are available all the time. Any level of multibeaming beyond 3 to 9 beams gives the multibeam instrument the advantage in terms of sensitivity purely because of the amount of time that can be dedicated to individual sources. The exception to this is where total observing time become unmanageable, for example a one year deep field observation needing nine years on the multibeam instrument

The other area where a single beam instrument will be better is in sensitivity limited detections of transient phenomena (flare stars, gamma ray bursters) where the longer integrations possible cannot be used. But a multibeam instrument has an *n* time better chance of catching such transients simply because if the larger number of beams.

Advantages

A major advantage of a multibeam wide field-of-view telescope is its upgradability. The decreasing cost of backend electronics means that more beams and improved imaging abilty can be added at a later time. As long as the field-of-view of the antennas is sufficiently large the added resources directly translate into increased astronomy throughput.

The higher Tsys of a multibeam instrument can also be viewed as an area where future upgrading is possible. As an example, Molonglo upgraded its 1960's vintage LNAs in the early 1990's [Large et al] and reduced their LNA noise temperature by a factor of 3. This improvement was mostly due to device improvements. Neither of of the above upgrade paths is available to an optimised single beam instrument such as a small parabola design where the best performance per dollar comes from using a cooled prime focus receiver. There is much less room for Tsys improvements where the front end amplifiers are already cooled and feed blockage particularly at low frequencies prevents significant focal plane arraying.

Astronomy advantages also accrue from multibeaming. Certain programs that are not viable on a single beam instrument become possible. For example, monitoring of sources such as pulsars and flare stars can be undertaken in parallel with other programs. If the field-of-view was 1000 square degrees then just 20 telescope pointings in a day give access to half the sky without any time being dedicated to the monitoring of a particular source. Allowing some time each day to such observations can give day to day monitoring of a large class of compact sources without impacting imaging and high sensitivity programs. This is an example of the greater amount of telescope time available and the finer divisibility of telescope resources allowing a greater range of programs to be undertaken.

For separately detected transient events such as gamma ray burster there is a definite possibility that the source is in the field-of-view. As an example an instrument with a 1000 square degree field-of-view has a 1 in 20 chance acquiring a source above the horizon instantaneously. For a single beam instrument the chances are negligible.

Snapshot imaging can benefit from multibeaming. If a single beam instrument devoted 10% of its time to snapshot imaging then on a multibeam instrument 10% of the beam are available. The longer observing time available can be used to improve the UV coverage which gives better imaging of complex sources. Alternatively, the long time can be used to image a greater number of sources.

Situations where simultaneous multiple beams are an advantage include pulsar timing and calibration. In pulsar timing work, it will be possible to target multiple pulsars simultaneously allowing direct inter-pulsar timing comparison. For calibration, a calibrator could be observed at all times giving continuous information on some instrumental and atmospheric errors. These type of observations are not possible on a single beam instrument.

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Reference

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