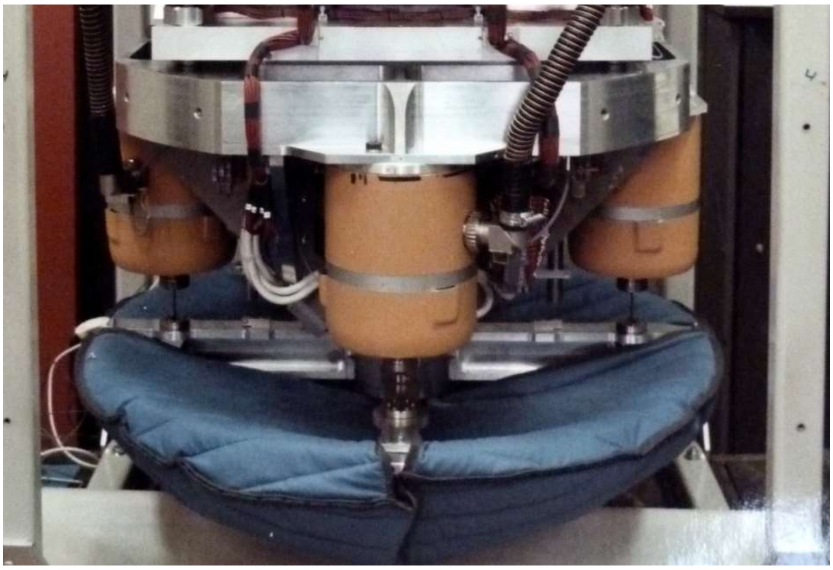
Possible Wobbler Solutions for AtLAST

1. Introduction

A fundamental issue in much of observational astronomy is that we are trying to measure signals that are at a much lower level than the power arriving at the detector with a range of other origins – the instrument, the telescope and the environment, including the atmosphere, and sometimes astronomical foregrounds and/or backgrounds. In the case of single-dish radio astronomy, it has been known for a long time that the basic answer to this is Dicke-switching: we find a way of modulating the astronomical signals, while leaving everything else un-modulated, so that synchronous detection then gives us what we want. To be effective the switching must take place faster than any variations in the unwanted signals.

With a Cassegrain telescope, one way of doing this is tilting the secondary mirror by a small amount. This is variously known as "chopping", "nutating" or "wobbling" the secondary. (It is often just called "beam-switching", although I believe this is generally taken to include various forms of switching in the instruments as well as moving the beam by tilting the secondary.) The pictures below show the chopping secondary for JCMT (van der Stadt, H. & Verkerk, J., 1987, *Appl*. *Opt*., 26, 3446) with the two-axis drive on the left and a cover on the light-weight mirror, while the mirror is shown on the right. The mirror has a diameter of 750mm and, for tilts that move the beam on the sky by a few beamwidths, a transition time of ~10ms is achieved, which allows efficient chopping at up to ~10Hz. There are similar systems on other telescopes, including the IRAM 30m and APEX.



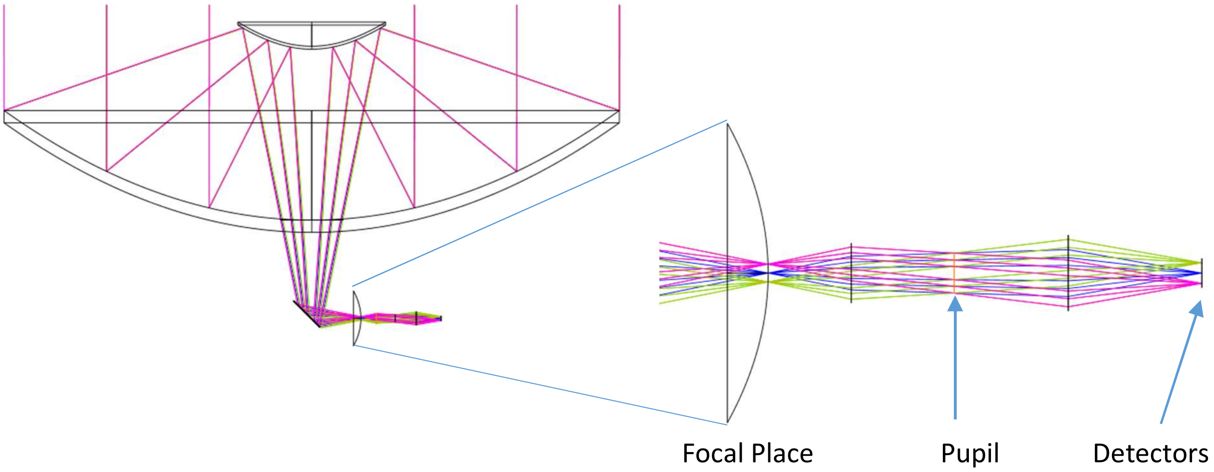
Interestingly, the original driver for using chopping secondary mirrors was to provide modulation when observing continuum sources with single-pixel bolometer detectors. At that time (the 1980s) spectral-line observations at millimeter wavelengths were made with Schottky-mixer receivers, which had relatively high noise temperatures (>1000K) but were pretty stable, so that moving the whole telescope on and off the source (generally called "position-switching") on timescales of several seconds, together with fitting and subtracting a spectral baseline (typically a low-order polynomial), was sufficient to give good results. With the advent of large arrays for continuum observations and very low-noise SIS receivers for spectral-line work, the position is reversed. In modern continuum cameras, fast modulation to remove instrumental noise is usually built into the detectors themselves, while fluctuations in the emission from the atmosphere and the like can be removed by performing a suitable scan pattern with the whole telescope. With modern heterodyne instruments, and in particular when performing long integrations and when measuring relatively wide lines, it is found that relatively slow position-switching does not do a really adequate job of removing spurious spectral features ("baseline ripple"), while chopping the secondary mirror gives better results.

For the very large secondary mirror planned for AtLAST – 12m in diameter in the baseline design – wobbling it at even a few Hz is not a realistic option. It would require very powerful drives and it would be difficult to avoid shaking the whole telescope structure. Moreover, from an optical point of view, tilting the secondary has never been an ideal solution, despite its widespread usage. One problem is that it introduces aberrations, so that only a limited "throw" is possible. Another is that the illumination pattern of the receiver onto the primary mirror moves and this means that the spill-over past the edge of the primary (some of which typically falls on the ground) is modulated. Some of the standing-wave effects, e.g. reflections from the secondary, may also be modulated. In seeking alternatives to wobbling the secondary mirror in AtLAST we can try to avoid these problems.

This note looks at the option of wobbling a mirror which is located at an image of primary mirror, a "pupil", formed in the optical chain between the telescope focal plane and the actual detectors. This is a pretty obvious idea – making corrections with a mirror that is at or near a pupil is, after all, standard practice in active systems on optical/IR telescopes – but I am not aware of it being used previously in radio astronomy. I was stimulated to think about it by Urs Graf, who has included this as an option in the design of the optics for the CHAI instrument on the FYST (CCAT-prime).

2. Switching at a Pupil Plane

Almost all of the instruments that we are likely to use on AtLAST will have additional optics between the telescope's focal plane and the detectors. In general, it will be possible to arrange these so that they form a real image of the primary at a convenient place. This diagram illustrates the concept, with the telescope optics on the left and an enlarged view of the receiver optics on the right:



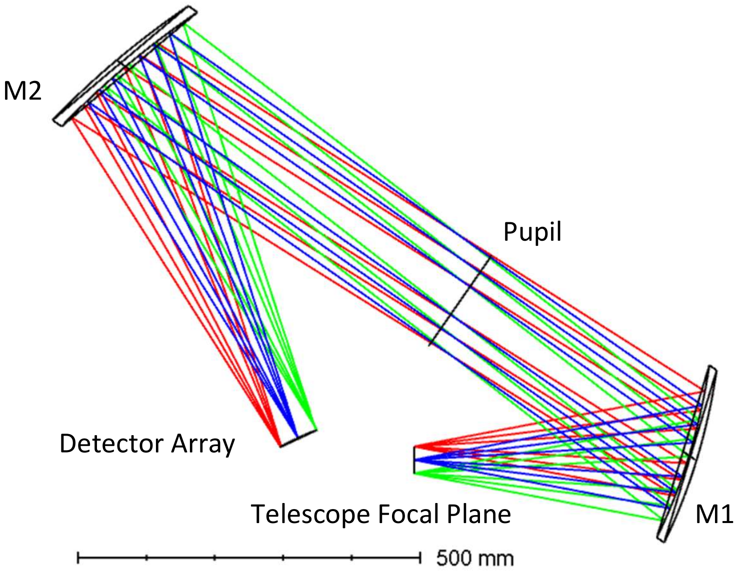
Here the active elements are shown as idealized lenses ("paraxial surfaces" in Zemax). Real schemes would use mirrors, or perhaps lenses if the optics can be cooled, i.e. are inside the cryostat.

I have shown the full 2-degree diameter field of view of AtLAST (the large curved surface), but the rays are traced for only a ~0.15 deg diameter FoV and the optics are sized accordingly. I believe that we will only need fast wobbling for instruments with a relatively small field of view: for the large cameras, internal modulation plus scanning the whole telescope will be the preferred option.

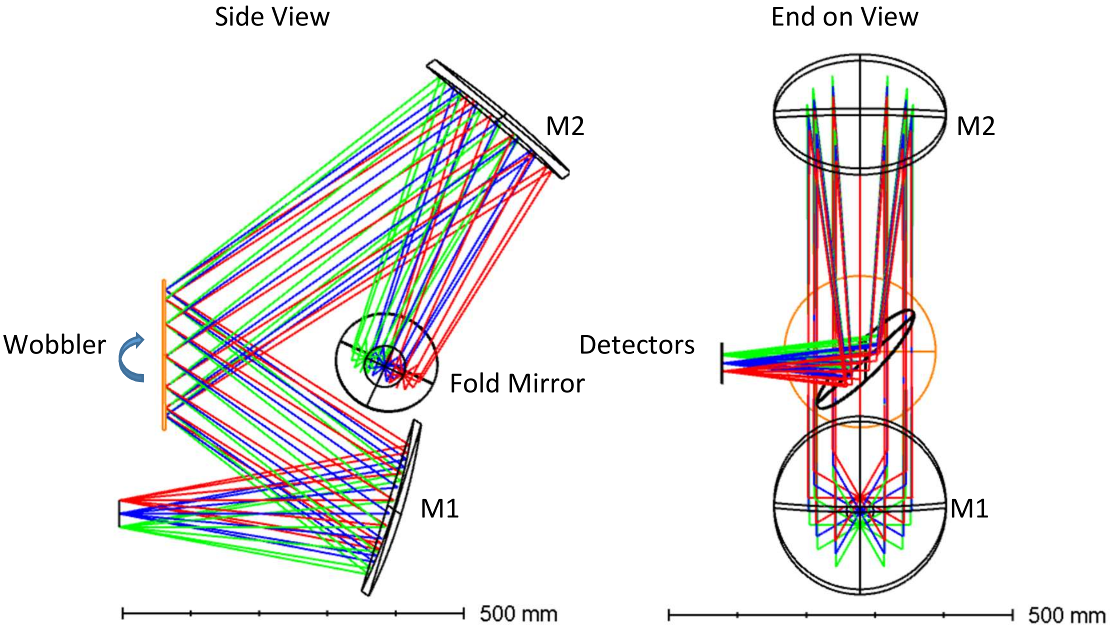
In fact, the most important case is probably for objects that are smaller than, or comparable in size to, the telescope beam. In that case we only need a small number of detectors (see below for more discussion) and the optics can be very compact. Instruments with larger fields of view require larger mirrors but, even for e.g. a heterodyne array with >1000 elements, the sizes are still reasonable. In particular, it should quite easy to provide a rapid modulation (10Hz or more) by wobbling a mirror located at or near the pupil.

3. Possible Design for a Small Field

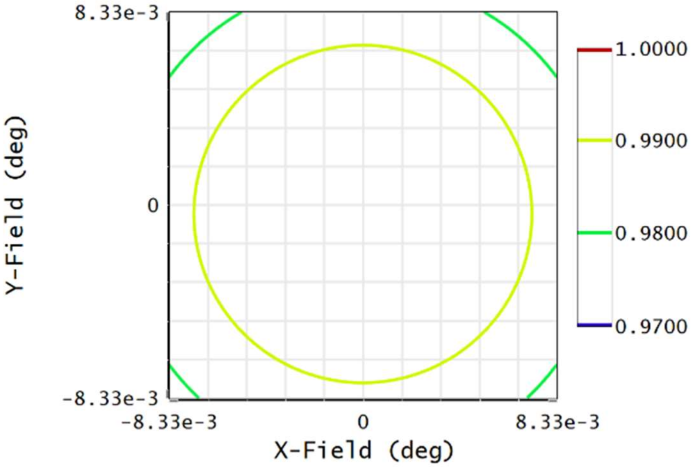
If we use mirrors for the optical elements we need these to operate off-axis. Here is a plausible example where the first mirror, M1, turns the beam through 35 degrees and forms an image of the primary, a “pupil”, that is 150mm in diameter. We choose the focal length of the second mirror, M2, to adjust the f-number to suit the detector design. Here the telescope focus, which has f-number = 2.9, is converted to f-number = 4, which might be a good number for a small heterodyne array. To have good optical properties (polarization, beam symmetry, etc.), the angle of incidence at M2 then needs to be adjusted to match the Mitzuguchi-Dragone condition. In this case we need to turn the beam through close to 30 degrees at M2.



The flat wobbling mirror is inserted at the pupil, with a convenient angle of incidence of 35 degrees. A second flat mirror is needed to fold the beam out of the plane and into the detector array:

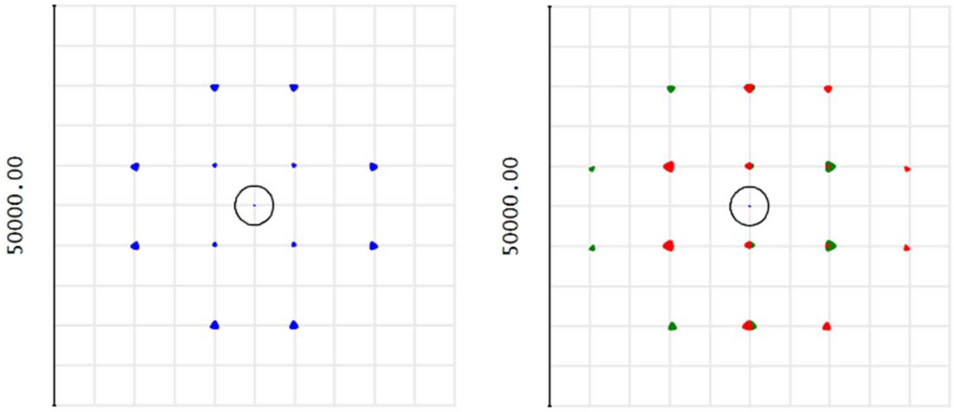


With this configuration, just using parabolic surfaces gives very good performance for a small field of view. Here is a Strehl plot at 1mm wavelength for a field which is 1 arcmin square. It can be seen that the Strehl is above 98% except right at the corners.



For a 50m telescope, the angular resolution (λ/D) at 1mm is about 4 arcsec so, if the pixel spacing is 2.5 times this (which is about the closest spacing for a feedhorn-coupled heterodyne focal plane array that we can use with good efficiency), the spacing would be ~10 arcsec. The field shown above is therefore large enough for a 6 by 6 array at this wavelength.

To illustrate the chopping action, it is simplest to look at spot diagrams in the focal plane. The plot on the left below shows a grid of points with 10 arcsec spacing (Zemax apparently only allows 12 spots in one plot). Because the performance is so good these are much smaller the diffraction beam – the circle at the center shows the approximate size of the beam (the half-power contour). The plot on the right shows the spots when the chopper mirror is tilted by +0.28 deg (green) and then -0.28 deg (red). This amount has been chosen so that the beams move by 10 arcsec, i.e. if you put a source in a particular beam with the wobbler in the +0.28 deg position, the source will shift to the neighboring beam when it is switched to the -0.28 deg position.

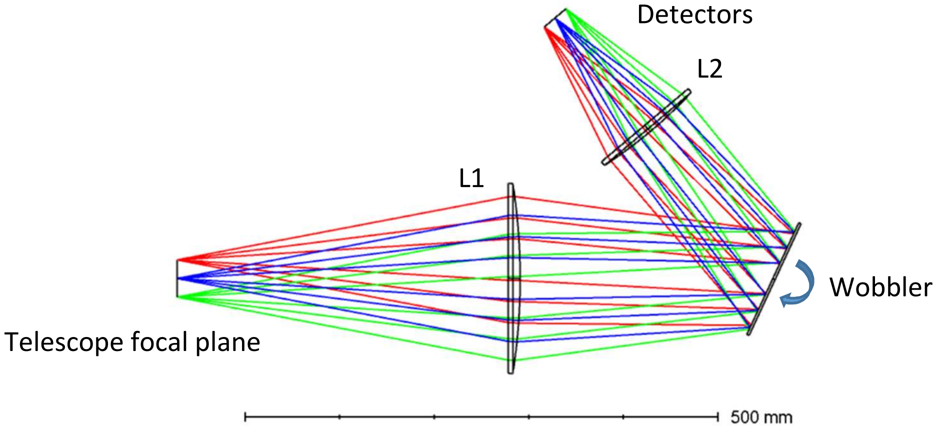


The pupil is 150mm in diameter, so the wobbling mirror only needs to be about 165 by 190mm in size. Clearly wobbling through such small angles will be no problem even at frequencies of many Hz.

Because we are wobbling at a pupil, there is essentially no movement of the illumination pattern on the primary and it is also extremely small at the secondary. The beams do move a few millimeters on M1 and on the telescope’s tertiary mirror, so it is important that these mirrors have smooth, continuous surfaces and are appropriately oversized.

4. Designs with Refracting Elements

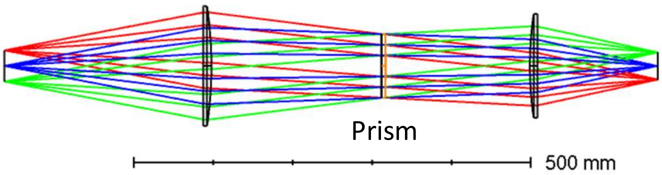
If the optics are warm, then obtaining low noise requires that we use mirrors, which can have extremely low ohmic loss. If, on the other hand, we are willing to put the optics and the chopper mechanism inside the cryostat, then we can use lenses. Their losses can be acceptable if these are made from, e.g., an appropriate grade of silicon and anti-reflection coatings are used on the surfaces. With lenses it is easier to accommodate faster f-numbers than with mirrors. In this example I have replaced the mirrors M1 and M2 with lenses, L1 and L2, and chosen the output f-number to be 2 instead of the 4 used in the designs above. This means that the spacing of the detector elements is reduced, which might be more suitable for detectors on wafer rather than built individually in blocks. The pupil size has been reduced to 100mm diameter. Here I have just used plano-convex lenses with conic surfaces, but the optical performance is very good – Strehl of better than 95% at 435 microns wavelength over a 1 arcmin square field.



It is true that low-loss lenses are harder to manufacture than mirrors, but this is not a big issue for the sizes used here. Building a chopping mechanism that operates at low temperatures and does not dissipate too much heat is probably somewhat more challenging. The beams will move on L1 and the cryostat window and filters which may also cause some problems.

An important advantage of having the chopper cold, however, is that it can also act as a cold stop to prevent the detectors seeing past the edge of the primary or secondary. To do this, it would be made slightly undersized and surrounded by cold absorbing material. (This idea is used in the 345HGz 16-element HARP array on JCMT and works well.)

In principle the mirror could be replaced by a prism, made of silicon or perhaps alumina, which would then need to be rotated by 180 degrees to perform a chop[1]. The only advantages I can think of for this scheme are that it is all fits in a relatively thin cylinder and that can be made still more compact. Here the diameter of the pupil has been further reduced to 80mm. The optical performance is still good.



The angle required in the prism is very small. If the material is alumina only ~0.2 deg on each side is required for a 10 arcsec throw. This means that the prism can be thin. In the diagram above it is shown

---

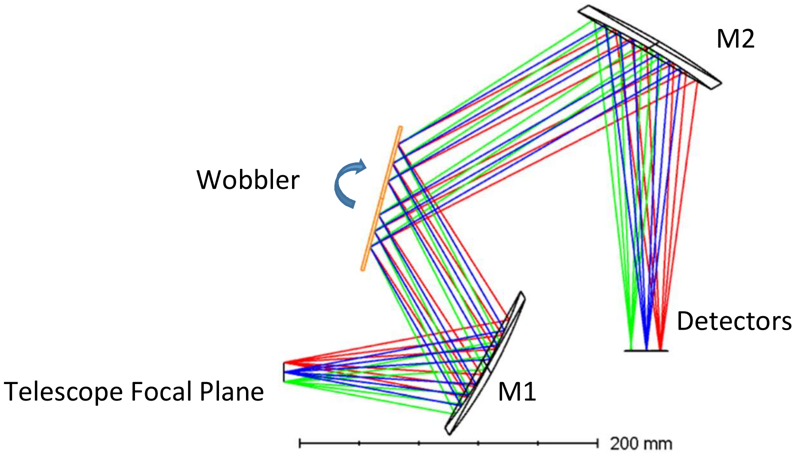
[1] I suppose that one could rotate it either about an axis in the plane of the prism (in the direction of the slope in the thickness) or about the optical axis of the system.

as 5mm thick and less is probably practical. Even so, I suspect that it would be difficult to move it fast enough for our purposes given that we have to turn it through a full 180 degrees.

5. Very Small Fields of View

In the above I have assumed that even for spectral-line observations, the instruments will have array detectors of some sort. It is worth pointing out, however, that for science cases which require high-quality spectroscopy for sources that are unresolved or only marginally resolved by the AtLAST beam, it is probably best to use instruments with a small number of detectors and to concentrate on making those as sensitive as possible, rather on than making arrays. In fact the optimum number in this case is probably just two[2], so the optics could be really small.

In this case the optical requirements are relaxed further (e.g. we no longer need to worry about exactly meeting the Mitzuguchi-Dragone condition, for example, and we can choose the angles of incidence to make the arrangement convenient). Here is a possible design where the pupil size has been reduced to just 50mm diameter.



The output again has an f-number of 4 and the rays have been traced for a 20 arcsec FoV, which would be easily large enough for a two-detector system at 1mm. Even with these angles of incidence (30 degrees at M1 and M2) and just using parabolas, the Strehl is well over 0.98 at 435 microns wavelength (690 GHz) and a chop throw of 6 arcsec (i.e. +/-3 arcsec), which would probably be about right for this frequency – this is a throw of 3.3 λ/D.

The actual tilt required of the wobbler mirror (for a wobble about an axis in the plane of the paper) is about +/-0.6 degrees for this 435-micron case. This is larger than the case discussed in section 3 but obviously there would still be no problem in switching fast with such a small mirror. Note that the angle required scales as the ratio of the size of the pupil to that of the primary. Expressed in a different way, the amount of linear movement at the edge of the wobbler that is required to move the beam on the sky by a given number of beamwidths is independent of the size of the wobbler, but proportional to the observing wavelength.

---

[2] Note that if your receiver has only a single-detector, the source is only observed for half of the time and this, together with the fact that you have to take the difference between the "on" and "off" observations, means that there is a loss of a factor of two in sensitivity compared to an ideal receiver, i.e. one which is completely stable so that no switching is needed. If the receiver has two detectors, however, the switching can be arranged to swap the source between them, as described previously. This recovers √2 in sensitivity because one is observing the source all the time. Although more complex chopping patterns can be used if you have more detectors, I am not aware of any chopping or switching method that would provide a further improvement in sensitivity for compact sources.

I would advocate providing the chopper with drives in both axes. It is probably worth designing the control system so that it can be used in ways other than a simple chop – for example to “jiggle” the position so that it fills in the positions between the beams and thus provide a well-sampled map while the telescope simply tracks the map center.

6. Larger Fields of View

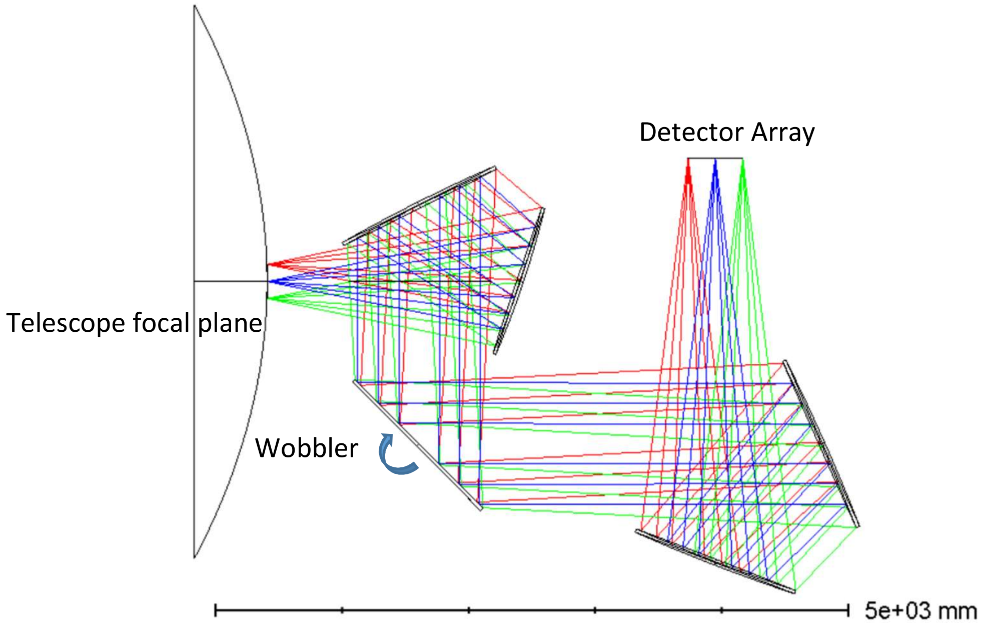
It is not clear to me that there are important use cases where one has a large field of view and needs a wobbler. As already noted, continuum observations with large detector arrays are usually performed by making the whole telescope scan the region to be mapped. So long as the scan is sufficiently fast this can remove most of the effects of fluctuations in atmospheric emission (see Morris et al. 2021, https://arxiv.org/abs/2111.01319 for a detailed study). In particular, one can exploit the fact that the noise is highly correlated between the detectors and make appropriate models of the effects so one can filter them out. There may, however, still be cases where it is better to combine a fast wobble with a scan. In particular, the scan could then be performed more slowly. This is probably more efficient if the region to be mapped is only a little larger than that of the detector array.

It is important to remember that the beam chopping completely removes the spatial frequency corresponding to the chop throw (and its multiples) from the data and greatly reduces the sensitivity to larger scale structure. This problem was already addressed long ago for simple beam-switching observations and methods for recovering images of extended sources were developed (see Emerson, Klein and Haslam, 1979, Astronomy and Astrophysics, Vol. 76, p. 92-105 and also Richer, 1992, MNRS, Vol. 254, p165-176). If one makes multiple maps with different chopper throws one can recover more of the missing information, but there is a still signal-to-noise penalty for large spatial scales. Clearly versions of these techniques applicable to the modern cameras with large numbers of detectors could be developed and might be very effective in some cases, such as deep surveys where one is doing a blind search for faint compact sources in relatively small regions of the sky. I have not worked through this in any detail but, on the assumption that there may be such cases where one needs a wobbler for a larger field than those discussed in section 3 above, I have had a look at some options.

Designs like those already described with two mirrors can certainly be scaled-up to provide larger fields. For example, with a 700mm diameter wobbler, which is still smaller than the JCMT secondary, I found that it was not too difficult to get >95% Strehl over a 0.125-deg square field at 850 microns wavelength. In principle this would be sufficient for a 50-by-50-pixel array at a spacing of 2.5 λ/D. Detectors which do not employ feedhorn coupling can be more closely spaced than this, so the pixel count would be even larger.

For large fields at higher frequencies it becomes difficult to get the aberrations low enough and make the geometry convenient. The imaging of the primary onto the pupil also starts to deteriorate. One possible approach is to replace each of the mirrors in the two-mirror relay systems by a small crossed-Dragone telescope. This makes it possible to compensate for the off-axis aberrations separately at each stage.

Here is an example of the double-Dragone system.



Again I have not explored how well this can be made to work in any detail, but the principle appears to be sound to me.

Acknowledgement

I am grateful to Tony Mroczkowski and Claudia Cicone for reading this memo carefully and making helpful comments and suggesting improvements. It is also a pleasure to thank Urs Graf for providing the initial stimulus for this work and for his comments on an earlier version of this note.

Richard Hills 20th Jan 2022