AtLAST – options for the basic layout of the telescope

Requirements

The goals that drive the basic design are the wavelength range (10 – 0.35mm), the aperture size (50m diameter) and the field of view (2deg diameter). This large throughput (over 6000m^{2}deg^2) is much higher than that of existing telescopes and presents a significant challenge, especially at the higher frequencies. The other critical issue is the need to accommodate a range of instruments and to be able to switch between them at least as often as a few times a day. This reflects the wide range of science planned for the telescope and the fact that conditions on the site are variable.

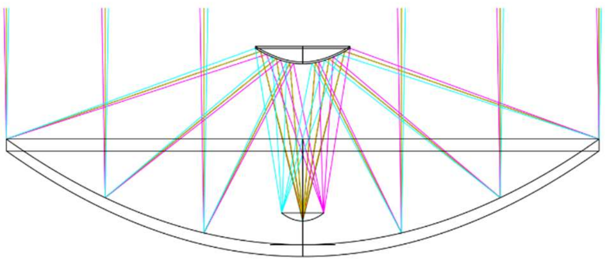
Initial range of possibilities

A survey of possible optical configurations considered a wide range of possibilities, of which many were clearly impractical, but there were four which appeared to be plausible options. These are:

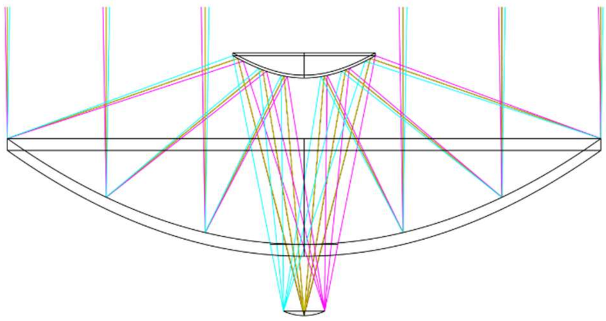
1) Cassegrain (with correction for Coma)

The Cassegrain configuration is of course the basic layout of the vast majority of existing telescopes. The main new factor is the large secondary mirror, which is necessary to keep the physical size of the focal plane within a reasonable bound. Two cases are illustrated here, 1A) with the focal plane in front of the primary mirror and 1B) with it behind the back-up structure. The "back focal distance", BFD, is -2m in the first case and +6m in the second. The focal length of the primary, Fp, is 17.5m, so that Fp/Dp is 0.35, which is a typical value for radio dishes. The diameter of the secondary, Ds, has then been chosen to produce a focal ratio of f/2 at the secondary focus: for 1A) Ds = 8m and for 1B) it is 12m. Making the secondary mirror large produces blockage, i.e. loss of effective collecting area, and increases the sidelobe level. Probably more importantly, it will become difficult, above a certain size, to support the weight and to maintain the required high surface accuracy. A diameter of 12m (an ALMA antenna!) seems feasible, but a size significantly larger than that would be problematic.

Case 1A)



Case 1B)

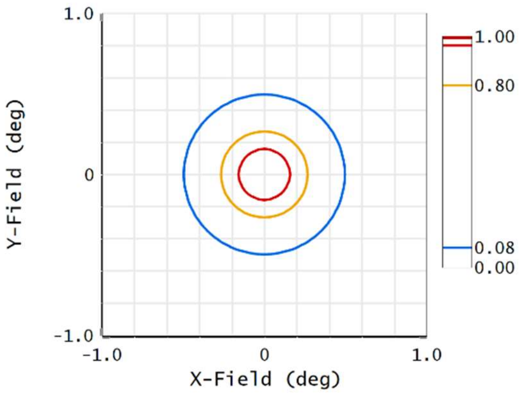


With f/2 at the focal plane, a 2-degree FoV corresponds to a diameter of 3.5m. Note the strong curvature of the focal plane, especially in case 1A). This is an intrinsic property of the Cassegrain configuration and the instruments would have to be designed to cope with this.

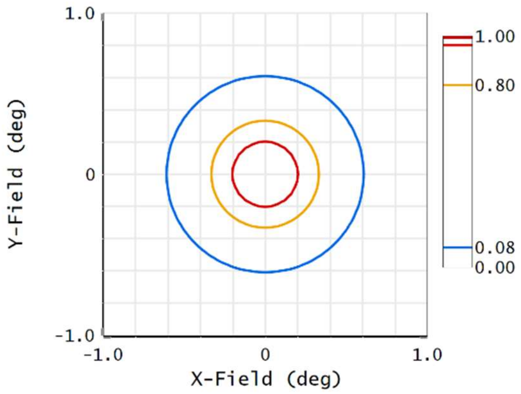
The principle form of aberration in a classical Cassegrain (i.e. a parabolic primary with a hyperbolic secondary) is Coma, but here the mirrors have been shaped to correct this. In addition to optimising the conic constants (the Ritchey-Crétien formulation), small 6th-order terms have been added, which improves the performance at the highest frequencies. These designs still however suffer substantial aberrationa, which is mostly astigmatism. This means that, for example, in case 1A) the geometric spot diameter at the edge of the focal plane is about 80mm, compared to the diffraction-limited size which is ~3mm at 1mm wavelength. The instruments will have to be designed with additional optics before the detectors so as to collect all the power arriving from the telescope and then correct the astigmatism and probably some other residual aberrations.

The image quality is very good in the inner part of the FoV. The plots below show the contours of 80% Strehl ratio at 450µm (red), 1.2mm (orange) and 4mm (blue). These show that even at 4mm wavelength the diffraction-limited field of view provided by the telescope optics is only about 1deg in diameter: to get the required 2deg will require corrections in the instruments at all wavelengths.

Case 1A)



Case 1B)

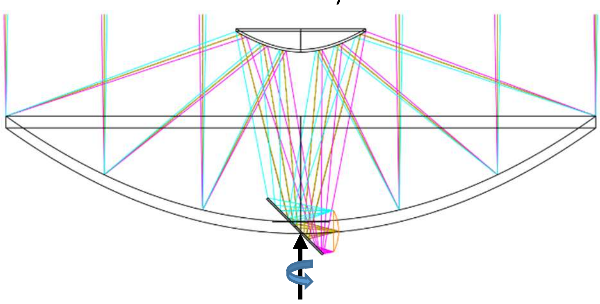


The major advantage of case 1) is that the mechanical design is relatively straight-forward and can follow that of existing telescopes. The disadvantages are the aberrations – especially curvature and astigmatism – and the fact that only one instrument can be in position at a time. Changing instruments would require a large and quite elaborate mechanism to move them. In the case of 1A) this would either have to lift the receivers up into place through the backing structure, when they are needed, or they could perhaps be housed in a cabin built at the vertex of the primary, so that only a lateral shift is required. In case 1B) a larger space would be available behind the backing structure to house the instruments, along with an interchange mechanism. In all cases the instruments would tilt with the elevation of the object being observed, which may cause difficulties with the cryogenics in some cases.

2) Nasmyth

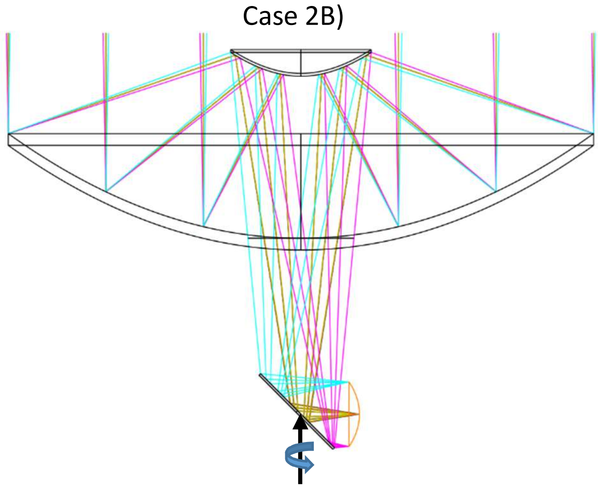
Adding a flat tertiary mirror at 45 degrees angle of incidence converts a Cassegrain configuration into a Nasmyth one. As in the previous case, two examples are given to illustrate the range of possibilities. In case 2A) the tertiary is close to the vertex of the primary, while in 2B) it is much further back (15m behind).

Case 2A)



Case 2A) has Ds = 11m to give f/2 at the focal plane, while Case 2B) has Ds =12. This results in f/3.5. The 2deg FoV then corresponds to a diameter of 5.5m.

Case 2B)



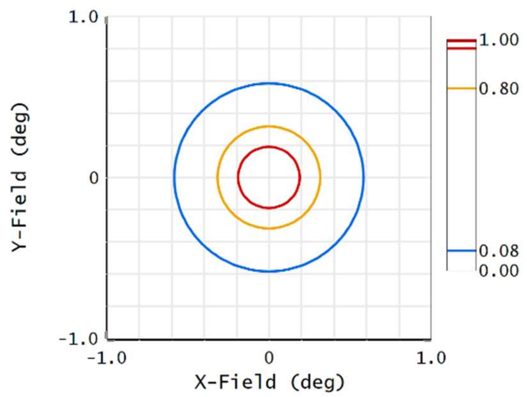
If the flat is mounted on a turn-table so that it can be rotated about the axis of symmetry of the telescope (as shown in the diagrams above), we can surround it with a ring of instruments and switching between them will be quick and easy. In two of these positions, the beam can be directed so that is parallel to the elevation axis, which means that the instrument could be attached to a non-tipping part of the structure or, more plausibly given the large size of the beam, the instrument could be mounted on bearings so that it can "counter-rotate" and therefore not be subject to a varying gravity vector. Additional instrument positions, which do tip with the elevation of the telescope, can be provided by turning the tertiary to intermediate positions. A further four quite large instruments could be accommodated in this way, or perhaps a larger number of smaller ones.

The idea is that in case 2A all the instruments would be housed in a large cabin that forms the hub of the primary, as on e.g. the Sardinia and Effelsberg telescopes. In case 2B the instrument housing would be need to be larger because of the slower f-ratio, but there is much more space available and access would be easier.

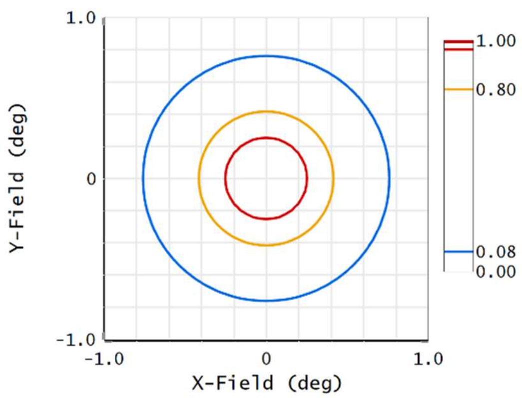
These two examples should perhaps be described as pseudo-Nasmyth configurations. A true Nasmyth has the tertiary on the elevation axis so that the beam can come out through the elevation bearings onto a non-tipping platform. This gives even better access, at least for the two non-tipping instrument positions. The optical properties are the same, however, since these depend only on the secondary diameter and the total distance from the vertex of the primary to the focal plane (the BFD). The BFD is 4m in case 2A and 20m in case 2B.

The Strehl plots for these cases are shown here, again for 80% at 450µm, 1.2mm and 4mm.

Case 2A)



Case 2B)



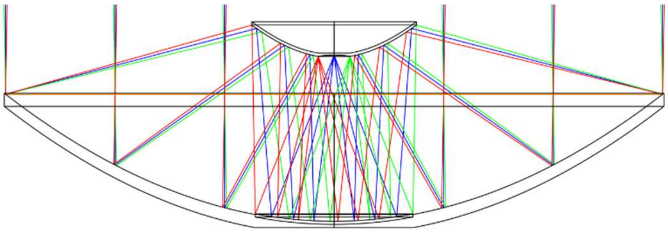
Clearly the slower f-ratio in case 2B) does provide a larger DLFoV, but it still falls well short of the full 2deg diameter, even at 4mm, so correction for astigmatism in the instruments will again be essential for these designs. The curvature is also substantial – the depth of sag of the focal plane is 0.88m. The field is however so large – 5.5m in diameter – that a single cryostat may not be feasible. A camera made from seven cryostats – a central hexagon with six more surrounding it – might be more practical. Tilting the front faces of the outer ones could help with the curvature problem.

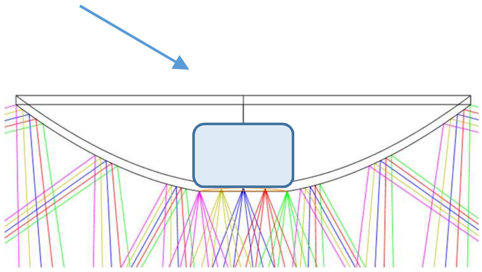
Case 2) is probably somewhat more difficult than case 1) from a mechanical point of view, but it offers significantly better accommodation for the instruments. The residual aberrations – curvature and astigmatism – are the main problem, so the adoption of this design requires us to have confidence that these can be solved in an effective manner. We also need to understand whether the choice of the f-ratio at the focal plane has implications for the feasibility of the instruments.

3) Three-mirror Symmetric

It is well known that with three mirrors it is possible to correct coma, astigmatism and field curvature – this is the basis for the LSST, JWST and ELT designs. If we follow the LSST concept and require that the tertiary is contiguous with the primary, and in fact go further and make the edge of the focal plane contiguous with the secondary as well, we get the overall layout shown in the plot on the left. The detail of secondary and the focal plane on the right. Here the instrument fits inside the structure of the secondary mirror. (In the LSST it is in front of it, which creates blockage.)

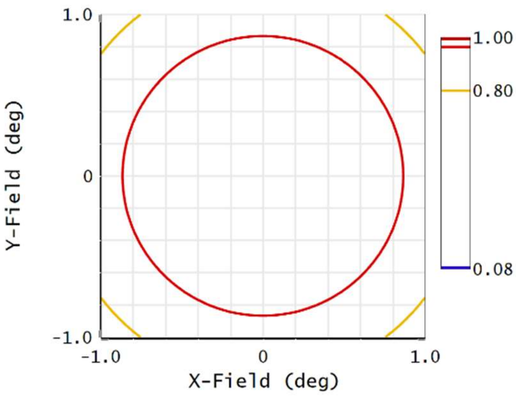
Case 3)





With these constraints and with the diameter of the secondary limited to 12.5m and that of the tertiary to 12m, the curvature is not perfectly corrected, but it is still much smaller than in cases 1) and 2), with a sag of only ~90mm across the 2.4m diameter focal plane.

The other aberrations are corrected very well and the full 2-deg FoV is diffraction-limited right down to 630μm wavelength. Using the same parameters as in the other cases gives this plot:



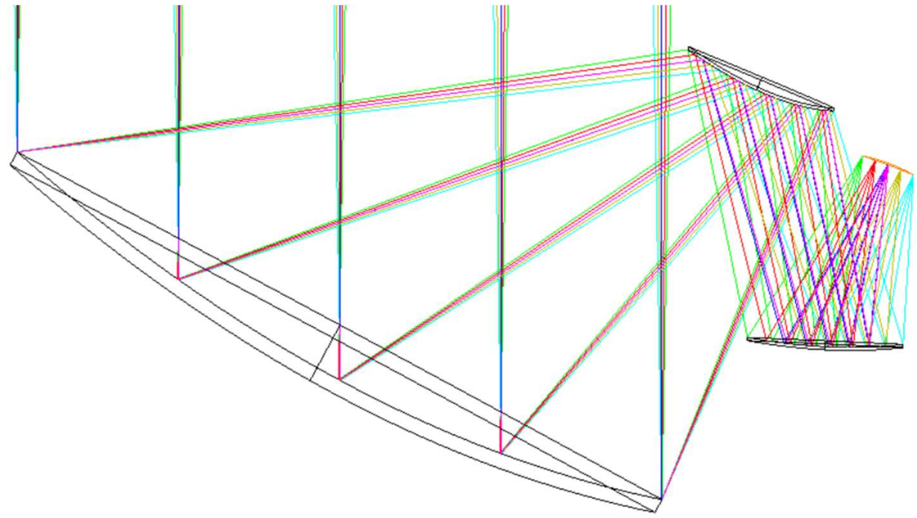
In order to make the receiver fit into the 2.4m-diameter region the secondary that is already blocked by the hole in the middle of the primary we have to bring the f-ratio at the focal plane down to f/1.38. Such a fast beam would be problematic for cameras based on re-imaging optics, such as are presently being design for CMB projects, so direct coupling to the detectors would probably be required. It might also be tricky to couple other instruments such as heterodyne arrays effectively to such fast beams. A further problem with this design is that the detectors see themselves directly reflected in the tertiary mirror – the narcissus effect – which is likely to cause standing waves and lead to baseline ripple and perhaps lack of stability. The option of putting a scattering cone at the centre, which is a good solution to this problem in the Cassegrain case, does not look viable here.

Clearly the biggest problem with this design is, however, the location of the focal plane. Access would be extremely difficult and changing the instrument would be a big job. Thus while this design has very good optical properties and might perhaps be suitable for, e.g. a survey telescope, where instruments are changed only very rarely, it does not appear to be a contender for AtLAST.

4) Three-mirror Off-Axis

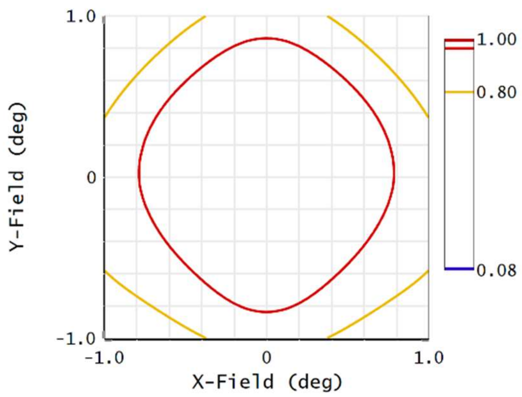
It appears that the disadvantages of case 3) can be overcome by going off axis. This brings the beam to a more convenient location, gives more freedom in the choice of f-ratio and removes the narcissus problem. In fact, it produces a completely clear aperture, so it can provide a “cleaner” beam than any of the other designs, which might be important for, e.g. high angular resolution studies of the CMB. Solutions which correct all the major aberrations are available, although an additional restraint on the angles of incidence and the powers of the mirrors (the Dragone condition) has to be met in order to produce a symmetric illumination and low cross-polarization. Here is an example of this type of layout, with the f-ratio at the focal plane chosen to be f/2.4:

Case 4)



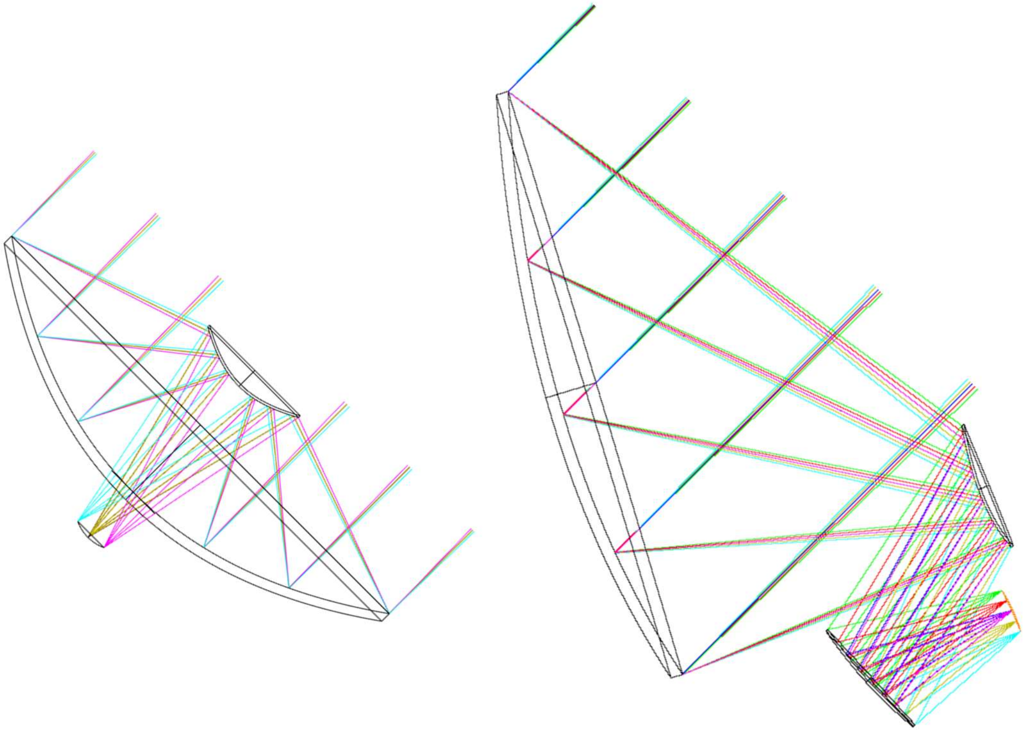
To achieve a circular aperture, the primary would need to be an ellipse of dimensions 57m x 50m, while the secondary is about 12m x 10m and the tertiary is nearly circular with a diameter of 12m.

The wavefront performance is nearly as good as case 3) with the full 2-degree diameter above 80% Strehl at 1mm wavelength and ~1.6deg at 450 µm.



The focal plane is only slightly curved in this design, with a “depth” of 0.2m over the 4.2m diameter of the focal plane, and the beam are nearly telecentric. In terms of the optics, then, this layout appears close to ideal.

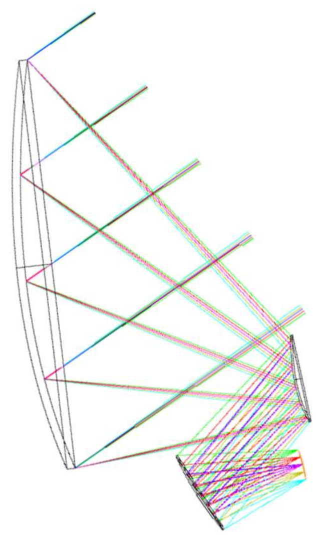
Manufacturing and supporting three large off-axis mirrors with the very high precision required is, however, a serious challenge. The structure would need to be substantially larger than for the symmetric designs and the geometry is significantly more difficult. (As an indicator, the GBT telescope, which has a 100m diameter effective aperture, is about 2.5 times the weight of the Effelsburg 100m.) To give some idea of the additional mechanical challenges, this diagram shows Case 1) and Case 4) on the same scale (both pointed to elevation 45 degrees).



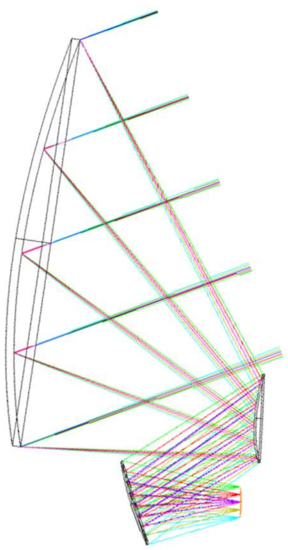
Here I have assumed that the instrument package is at the bottom. This is the opposite of what was chosen for the GBT, but is what is being used for most other off-axis designs, e.g. for the SKA. Access to the instruments is then relatively easy, when the dish is pointed down, but the instruments would tilt with the dish and it would not be possible to change between e.g. two large cameras simply by flipping a mirror.

Note that, if the current goal of pointing down to 20 degrees elevation is to be met, then this adds to the mechanical challenges. A limit of 35 or perhaps 30 degrees would be more realistic for this case.

Elevation 35°



Elevation 20°



Preliminary Conclusions

Although the Cassegrain design, case 1), appears to be the lowest cost option, it is not really compatible with the goals of having access to instruments and being able to switch between them quite quickly. Nasmyth designs, case 2), can meet these goals, but have a curved focal plane and do not deliver diffraction-limited images over the full field of view, leaving those problems to be solved by the instrument designers. The three-mirror symmetric design, case 3), does deliver excellent images, although the focal ratio is uncomfortably fast, but it has very poor access to the instruments. The off-axis three-mirror design, case 4), has excellent optical properties and reasonably good access to the instruments, although not as good as case 2). Its mechanical design would, however, be in largely uncharted territory and it seems inevitable that the cost would be substantially higher than any of the other cases.

Based on these considerations, it seems clear that the studies of the telescope design should concentrate on variations of case 2). In parallel it will be important to assess the feasibility of making the necessary corrections for field curvature, astigmatism, and probably some other residual aberration terms, in the instruments. We do not, of course, have to demonstrate this by producing detailed designs which are based on proven technology – from recent experience we can confidently predict that there will be a great deal of progress in instrument design in the next 10 or 20 years – but we do need to establish that there are no fundamental blocks to being able to do this. It would also be very valuable to establish whether instrument concepts drive the f-ratio at the focal plane strongly in one direction or the other.

If, in the worst case, these investigations show that there are strong reasons to think that the aberration issues will never be adequately resolved, even with ingenious designs of instrument, then it would seem necessary to re-assess the goal of achieving diffraction-limited imaging over the whole field and/or to develop a more radical design, perhaps based on case 4).

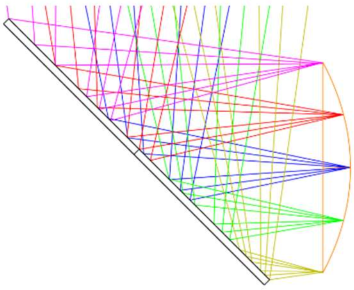
Richard Hills — 2nd May 2021 addendum below 4th May

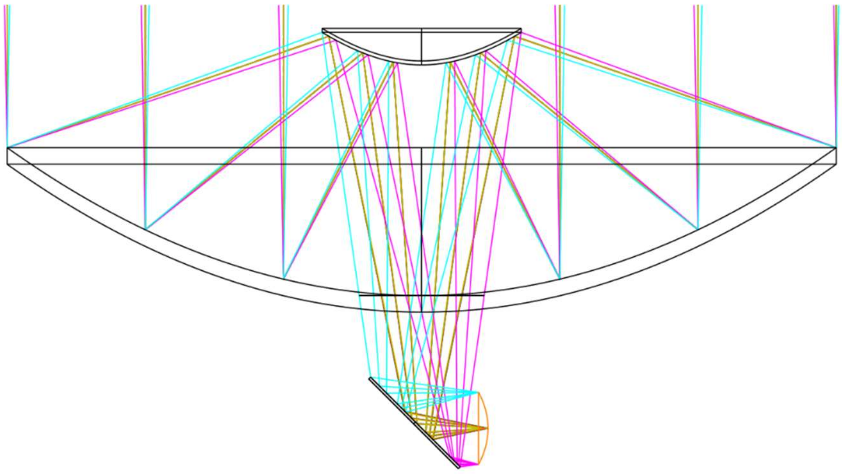
Optics for Preferred Case

After discussion of mechanical and practical issues it was agreed to select for further study a "true Nasmyth" case, where the beam is turned onto the elevation axis. In optical terms this lies between cases 2A and 2B in the note above.

Parameters: Dp = 50m, Fp = 17.5m, so Fp/Dp = 0.35, Ds = 12m, BfD = 12m, T = 8m. (T is the distance from primary vertex to center of the tertiary, which is on the elevation axis, so the distance from the middle of the tertiary to the middle of the focal plane is 4m.)

This looks like this, with an enlarged view of the tertiary and focal plane below:

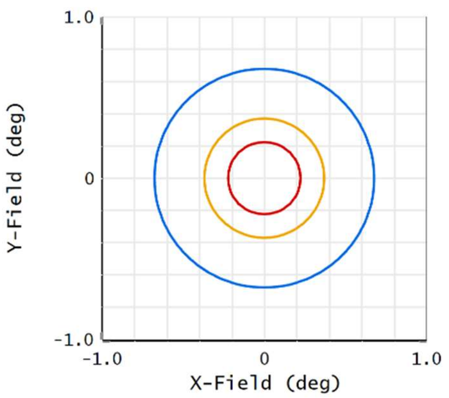


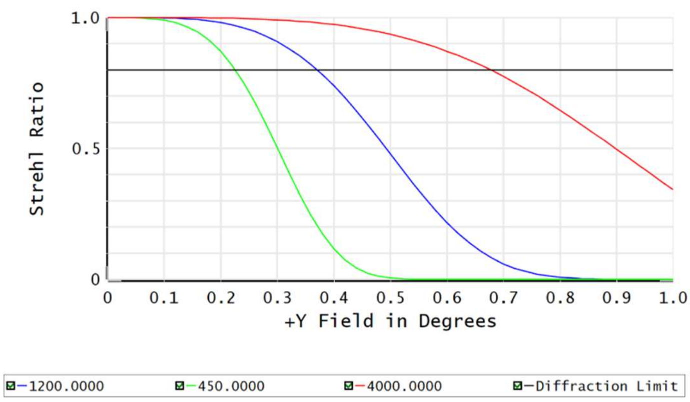


The diameter of the focal plane is 4.325m and the effective f-ratio is f/2.52. The depth of the focal plane (center to edge) is 560mm. The angle of incidence of the chief ray on the focal surface at the edge of the field of view is 23.5 degrees.

The tertiary mirror (here assumed to be flat) needs to be at least 7.65 x 5.30m.

The Strehl plot (0.8 at 450um, 1.2mm and 4mm) is on the left below and the Strehl versus field radius is on the right. The performance is good with just conic sections for the surfaces – higher-order terms do not improve it significantly.





Note that I have assumed the secondary is designed to be large enough to allow us to use the full diameter of the primary at all positions on the focal plane. This means that it will be necessary to have an internal Lyott stop in the instruments in order to avoid them picking up spill-over from the ground over the edge of the primary. I believe that this is the best choice for AtLAST.

Richard Hills 4th May 2021