Subaru PIAA coronagraph optics specifications

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1 Purpose of test, overall optical design

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Our team at Subaru Telescope is planning the construction of a coronagraph which is to be installed at the telescope in 1 to 2 years from now. The coronagraph function is to efficiently remove the light of a star to acquire an image of much fainter planets very close to the star. An approximate optical design is shown in figure 1: the coronagraph is located between the Subaru Adaptive Optics system (AO188) and the HiCIAO camera.

The Phase-Induced Amplitude Apodization (PIAA) technique, which we plan to use for this coronagraph, is described extensively in the paper "Phase-Induced Amplitude Apodization of Telescope Pupils for Extrasolar Planet

Imaging", available on :
http://www.naoj.org/staff/guyon/publications/PIAA.ps

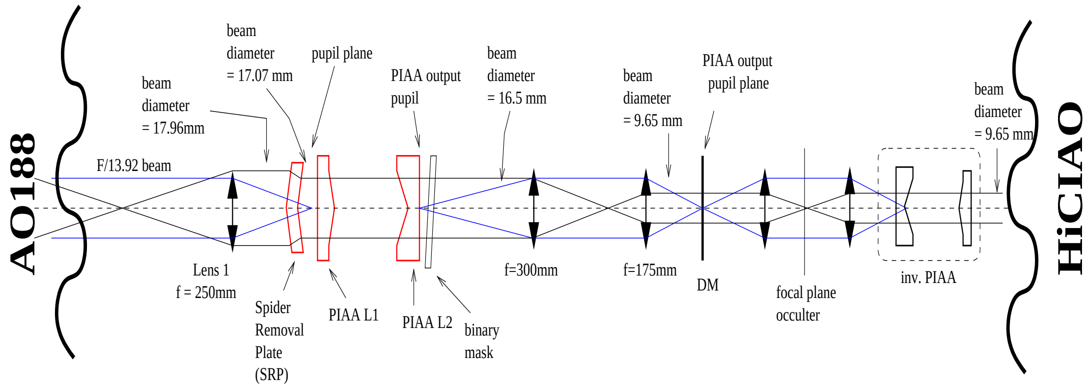

Figure 1: Overall optical layout for a PIAA coronagraph for Subaru Telescope. The optical components in red are described in this document: the Spider Removal Plate (section 2) and the PIAA lenses L1 and L2 (section 3).

A key feature of our coronagraph design is a beam shaping unit, which converts the telescope beam into an approximately gaussian beam. This gaussian beam yields an image free of Airy rings, in which the starlight can be efficiently removed.

We are looking for manufacturers for some critical optical components of the coronagraph:

1. A pyramid-shaped transmissive plate. See section 2 for detailed specifications.

2. The beam shaping optics (or PIAA optics) for the Subaru PIAA design. They consist of 2 aspheric lenses. See section 3 for detailed specifications.

3. Another set of PIAA lenses to by used only for tests in the laboratory. See section 4 for detailed specifications.

2 Specifications for the spider removal plate (SRP)

2.1 Optical design

The Subaru Telescope beam has a central obstruction (due to the secondary mirror) and also 4 spider vanes (due to the support structure for the secondary mirror). The pupil geometry, as measured from an image acquired on the telescope, is shown in figure 2.

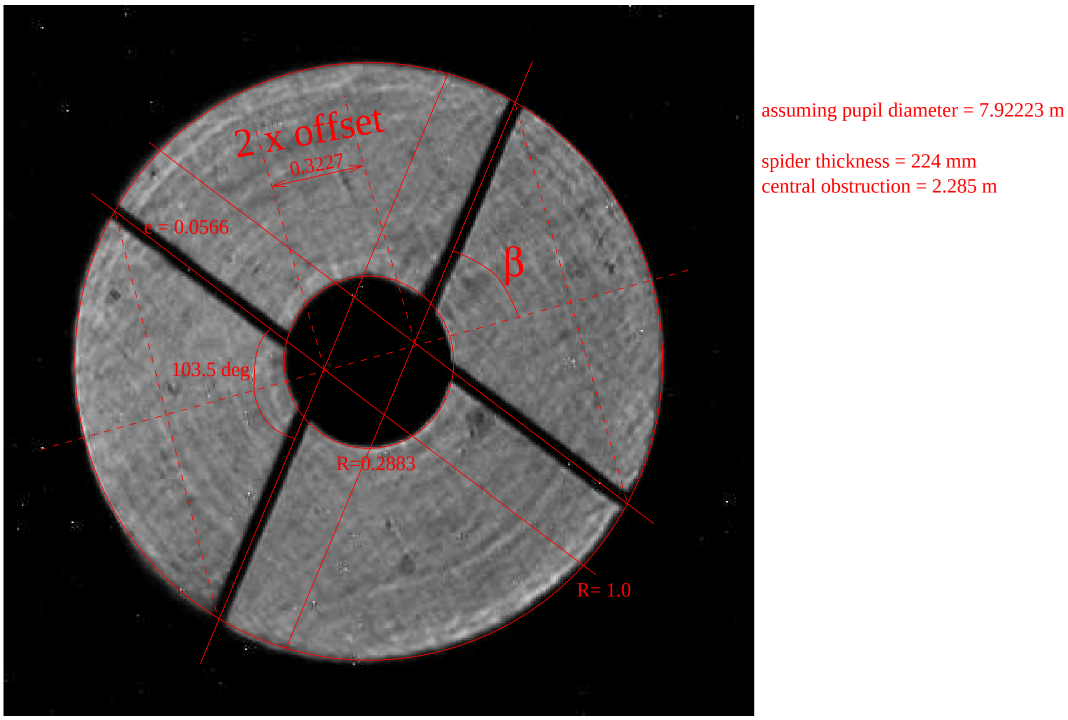

Figure 2: Subaru Telescope pupil geometry.

We wish to remove these spider vanes with a phase plate, which essentially translates the 4 "pieces" of the beam closer together to reduce the gap due to the spiders. Since we want to avoid having gaps in the output beam, we need to be conservative to allow for measurement errors and missalignement.

The SRP consists of 4 tilted plane-parallel plates, each translating a "piece" of the pupil inwards, as shown in figure 3. It can be best described as a "pyramid-shaped rooftoop" of constant thickness. It can consist of 4

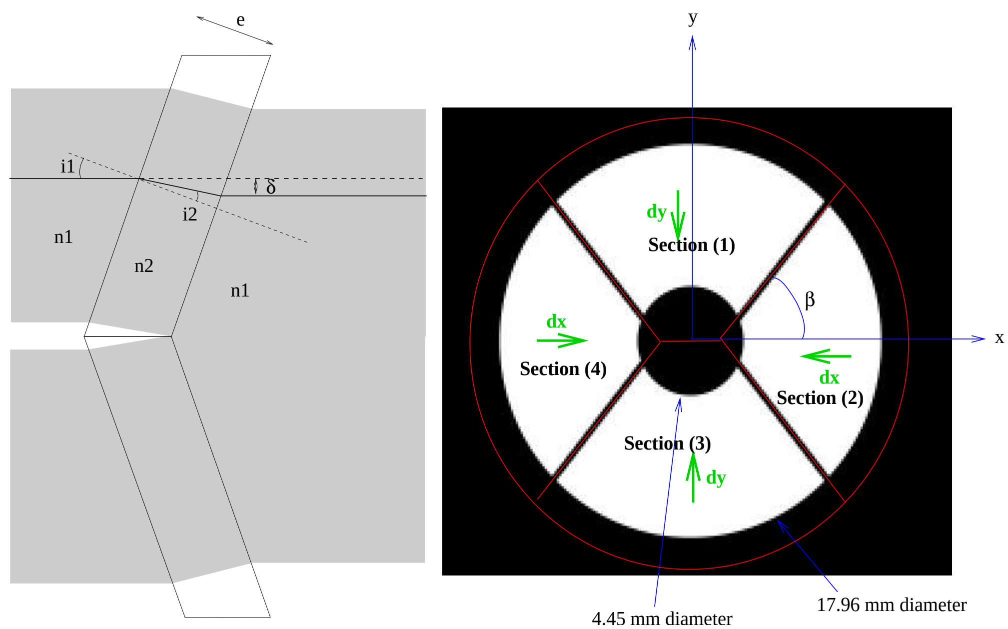

Figure 3: Spider Removal Plate (SRP) and pupil geometry.

separate plates assembled together, or one single plate polished down to this rooftop shape.

The spider vanes thickness is 200mm with a pupil size of 7.92223m. In the collimated beam in front of the SRP, this thickness corresponds to 0.453 mm on the 17.96mm diameter pupil image.

As shown in table 1, the SRP needs to fill up a 0.567 mm spider vane gap in the 17.96 mm diameter beam. This is achieved by a combination of δx and δy translations as shown in figure 3.

Each of the 4 segments of the SRP is a tilted plate. The tilt angle is function of the amplitude of the translation to be achieved. There are several solutions to remove the spiders, one of which is to have $\delta x = 0$ and to rely entirely on δy to remove the spiders. We chose for the SRP design $\delta x = \delta y$ to ensure that the phase offset seen by the 4 parts of the beam is identical (assuming the 4 plates have the same thickness).

Since β is different from 45 deg, the SRP is not continuous at the interface between the 4 plates - there are steps running along the 4 interfaces.

Since the spider gap (denoted *gap*) must be fully filled up, we must also

	expected	measured	adopted	size @ SRP
Pupil diam.	7.92223 m	7.92223 m	7.92223 m	17.96 mm / 17.07 mm
Centr. obst..	2.2 m	2.285 m	2.3 m	5.214 mm / 4.512 mm
Spider thick.	0.2 m	0.224 m	0.25 m	0.567 mm / 0.000 mm
Angle β	N/A	51.75 deg	51.75 deg	51.75 deg
Offset	N/A	1.278 m	1.278 m	2.897 mm

Table 1: Pupil geometry for the SRP. The two numbers given for "size @ SRP" are for the SRP input and output respectively. The adopted values for central obstruction and spider thickness are larger than the measured value to allow for small alignement errors.

have:

$$\delta x \sin(\beta) + \delta y \cos(\beta) = gap \tag{1}$$

which leads to $\delta x = \delta y = 0.40373mm$

This offset can be converted in a tilt angle by using geometrical optics equations:

$$n1 \sin(i1) = n2 \sin(i2) \tag{2}$$

$$\delta = (e/\cos(i2)) \sin(i1 - i2) \tag{3}$$

With $e = 15mm$ and $n = 1.4434$ (fused silica at 1.6 micron), we find that the tilt angle for the 4 plates should be 5.00407 degree.

2.2 Tolerance analysis / Surface accuracy requirements

The requirements on the surface accuracy of the SRP are:

- Over each of the 4 sections of the SRP, the transmitted wavefront should be no worse than $\lambda/20$ flatness at $\lambda = 0.6\mu m$.
- A particularly challenging part of the SRP is the interface between sections: the above wavefront requirement cannot be met strictly up to the interface for obvious manufacturing reasons. We have estimated how close to the interface does the SRP need to properly work by asking the SRP to reduce the spider thickness instead of fully removing it (see figure 4).**We find that a residual spider thickness of $15\mu m$ is acceptable after the SRP.**

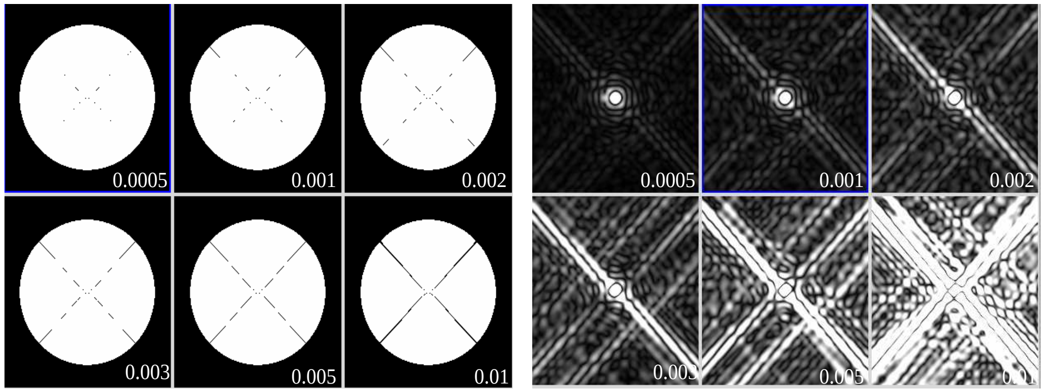

Figure 4: Effect of residual SRP spiders in the output beam of the beam shaping PIAA optics (left). The corresponding images of a bright star and a 10^{-6} contrast companion at 2 λ/d are also shown (right). As the residual spider thickness (white number on each image, unit is the full beam diameter) increases, the ability to detect faint companions suffers.

- The tilts on each of the sections of the SRP should be accurate to 2% or better (relative to the nominal tilt).

3 Specifications for PIAA system 1

NOTE 1: The current nominal beam diameter for the PIAA system is 16mm. If this poses serious manufacturing challenges, we will consider increasing it to up to 40mm.

NOTE 2: If the high asphericity of these optics makes them challenging to manufacture, we can consider spacing the 2 lenses further apart in the system, which would make the lenses surfaces flatter.

3.1 Overall description

This pair of lenses will accept a 16mm diameter collimated input beam, and will produce a 16mm diameter collimated output beam with an approximately gaussian intensity profile. The distance between the 2 lenses will be 96mm. The input lens is L1 and the output lens is L2.

Figure 5 shows the 2 lenses L1 and L2 to be manufactured. The red circles in this figure show the areas of the lenses which may be challenging to manufacture.

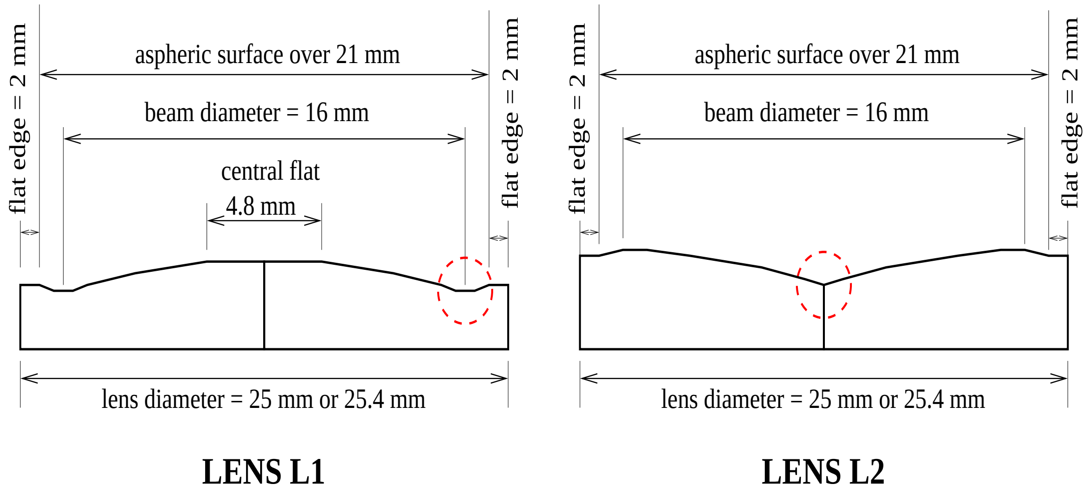

Figure 5: Schematic description of the 2 PIAA lenses.

Each lens has a flat side and an aspheric side. The aspheric shape is circular-symetric: the sag is simply a function of the distance r to the optical axis/ center of the lens. Lens thickness is not specified and can be chosen to facilitate manufacturing. The lenses can be made of any relatively low dispersion glass/crystal (Fused silica acceptable; Barium Fluoride, Calcium Fluoride or Lithium Fluoride preferred). The lenses need to be used in visible (He-Ne laser) for testing and in the near-IR (from 1.2 to 2 micron) when used on the telescope. Lower dispersion and lower refraction index materials are preferred, but surface accuracy should be the main driver for the choice of the material. The lenses do not need to be anti-reflection coated.

Our required wavefront accuracy, to be delivered by the beam shaping system, is lambda/20 RMS in the visible. We can accurately measure the ouptut wavefront in our laboratory, and we will consider having a corrective plate manufactured to remove residual wavefront errors: we are therefore also considering beam shaping optics which would not reach the lambda/20 RMS requirement.

3.1.1 PIAA lens 1, L1

The exact sag profile for lens L1 is given in file “lens1_type1.dat”, and can be decomposed in several zones:

- **Central flat (0 - 2.4mm radius):** The input beam for our experiment is 16mm diameter, but the central 4.8mm is not illuminated: the shape of the lens over the central 4.8mm is therefore not important. We have arbitrarly chosen a flat profile for this central region, but we could also choose to adopt a profile which gently transitions into the next part of the profile

- **Aspheric part (2.4mm - 10.5mm radius):** This is the part of the lens which performs the beam shaping. The lens is converging in the central part of the profile (out to about 6mm radius) but becomes diverging in the outer part of the aspheric profile (especially at 8mm radius). Our telescope beam will only illuminate the lens out to 8mm radius, so the surface figure accuracy is not critical from 8mm to 10.5mm radius. The radius of curvature of the surface is smallest at 8mm, and the exact lens shape in this outer part of our beam is critical to the beam shaping.

- **At the edge of the lens, a flat surface facilitates mounting.**

The approximate functional dependence of surface sag versus position on the surface is shown in Figure 6.**The relatively sharp bend in the outer part of lens L1 is critical to the success of the experiment.** The maximum departure from a sphere in L1 is $\approx 0.5mm$.

3.1.2 PIAA second lens, L2

This lens is fully illuminated from 0 to 8mm radius. The aspheric shape extends from 0mm to 10.5mm radius. The approximate functional dependence of surface sag versus position on the surface is shown in Figure 7 and given in file "lens2_type1.dat". This lens is converging, and its center is a cone-shaped "dip". It is important to approximate this cone as best as possible, avoiding to round off this feature too much. Just as for Lens L1, the surface accuracy from 8mm radius to 10.5mm radius is not critical, and a flat surface at the edge facilitates mounting. The maximum departure from a sphere in L2 is $\approx 0.5mm$.

3.1.3 Notes

- The aspheric shapes were computed assuming refraction index = 1.46, and may slighly change depending upon material choice. This change

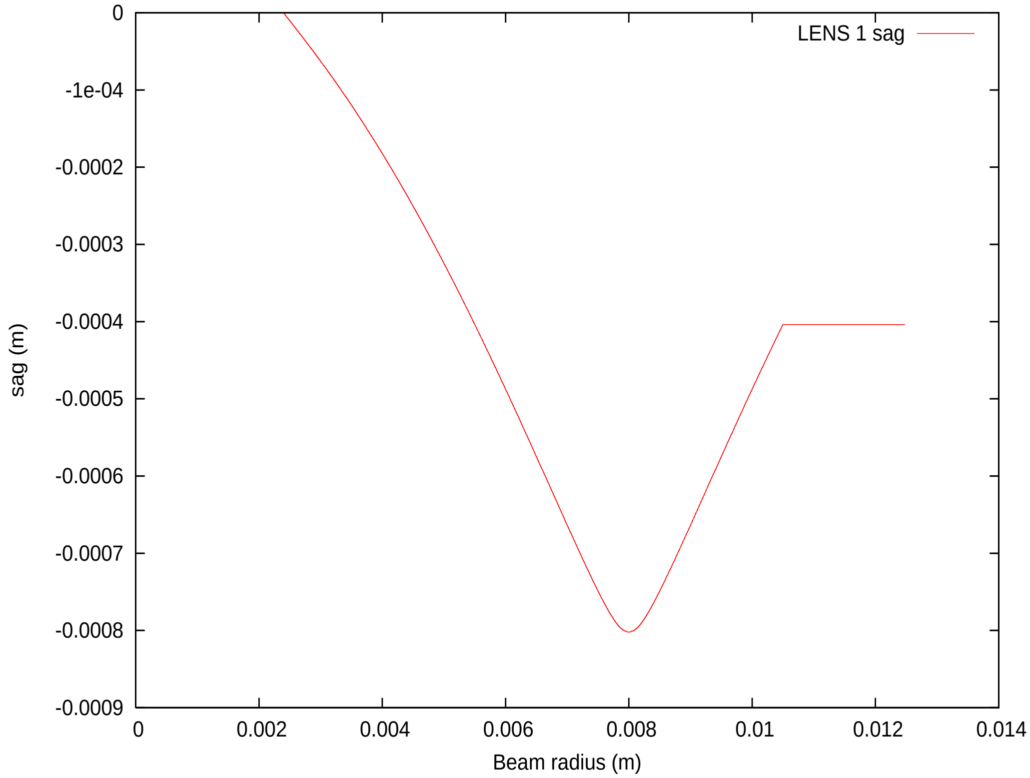

Figure 6: Sag profile for lens L1.

would be very minor: the overall shape and characteristics of the lenses will stay the same.

- We have adopted a 16mm beam size and a 25mm lens size. We can change these numbers to facilitate manufacturing if needed. For example, we could consider 50mm lens size with 32mm beam diameter if needed.

- There is no strict requirement on the scattering at the surface of the lenses.

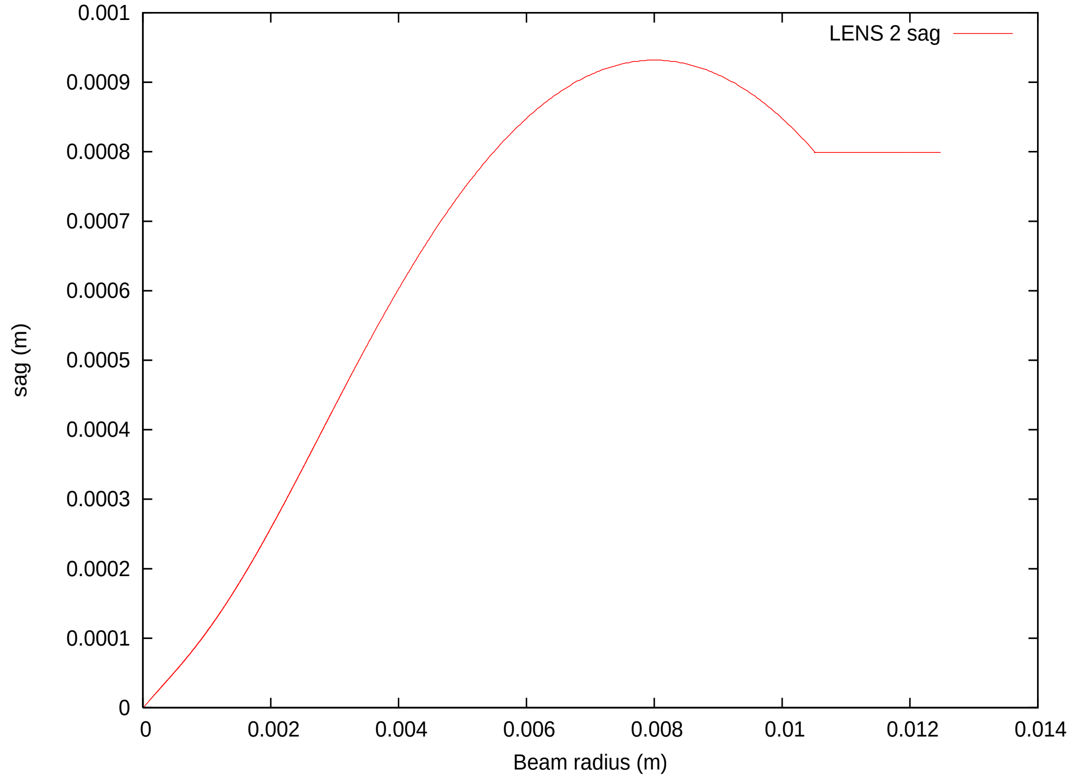

Figure 7: Sag profile for lens L2.

4 Specifications for PIAA system 2

This PIAA system is very similar to the previous one, the only difference being that it is designed to work with a beam without central obstruction. The central flat in lens L1 therefore disappears, and there is no discontinuity in slope at the center of lens L2.

The sag profiles for both lenses are given in figures 8 and 9 and are also given in files "lens1_type2.dat" (lens L1) and "lens2_type2.dat" (lens L2).

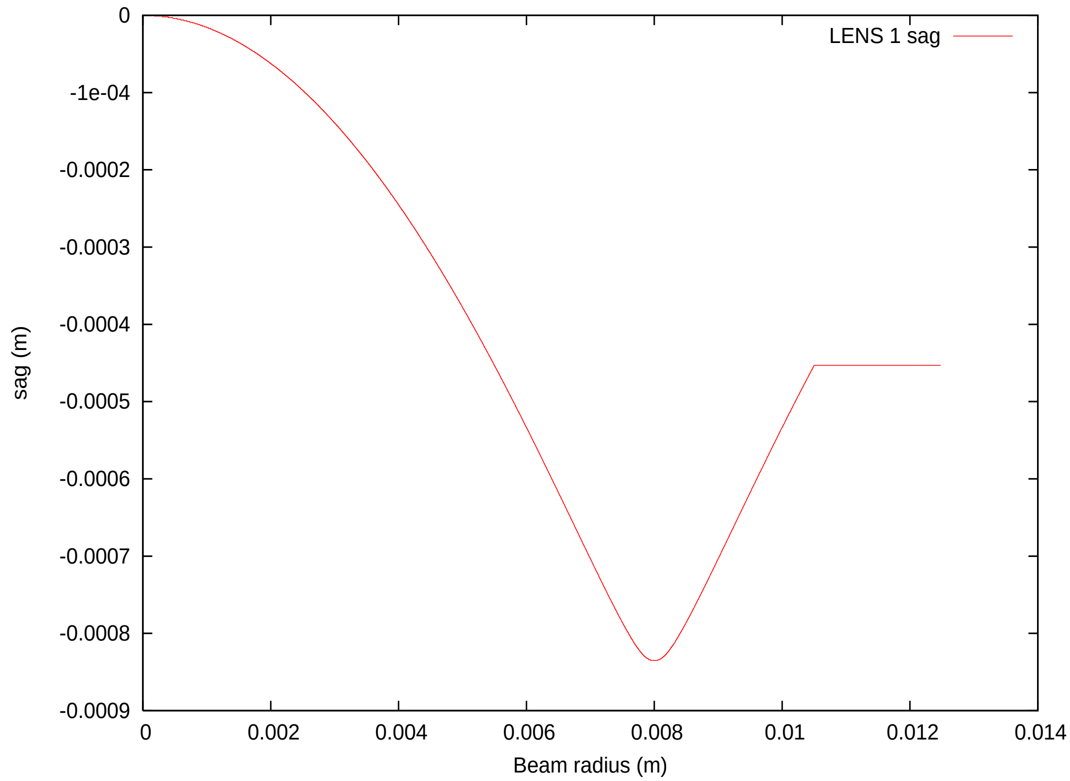

Figure 8: Sag profile for lens L1.

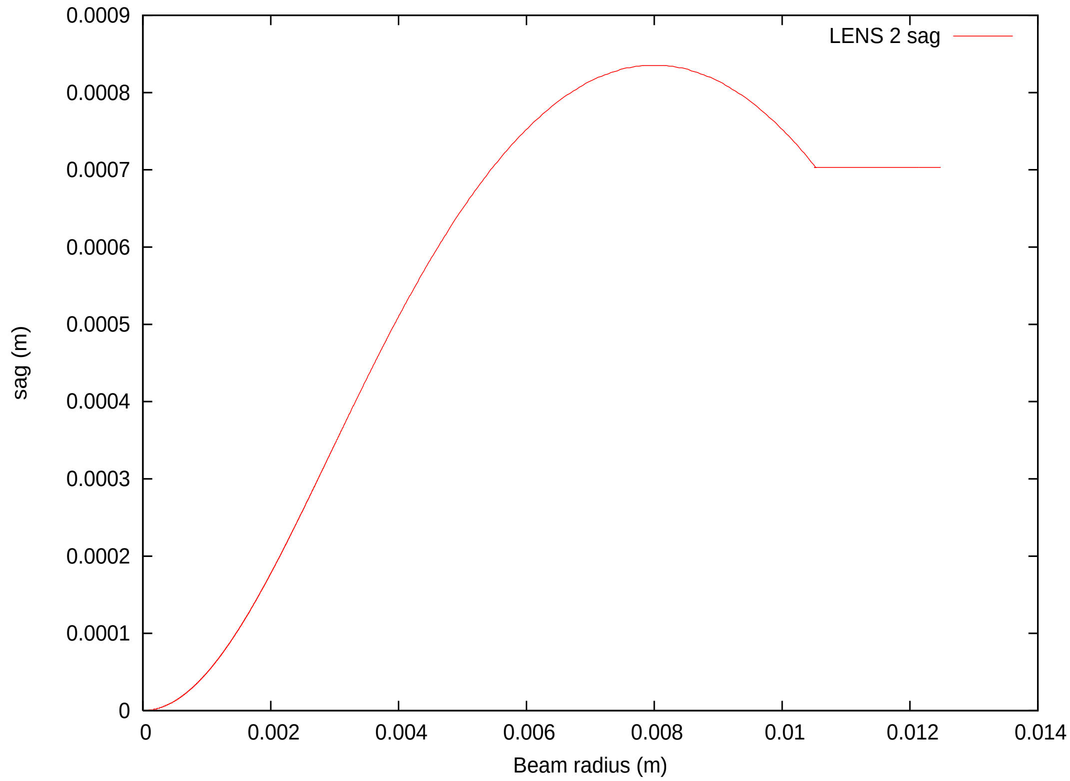

Figure 9: Sag profile for lens L2.