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LIGO Laboratory / LIGO Scientific Collaboration

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aLIGO Hartmann Sensor Optical Layouts (H1, L1, H2): End Test Mass

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1 Introduction

The purpose of this document is to describe the End Test Mass (ETM) Hartmann Wavefront Sensor (HWS) optical layout. For reference, the location of the ETM Transmon assembly in its BSC chamber and the in-air table that supports the HWS optics is shown in Figure 1.

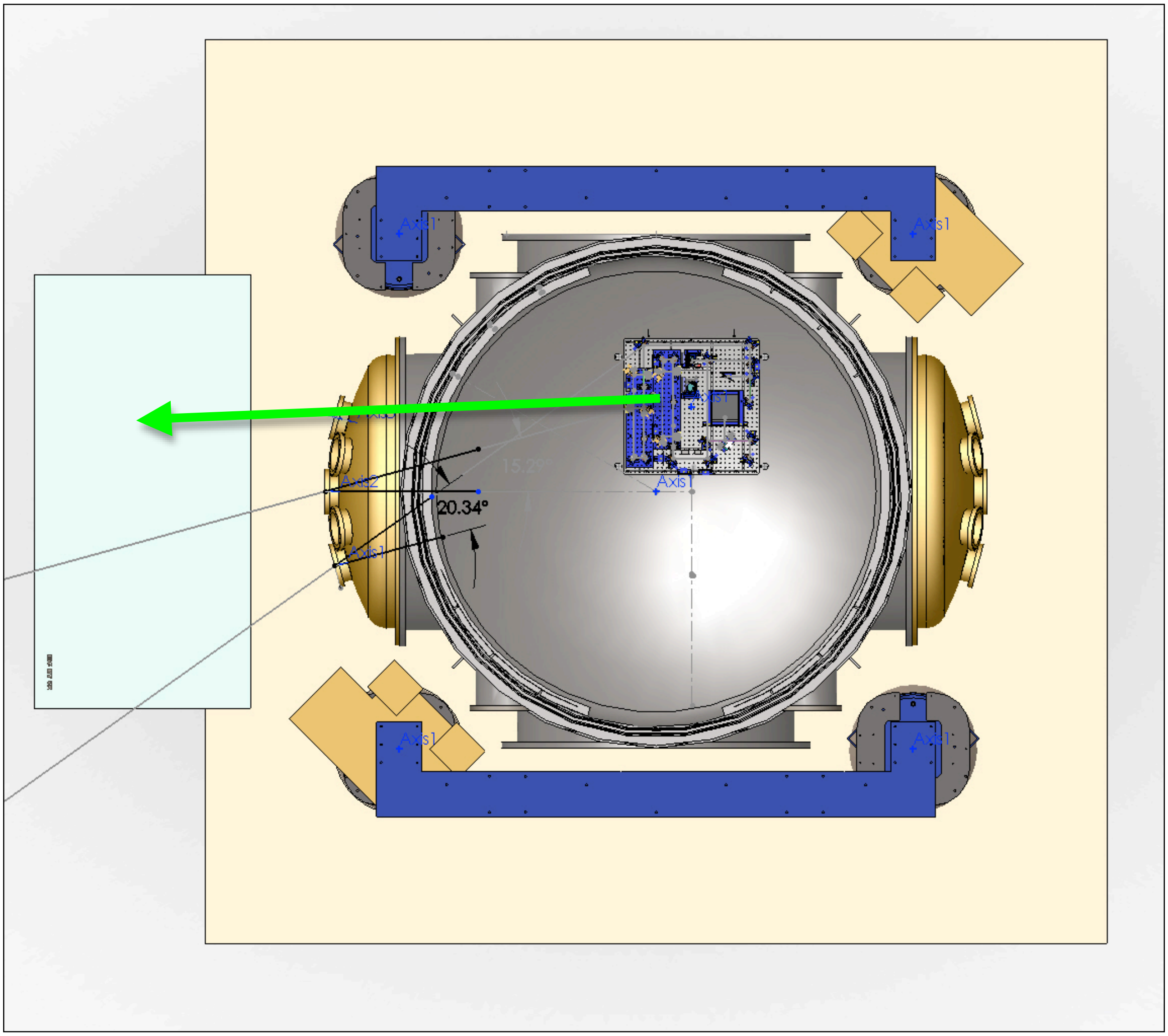

Figure 1: H2 Y-ARM ETM. This image shows the Transmon in its BSC chamber and the in-air table (left) that houses the in-air HWS optics. The green line shows the viewport through which the HWS beams enter and exit the vacuum.

2 Requirements

A probe beam and secondary (sometime called "reference") beam must be transmitted from the ETM to the Hartmann sensor. The telescope on the Transmon assembly combined with optical layout on the in-air table must:

- For the probe beam:
  - **Image** the ETM_HR surface onto the surface of the HWS
  - With a **magnification** of 1/20.5x
  - Where **all imaging optics are outside the vacuum system** (the first optic imaging optic on the in-air table can be no closer than 4680mm to the secondary mirror on the transmon table).
- For the secondary/reference beam
  - Transmit the beam from the ETM_AR surface through the Transmon telescope and onto the HWS. No imaging is required.

2.1 Beam source

The HWS beams originate as pick-offs of the 532nm ALS Innolight Prometheus laser that is mode-matched to the 4km FP arm, as illustrated in Figure 2. A pick-off of the beam reflected from the ETM HR surface is the probe beam for the Hartmann sensor. The reflection from the ETM AR surface is the secondary beam for the Hartmann sensor. As such, it is a necessary condition for running the HWS that the ALS beam is not locked to the cavity.

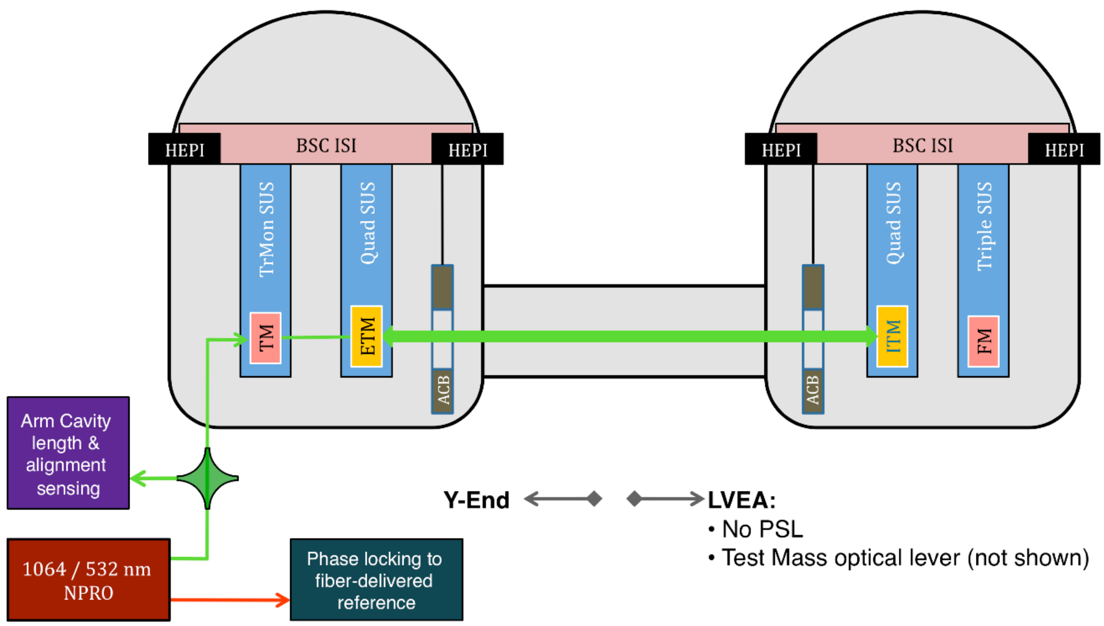

Figure 2: Taken from T1100080. Block diagram of the H2OAT integration phase. ETM: End Test Mass; TM: Transmission Monitor; ITM: Input Test Mass; FM: Fold Mirror; ACB: Arm Cavity Baffle; ISI: Internal Seismic Isolation.

2.1.1 Signal on Probe beam

As illustrated in Figure 3, the 532nm beam double passes the ETM mirror substrate and includes a reflection from the HR surface. As such it accumulates wavefront distortion (our signal) from the thermo-refractive lens within the substrate of the ETM and the thermo-elastical deformation of the ETM HR and AR surfaces.

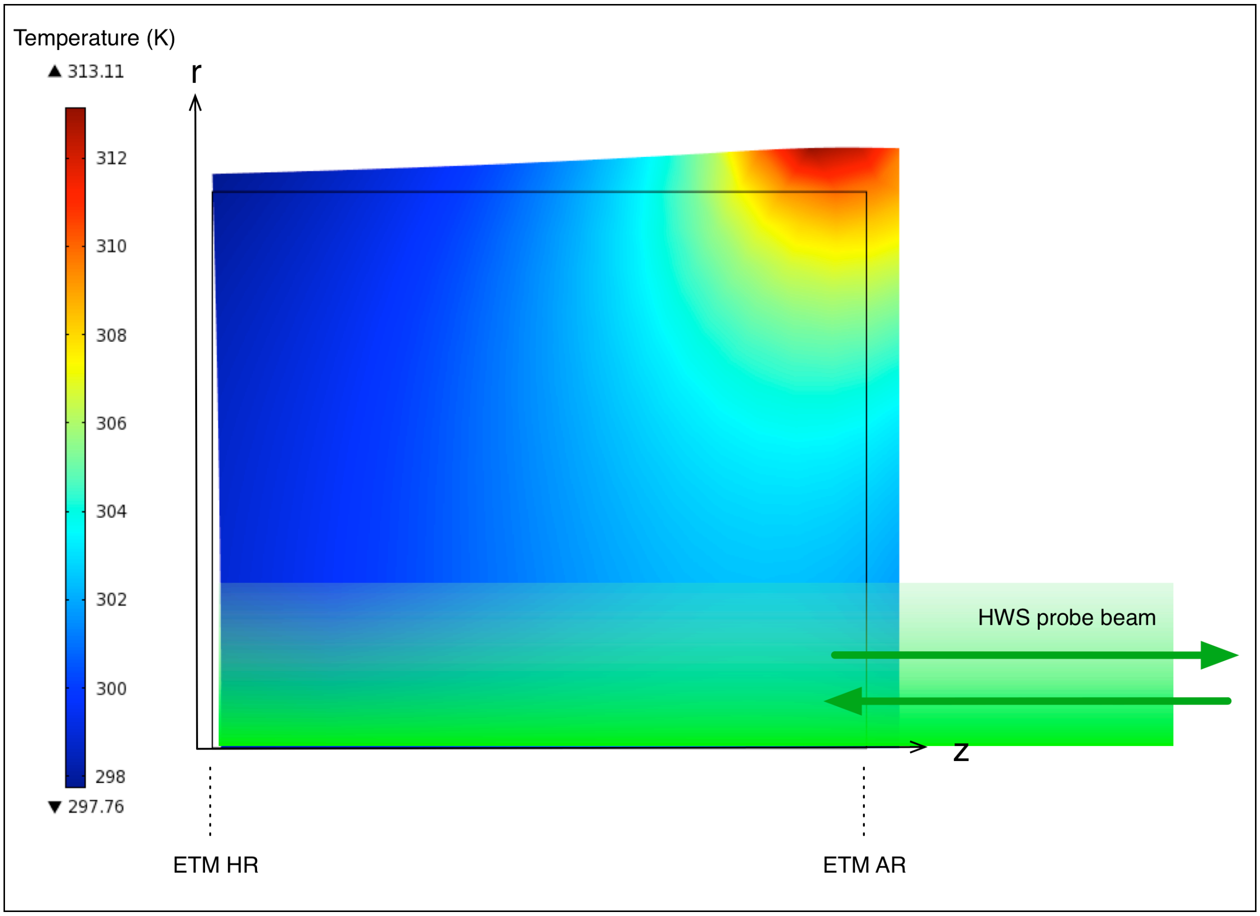

Figure 3: An ETM with ring heating applied. The temperature profile and thermal elastic deformation are visible. The HWS probe beam is shown transmitting through the substrate and reflecting off the ETM_HR surface.

2.2 Secondary beam source and signal

There will be a reflection of the incoming green ALS beam from the ETM_AR surface. This is illustrated in Figure 4. This beam is also transmitted through the Transmon telescope back to the HWS. It is used to periodically check the thermal defocus of the Transmon telescope (see Section 4.1).

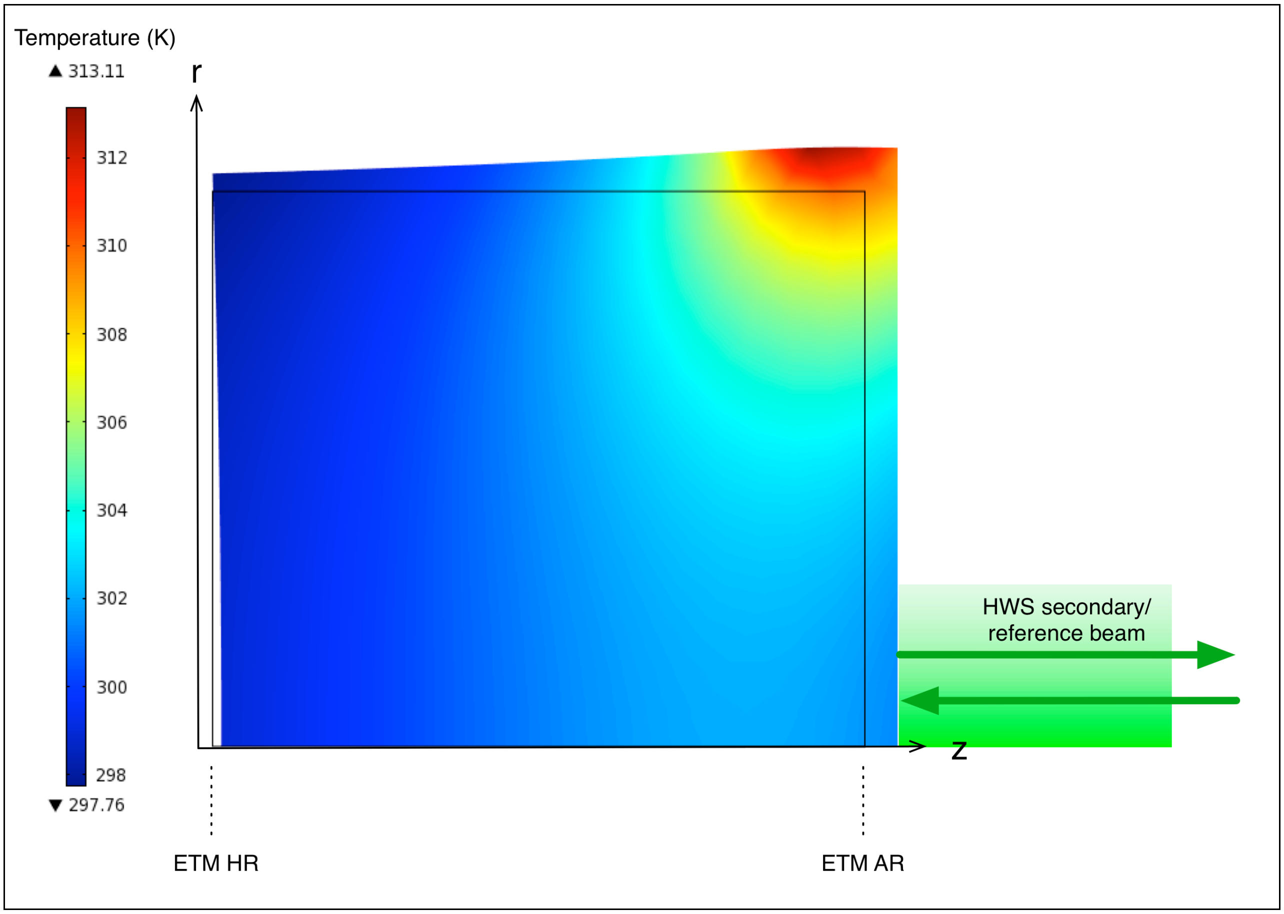

Figure 4: An ETM with ring heating applied. The temperature profile and thermal elastic deformation are visible. The HWS secondary beam is shown reflecting off the ETM_AR surface.

2.3 Probe beam imaging solution to HWS (H2 ETMY)

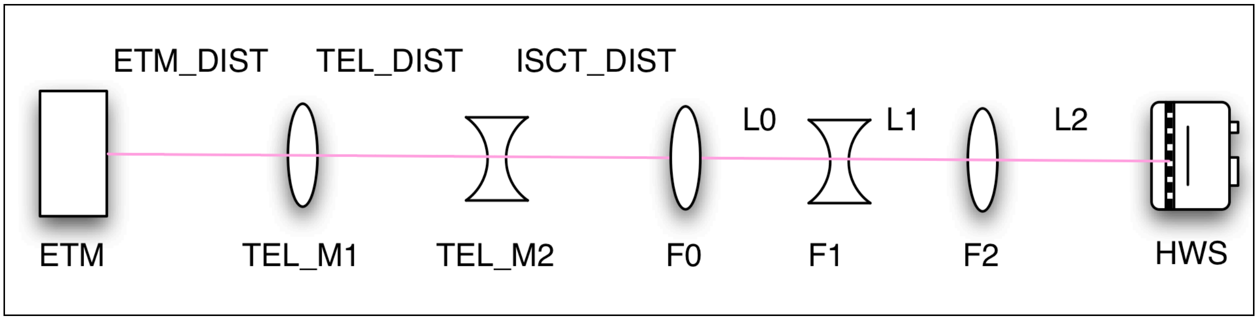

Figure 5: The optical train from the ETM to the HWS. The transmon telescope is represented by elements TEL_M1 and TEL_M2 and the HWS imaging system by the elements F0, F1 and F2.

A three-lens solution that images the ETM_HR surface onto the HWS is show schematically in Figure 5. The details of this solution are listed in below in Table 1.

Table 1: HWS Imaging telescope properties

Name	Optical Element	Value
ETM_DIST	propagation	L = 1429 mm
TEL_M1	curved mirror	R = 4000 mm
TEL_DIST	propagation	L = 1902.6 mm
TEL_M2	curved mirror	R = -200 mm
ISCT_DIST	propagation	L = 4680 mm
F0	lens	F = 782.7 mm [CVI PLCX-50.8-360.6-UV-532]
L0	propagation	L = 614 mm
F1	lens	F = -335.4 mm [CVI PLCC-25.4-154.5-UV-532]
L1	propagation	L = 1313 mm
F2	lens	F = 1677 mm [CVI PLCX-25.4-772.6-UV-532]
L2	propagation	L = 1338 mm

The total ABCD matrix of this system is $\begin{pmatrix} -0.049 & 0.009 \\ 0.00 & -20.498 \end{pmatrix}$.

The probe beam size at the ETM is set by the eigenmode of the 532nm in the arm-cavity.

General Advanced LIGO

In general, for Advanced LIGO, the beam size and radius of curvature of the green beam at the HR surface of the ETM are:

- $R_{ETM:HR} = 2245$ m
- $w_{ETM:HR} = 43.85$ mm

After the beam has passed through the ETM, which acts as a lens, the beam parameters at the ETM_AR surface are:

- $R_{ETM:AR}$ = 1537 m
- $w_{ETM:AR}$ = 43.85 mm

One Arm Test

For the One Arm Test, the beam size and radius of curvature of the green beam at the HR surface of the ETM are:

- $R_{ITM:HR}$ = 2307 m [ETM02, see E1000776]
- $R_{ETM:HR}$ = 2312 m [ETM04, see E1000778]
- $w_{ETM:HR}$ = 31.50 mm

After the beam has passed through the ETM, which acts as a lens, the beam parameters at the ETM_AR surface are:

- $R_{ETM:AR}$ = 1583 m
- $w_{ETM:AR}$ = 31.50 mm

Figure 6 shows the propagation of the HWS beam from the ETM through the optical system described in Table 1.

2.3.1 ISCT_DIST

The distance from the secondary mirror of the Transmon telescope to the first lens, F0, of the HWS imaging system was derived using the diagram G1100873 that shows the Transmon table in and around BSC6.

- There is 732 mm from the secondary mirror of the Transmon table to the upper periscope mirror on the Transmon table.
- The beam traverses 595 mm on the surface of the Transmon table
- The beam traverses 2332 mm from the Transmon table to the upper periscope mirror on the in-air table.
- The beam traverses 1020 mm from the upper periscope mirror to the first lens, F0, in the imaging system.

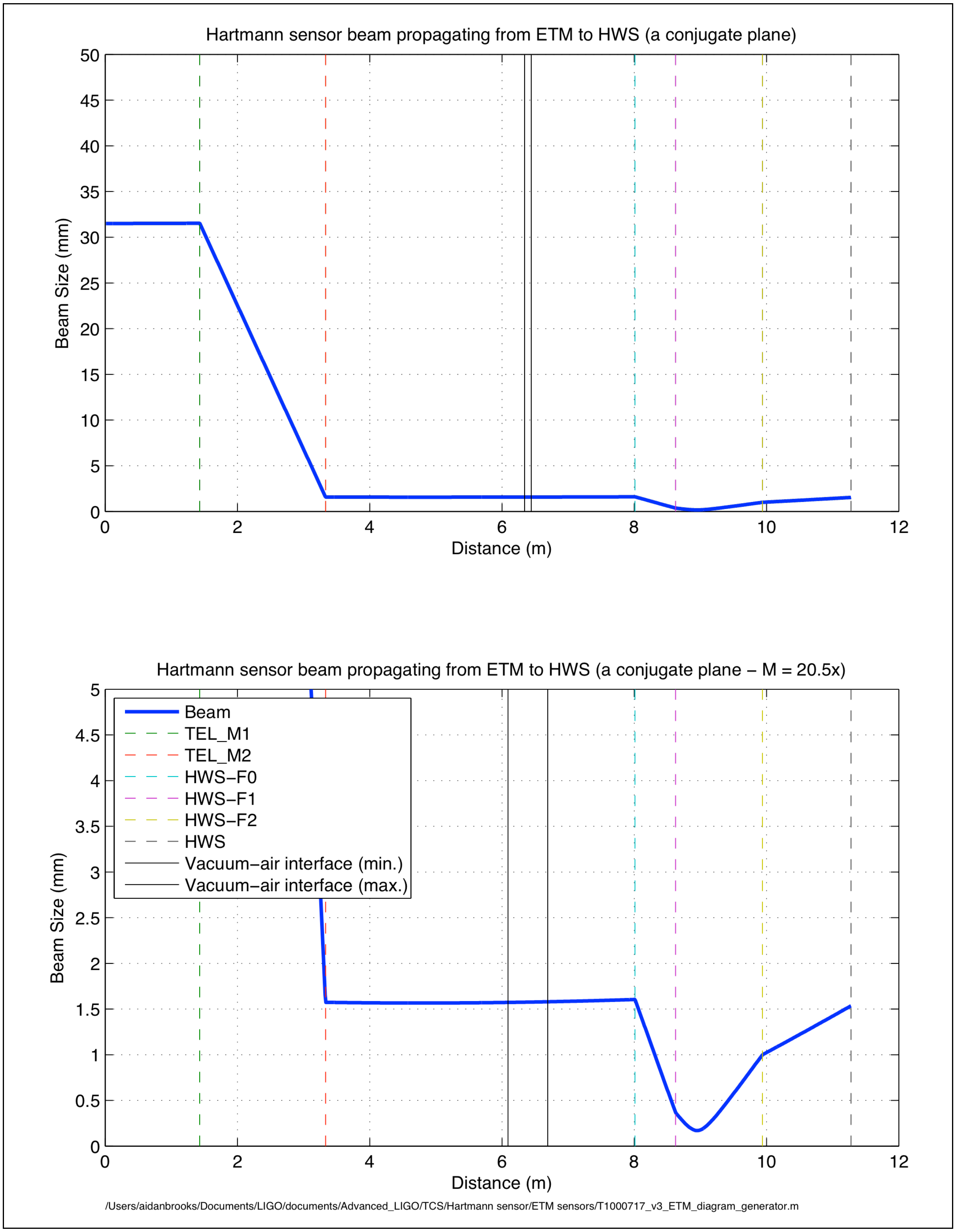

Figure 6: Beam size of the HWS probe beam propagating from the ETM to the HWS

2.4 Secondary beam propagation to HWS

After the Transmon telescope, the secondary beam is propagated directly to the HWS. This is shown in Figure 7.

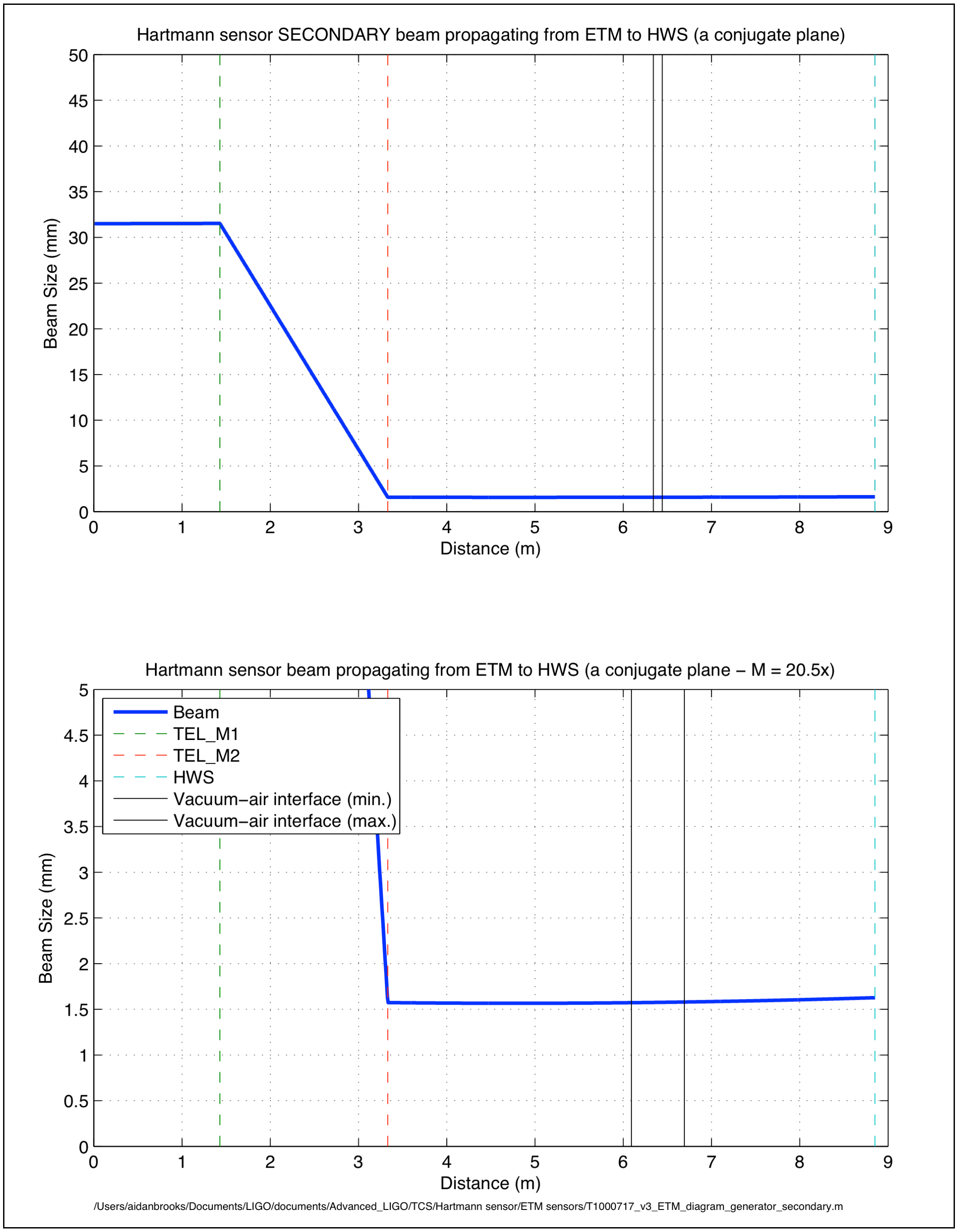

Figure 7: Secondary beam propagating from ETM AR surface to HWS.

3 Optical Layout

The optical layout for the ETM-HWS, ***for the One Arm Test***, is detailed in D1100607: ALS Y-End Station Optical Table Layout. That diagram is reproduced here in Figure 8. The layout for ***general Advanced LIGO*** end station in-air tables will be very similar but will be influenced by the results of the One Arm Test and also by the exact location of the remaining Transmon Tables in their respective BSC chambers.

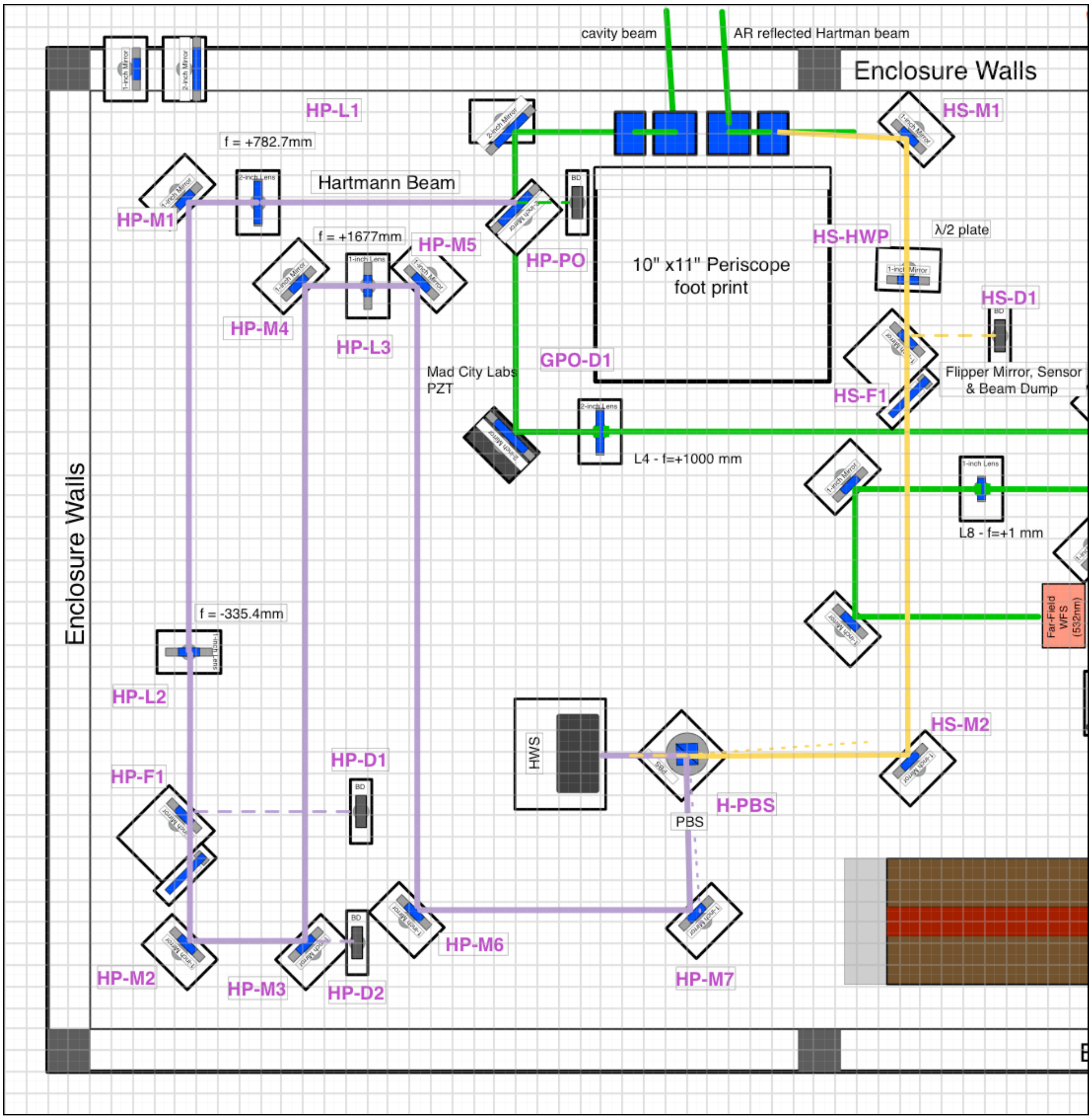

Figure 8: The optical layout for the ETM HWS for the One Arm Test. The in-air table has been cropped to only show the HWS region.

4 Other issues

4.1 Thermal defocus

The residual thermal defocus at the HWS is approximately 3.5E-4 m^{-1} K^{-1}. This is below to the acceptable limit of thermally induced defocus is S = 7.4E-4 m^{-1}, where S is defined implicitly in the expression for a quadratic wavefront distortion, $W = 0.5\ S\ r^2$. However, approximately 90% of this thermal defocus comes from the thermal expansion of the Transmon telescope. The secondary beam will be able to measure this effect and it can be subtracted off the probe beam measurement for increased accuracy.