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MEMORANDUM

DATE: 16 Mar 2018

TO: Fred Raab
CC: Calum Torrie
FROM: Dennis Coyne
SUBJECT: **Vertex to end station chamber positioning requirement**
Refer to: LIGO-T1800103-v1

Contents

1   Question
At a recent meeting at IUCAA regarding interfaces between the vacuum system and the civil construction, the following question was posed by the LIGO-India Chief Architect (Nagaraj):
> *What is the x and y tolerance on placement of the end station BSCs relative to the vertex?*

2   Answer
The center of each end-station BSC chamber should be positioned, relative to the BT/VE interface monument, to within ± 2 mm in both transverse directions (laterally and vertically) and to within ± 5 mm of the design position in the axial (longitudinal) direction.

The BT/VE interface monuments should be positioned by survey to within ± 5 mm of the design position in the axial (longitudinal) direction.

The resulting tolerance for the position of the center of the end station BSC chamber relative to the vertex is ± 10 mm.

3   <u>Background and references</u>

Background notes and references supporting this answer are given in the following subsections.

3.1   LIGO's basic approach to setting positional requirements

The LIGO project defined survey monuments (brass plugs set in concrete) at the interface between the Vacuum Equipment (VE) and the Beam Tube (BT), known as BT/VE monuments. The locations of these interface monuments were surveyed by third party surveying companies. Positional requirements for the VE contractor and the BT contractor were then set relative to these interface monuments. By this method the positional tolerances of the BT and VE are not additive.

The original, fundamental alignment/tolerance specification for the vacuum chambers (part of VE) is defined in section 5.1.4 of E940002-x0:

> *All chambers shall be aligned to within ± 2 mm in both transverse directions and ± 25 mm of the design position in the axial direction. All other vacuum chamber and spool dimensions shall be ± 3mm, ± 1 degree and ± 3 mm per 3 m section of tube.*

(These requirements are repeated in PSI document V049-2-095, "Design Goals/Requirements Procedure", Spec. Reference 5.1.4. This document can be found within C960965-x0, file C960965-01-V.pdf, pg. 49 of 522). These chamber positional requirements are relative to the interface survey monuments.

The basic procedure for pre-alignment/positioning of the chambers using a dolly, for the purpose of establishing the location of drill holes for embedded bolts, and then final alignment with the dolly is described in sections 2.4 and 7.2 of C960967-x0, revision-03, "LIGO Vacuum Equipment, Final Design Report - Installation/Commissioning, Volume IV"

3.2   Chamber placement accuracy

The as-built, actual chamber positioning accuracy, relative to the BT/VE monuments, is typically[1] < 2 mm longitudinally.

3.3   Survey accuracy

In order to state the positional accuracy of the end station chamber relative to the vertex, we need to know the accuracy of the surveyed interface monuments. The survey requirements are defined in D961249-x0. The distance from the vertex to a marker/monument at the location of the center of the end station BSC chamber is required to be 4km ± 5 mm. The requirement for the distance from the vertex to the BT/VE interface at the end station is 3,988,500 ± 5 mm.

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[1] Document C990033-x0 (pg. 4, 32) gives the as-installed end station BSC positions for LLO (didn't find the LHO equivalent document):
LBSC4 (LLO, X-end): 0.3 mm lateral, -1.6 mm longitudinal
LBSC5 (LLO, Y-end): 0.2 mm lateral, 0.3 mm vertical, -0.2 mm longitudinal

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The survey results for the LHO BT/VE interface monuments is given in document D961471-x0. The distance from the vertex to the BT/VE interface monument is found to be correct to within ~ ± 3 mm.

An analysis of the survey results is given in T980044-v1. However in this analysis of a best fit to the BT supports, the BT/VE axial locations were taken at their theoretical valves, with the exception of the nearest ones to the vertex (which were found to be ~3mm in error).

3.4   Optical measurement of the arm cavity length

A two "color" (frequency) approach was used to measure the length of the Fabry-Perot X-arm length in Initial LIGO (iLIGO). The intended X and Y Fabry-Perot arm cavity lengths for iLIGO (E000053-x0) were 3,995,055 mm. The actual lengths[2] were {X, Y} = {3,995,084.18, 3,995,044.37} mm. The X-arm was 29 mm long, and the Y-arm was 11 mm short, of their intended lengths. These errors include the placement of the detector equipment (not just the vacuum equipment).

3.5   Subsequent detector system implicit requirements?

Since the Advanced LIGO (aLIGO) detector system was designed and built after the vacuum system and facilities/buildings, it is reasonable to consider whether the aLIGO detector system:
   a) relied upon the actual chamber positions rather than the theoretical positions, or
   b) is not capable of accommodating the positional tolerances of the original specification.

Regarding a), the detector design is not biased to take into account known positional errors of the vacuum equipment.

Regarding b), the mechanical assembly can accommodate easily 30mm (or more) axial shift in the position of the End Test Masses (ETM) and their associated suspension assemblies (as shown in E1200345).

However the RF frequencies employed by the interferometer sensing and control system set limits on the allowable arm cavity length range. The modulation frequencies and arm length were picked (T1000298) for aLIGO such that the f1 sideband (9 MHz) is 500 Hz away from exactly anti-resonant in the arms, and thus the f2 sideband (45 MHz) is 2500 Hz away from anti-resonant. This guarantees that the f2 sideband is far (about 16 kHz) away from resonance, which minimizes the arm-cavity phase shift the f2 sideband sees. A tolerance in arm cavity length of ± 30 mm results in f1 being either 433 Hz or 567 Hz from exact anti-resonance, for +30 and -30 mm shifts respectively. The f2 sideband is 16,603 Hz and 15,920 Hz from resonance, for +30 and -30 mm shifts respectively. These frequency offsets are more than adequate.

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[2] iLIGO electronic log entry:
http://ilog.ligo-
wa.caltech.edu/ilog/pub/ilog.cgi?group=detector&date_to_view=05/14/2003&anchor_to_scroll_to=2003:05:14:17:07:59-rick

Although the modulation frequencies could in principle be shifted/adjusted to adapt to a wide range in arm length, the resonance conditions for the power and signal recycling cavities would need to then be adjusted; this is not practical since many optics are involved and there is in general small tolerance for shifts in the locations of the recycling cavity optics.

3.6 Conclusion

With survey marker tolerance of ± 5 mm and as-built placement of the chamber center to ~ ± 3 mm, the resulting arm length error was up to ~30 mm due to tolerance build up in the overall assembly. This magnitude of arm length error is tolerable, with some additional margin. However if the original chamber axial location tolerance (± 25 mm) was realized (rather than the as-built error of ~ ± 3 mm) there would be considerably less margin. Since the chamber are capable of being placed to a tighter tolerance, I suggest an axial tolerance for chamber placement, relative to the interface BT/VE monuments, of ± 5 mm.