

Understanding LIGO Coordinate Systems

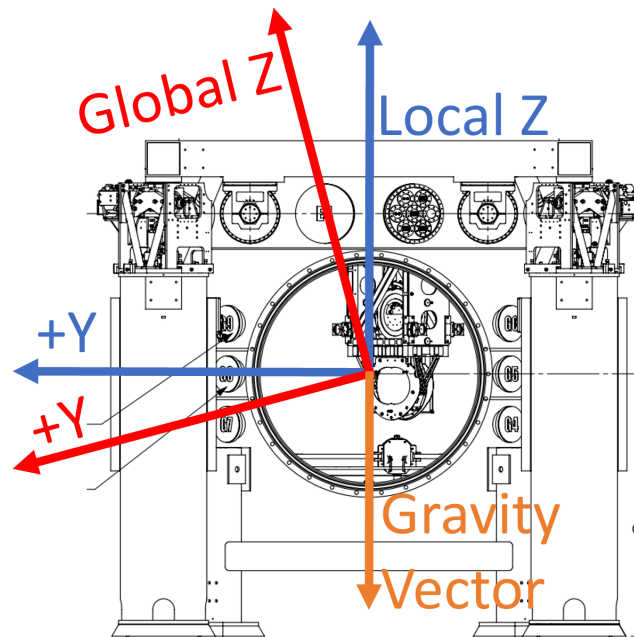
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1 - Introduction

Since its inception, defining and understanding the coordinate systems of LIGO has been a difficult task. Historically, there are two main coordinate systems that have been used: LIGO Global and LIGO Local. Both coordinate systems originate at the center of the BSC2 chamber, but are slightly rotated with respect to each other. For LIGO Local, the Z vector is opposite Earth's gravity vector at BSC2 and the X and Y vector run along the beamtube but do not perfectly follow the beamtube pointing like LIGO Global. For LIGO Global, the X and Y vectors follow the beamtube center line. As a result, the Z vector is not directly opposite of the Earth's gravity vector. One way of thinking about LIGO Global is it is the error of the arms off of a perfectly level plane.



* Image of BSC2 and Beamsplitter - view looking toward +x direction. Global tilt greatly exaggerated

LIGO Local and LIGO Global Coordinate Systems make up the majority of the work done at LIGO. The further away you get from BSC2, the LIGO Local Z vector gets more misaligned with the Earth's gravity vector. This proves troublesome for setting up various equipment. Most of the survey equipment and interferometric equipment requires it to be level where it is set up and not some far off coordinate system tied to BSC2. This requires thinking in a third coordinate system, Device Level Plane, where the Z vector is above the device, opposed to gravity, and X and Y generally follow the arms much like LIGO Local does at BSC2.

2 - LIGO's many Coordinate Systems and why we have them

2.1 - LIGO Local (Building Local)

LIGO Local's origin is centered in the middle of the BSC2 chamber. The XY-plane of LIGO Local is perpendicular to gravity at the origin.

LIGO Local treats each VEA as one flat space. Within a 50m radius around the origin, the orientation of Earth's gravity vector does not change drastically. There is a max deviation of $\sim 0.2\text{mm}$ in Z at 50m distance from origin if you consider the change in gravity or consider the LVEA one flat space. This is considered acceptable for any positioning work done in the VEAs, so it is safe to assume the VEA is one flat space. For pointing, especially for optics in the LVEA that are all within 23m radius from origin, the curvature of the earth pointing accommodation in pitch is within $43.8\mu\text{rad}$ (or 0.65 arcsec), which is negligible. For the core corner optics (BS and ITMs), the errors in the approximation location and pointing accommodation are typically small because they are close to the origin (within 10m).

Historically, most of the surveying done in the LVEA has been done in LIGO Local. This is because the traditional surveying equipment (e.g. auto level, theodolite) were leveled to the Earth's gravity at that device's location. Outside of the LVEA, LIGO Local starts introducing errors, especially in pointing and height locations/measurements. For example, while installing the Filter Cavity beamtube sections (total length of $\sim 300\text{m}$), the curvature of the earth was taken into account in theodolite's angle and height to properly set the beamtube and have correct alignment. Another example is the FC2 optic at HAM8 $\sim 279.4\text{m}$ in +y direction needs $\sim 43.8\mu\text{rad}$ pitch adjustment to the global pitch value, compared to where the pitch adjustment is small and negligible within the LVEA (mentioned above).

2.2 - LIGO Global

Per its name, LIGO global is a one unified coordinate that theoretically works for all locations (Corner Station, End Stations,...). LIGO Global's origin is centered in the middle of the BSC2 chamber (same as Corner Station LIGO Local origin) and its X and Y vector follow the beam tube center line. Since Hanford and Livingston beam tubes have different angles due to different local topology and construction, the exact angle of the beam tubes are different from site to site.

LIGO Global ties the corner station to the end stations. By following the angle of the beamtube or global X-Y axes, the focus is on the overall assembly and the pointing of optics without concern about local gravity. Because LIGO Global takes a more holistic

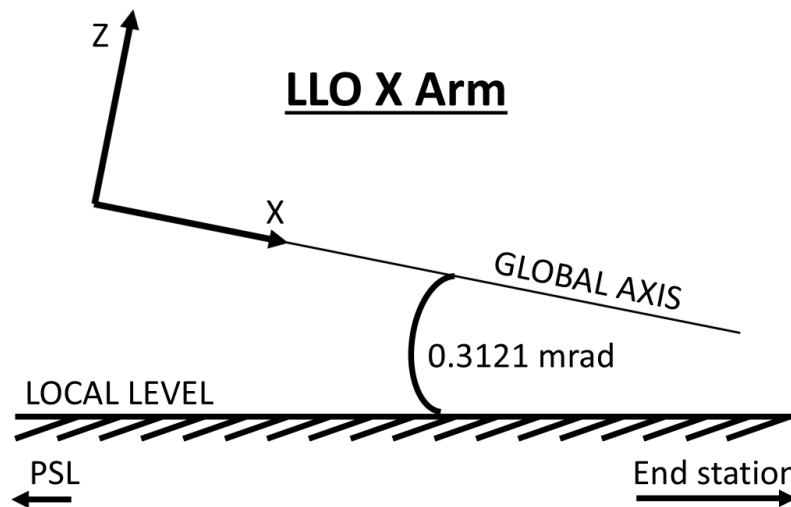
approach to the Interferometer, it was made to be the coordinate system that **Most CAD Drawings** are done in.

Since, LIGO Global follows the arbitrary pointing angle of the beamtube, it is a hard coordinate system to survey in with traditional survey equipment. This creates somewhat of a problem since all of the CAD models for the Interferometer are in LIGO Global and all survey work is performed in LIGO Local. This led to the need of conversion of numbers from one coordinate system to the other, and potential errors when miscommunication arises (i.e. LLO's HAM7 height). However, the current surveying method using FARO Laser Tracker has its own CAD software that works in any arbitrary coordinate system and can measure/compare objects to the CAD model in real time. In other words, one can now survey objects directly into LIGO Global coordinates without any conversion needed.

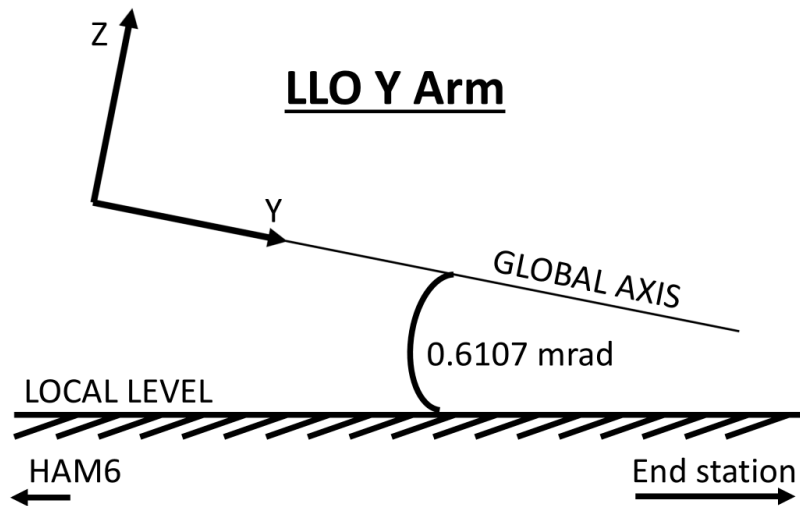
Below are the angle of the beamtubes between global and local axes:

2.2.1 - LLO

The angle of the X-Arm Beamtube is $\theta_{XLL0} = 0.3121 \text{ mrad}$

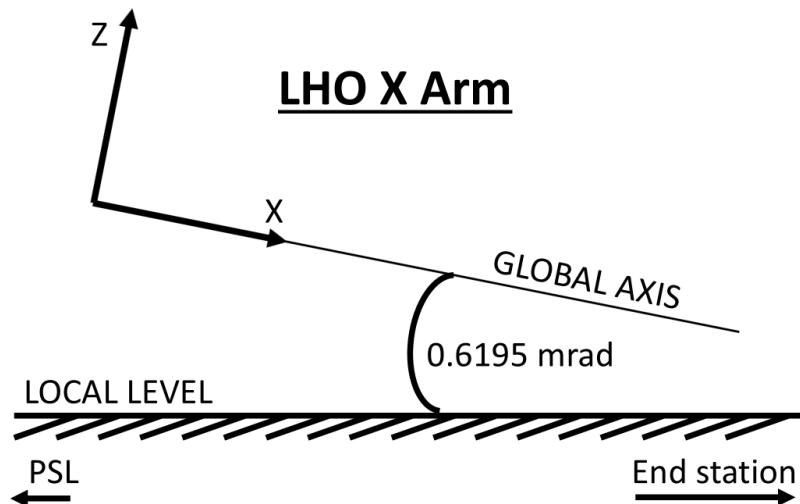


The angle of the Y-Arm Beamtube is $\theta_{YLL0} = 0.6107 \text{ mrad}$

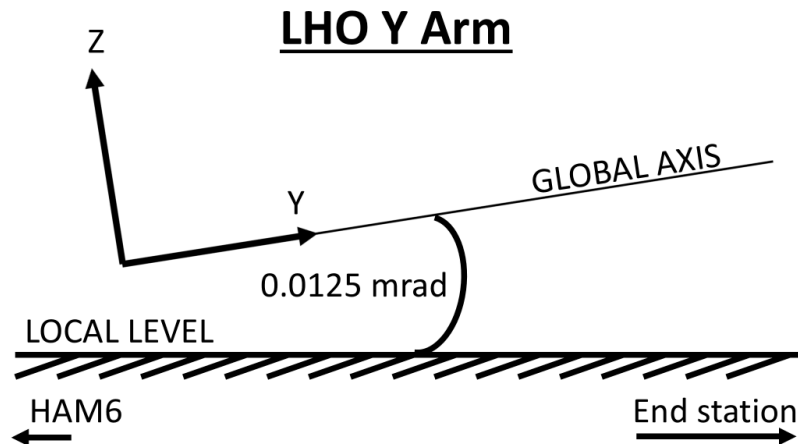


2.2.2 - LHO

The angle of the X-Arm Beamtube is $\theta_{XLHO} = 0.6195 \text{ mrad}$

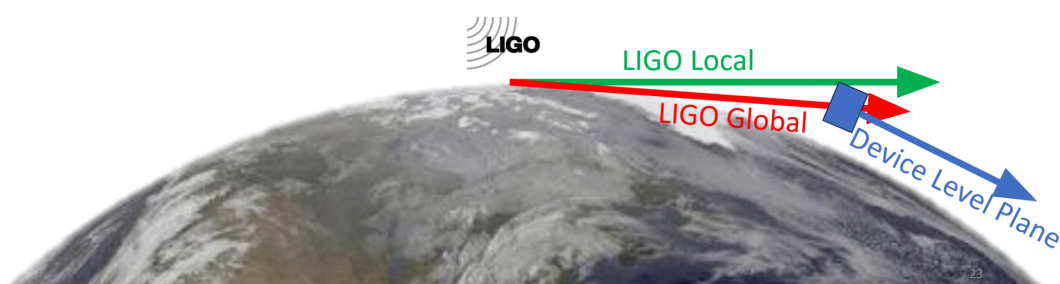


The angle of the Y-Arm Beamtube is $\theta_{YLHO} = -0.0125 \text{ mrad}$



2.3 - Device Level Plane (a.k.a Local Local, True Local, Chamber local,...)

The Device Level Plane is a coordinate system separate from the Interferometer where the Z vector is opposite Earth's Gravity vector at any arbitrary location you would set up some equipment. The X and Y vectors could be aligned with the general X and Y beamtube but they won't have the same pointing. While this is not really a defined coordinate system in any LIGO documentation, it is an important concept for understanding the potential pitfalls of both LIGO Global and LIGO Local.



The Device Level Plane is essentially the coordinate system that traditional survey equipment like the Theodolite or Autolevel uses. In the LVEA, the Device Level Plane can deviate from LIGO Local, as the XY planes of each coordinate system are not exactly parallel. The further the device is set up from BSC2, the more one has to accommodate for the Device Level Plane to LIGO Global, especially in height and

pointing, to make sure you maintain the proper pointing. This was roughly explained in the sections above.

In the past, technical drawing's "Local CS" are either LIGO local (or sometimes LIGO global - varies between documents) shifted/translated to to the center of the chamber of interest, e.g. HAM6 chamber center. Therefore, the theoretical location of components inside a specific chamber are relative to that chamber's center. The discrepancy is coming from 2 factors. One is the actual beamtube height transferred around the building, which is about 0.2mm in Z for 50m distance, and the other is the assumption of gravity vector is negligible within LVEA, which is under 0.1mm in Z for the furthest chamber (HAM1 or HAM6 ~23m away from BSC2 center). The total Z discrepancy is sub 0.3mm with the assumption that the building is one flat surface.

Take HAM8 ISI that is ~300m away from the LVEA as an example. The ISI table top needs to be positioned Globally to make sure that it is in the right location but in reality, it was positioned using devices that are leveled Locally with respect to Earth's gravity vector where it sits rather than at BSC2. As a result, the CAD drawing for HAM8 says that all the support tubes for HAM8 are at the same height globally but in reality, they are at the same height locally. Ultimately, the ISI was set so that the ISI center is at the global position from CAD, but the table surface is flat in the Device Level Plane or relative to the Chamber local location. Note that another assumption is that the Device Level Plane and Local chamber level plane are the same because they are close to each other, typically within about 5m of each other.

2.4 - End Station Coordinate Systems

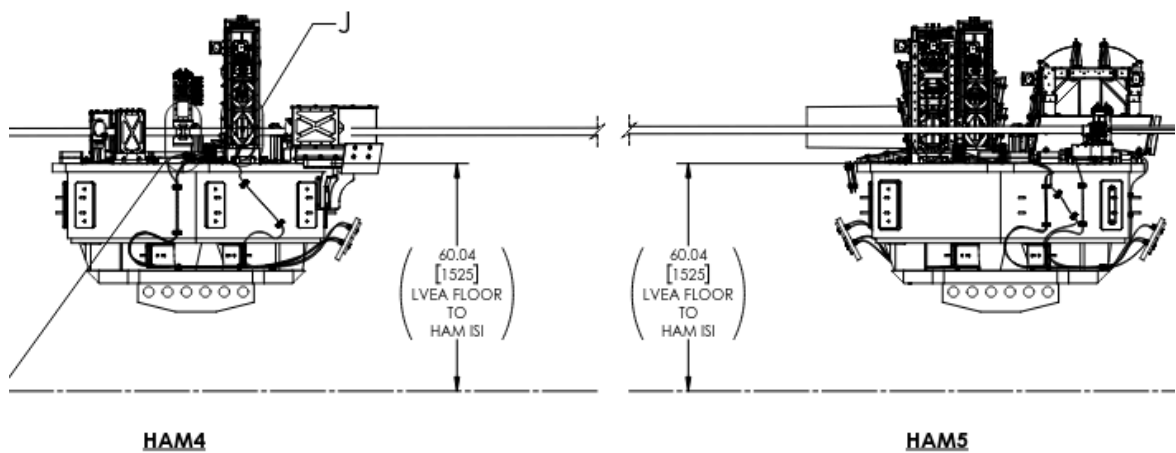
The End Stations are somewhat unique relative to the corner. The End Station VEAs are relatively small compared to the LVEA and the BSCs are sparsely populated. Because of this, they get surveyed in their own Local Coordinates that are separate from each other and the corner but propagated off of original monuments. Because of these factors, the End Station gets treated mainly in its own Local coordinate system.

2.5 - Other coordinate systems you'll run into around the DCC

When surfing the DCC, nearly all documents have dimensions in LIGO Global coordinates. This is because most of the CAD drawings are in LIGO Global. There are some documents that use LIGO Local coordinates but they are usually clearly specified and most are conversions from LIGO Global to LIGO Local and will have both numbers displayed.

There are two common pitfalls that you can run into on the DCC: Dimensions from the Floor and "LOCAL COORDINATES" on CAD Drawings.

- 1) The LVEA Floor is not perfectly flat despite all of the slab specifications and surveying should only be done from LIGO Local or LIGO Global. Even if the LVEA floor was perfectly flat, it follows LIGO Local and not LIGO Global therefore it shouldn't be included in a CAD drawing. Take for example the graphic in [D1900174-v4](#) detailing the A+ (PLUS), L1 OPTICAL LAYOUT, SW (LLO). If you look at the ISI table top position for HAM4 ([D0900423](#)) and HAM5 ([D0900459](#)), both tables have a global Z of -325. The tables are separated by approximately 16 m and while they are level globally, 16 m at LLO in Y corresponds to nearly 1 cm of height difference between the two chambers when measured locally. Therefore the statement that both ISI tables are 1525 mm off of the floor is incorrect.



Floor measurements like the one displayed above should be avoided as they rarely take into account Global/Local conversions

- 2) Many drawings on the DCC define "LOCAL COORDINATES" that are used to make it easier to align things such as a suspension on the ISI table. These "LOCAL COORDINATES" are sometimes translated from LIGO Global Coordinate Systems and sometimes translated from LIGO Local Coordinate Systems. There is a ~0.4mm discrepancy between chamber local CS translated from LIGO Global vs LIGO Local, but it is a Local CS coordinate definition consistency issue between drawings.

PRM	X	Y	Z
HAM2 Center Global	-20122.00	0.00	0.00
HAM2 Center Local	-20122.00	0.00	6.28
PRM Point Global	-20189.60	-628.00	-104.10
PRM Point Local	-20189.63	-628.06	-97.42
PRM Point Global Shifted	-67.60	-628.00	-104.10
PRM Point Local Shifted	-67.63	-628.06	-103.70
PRM Point true Local	-67.63	-628.06	-103.76

3 - More calculations/examples - LIGO Global vs LIGO Local

It is relatively easy to convert between Global and Local coordinates. In past documentation, it was suggested to convert using the following assumption

“In the LVEA the x and y coordinates are approximated to be the same in both building [LIGO Local] coordinates and global coordinates. The error from this approximation scales with the distance from the origin, but even 4km away the error is less than 1mm.”

Using this assumption, you can convert between LIGO Global and LIGO Local by using the following formula:

$$Z_{Global} = Z_{Local} + X \tan(\theta_X) + Y \tan(\theta_Y)$$

Using this formula, you find that for every meter you move about the LVEA, the correction from global to local is non-trivial. At LLO, 1 meter in X corresponds to 0.31 mm in Z and 1 meter in Y corresponds to 0.61 mm in Z. At LHO, 1 meter in X corresponds to 0.62 mm in Z and 1 meter in Y corresponds to -0.01 mm in Z. These deviations aren't very large at the BSCs but become significant quite quickly as you get further around the LVEA.

The assumption that X and Y coordinates are the same isn't the best once you start moving up or down in Z. It is more accurate to use a 3D rotational matrix to calculate the change from Global to Local. [3D Rotational Equations](#).

Using these equations, you can calculate how much X and Y deviate between global and local when you move vertically in Z. At LLO 1 m off of the beamline in Z, corresponds to a global/local deviation in X by 0.31 mm and Y by 0.61 mm. At LHO 1 m off of the beamline in Z, corresponds to a global/local deviation in X by 0.62 mm and Y by -0.01 mm. Historically, these deviations were not given much thought as they are hard to survey, but this deviation can be picked up with the FARO when surveying floor monuments or ISI support tubes which are over a meter from the beamline.

4 - Some Related Documentation

- aLIGO Coordinate Systems T0900340 <https://dcc.ligo.org/LIGO-T0900340>
- LIGO Coordinate System L950128 <https://dcc.ligo.org/LIGO-L950128>
- aLIGO, Coordinate Systems E1300950 <https://dcc.ligo.org/LIGO-E1300950>
- Determination of Global and Local Coordinate Axes for the LIGO Sites T980044 <https://dcc.ligo.org/LIGO-T980044>