Magnetic and RF coupling

Caveat for all PEM injection results: this is not an exact science. For example, we ignore directionality (e.g. direction to source of sound). We rely on the complexity of the system for scattering, coupling between axes etc. Experience suggests that one sigma uncertainty is about a factor of 2.

LHO

***Summary**: Ambient magnetic fields are unlikely to produce DARM noise at more than 1/10 of the DARM floor. There is high magnetic coupling at the EY satellite box rack. Coupling of self-inflicted magnetic fields in the CS ebay may keep us from reaching design sensitivity unless corrected.*

Radio signals at 9 and 45 MHz would have to be at least 200 times background on the radio channels before they start to show in DARM. Injections at the following unmonitored frequencies were not seen in DARM:
10.000000 MHz
21.500000
24.078360
35.500000
71.000001
79.200000
80.000000

We injected an rf sweep from 9 kHz to 100 MHz to check for coupling from environmental rf to the interferometer. We found no evidence for strong coupling at any frequency within the band. An initial upper limit for coupling is that a signal will need to show up with an SNR of 100 on the RF scanner to have an SNR of 1 in DARM

LLO

***Summary:** Ambient magnetic fields are unlikely to produce DARM noise at more than 1/100 of the current DARM floor. There is high magnetic coupling in the output arm of the LVEA, but not high enough to keep us from reaching design sensitivity.*

Radio signals at 9 and 45 MHz would have to be at least 100 times background on the radio channels before they start to show in DARM.

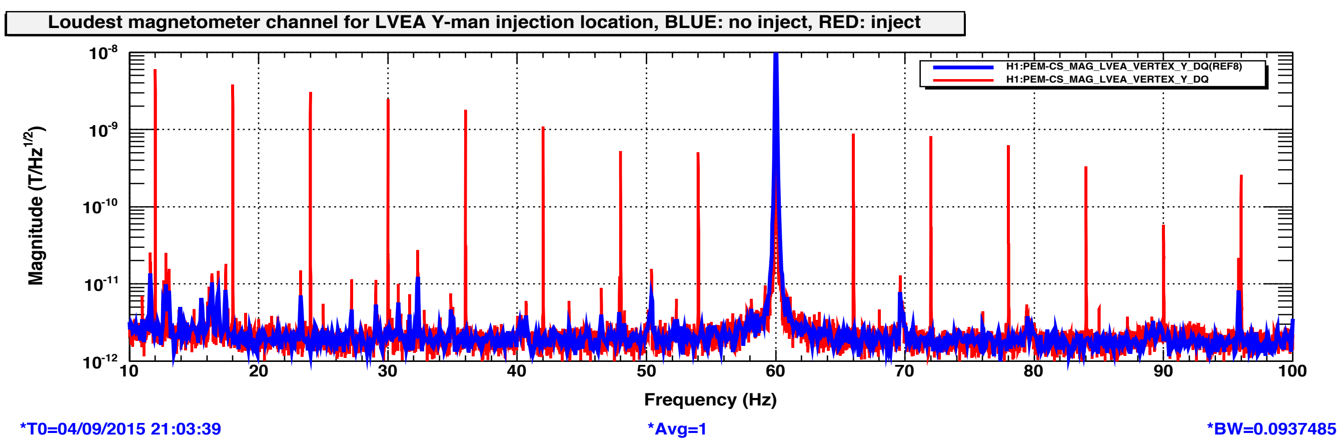
PEM injection, the Coupling Function, and Estimated Ambient contribution.

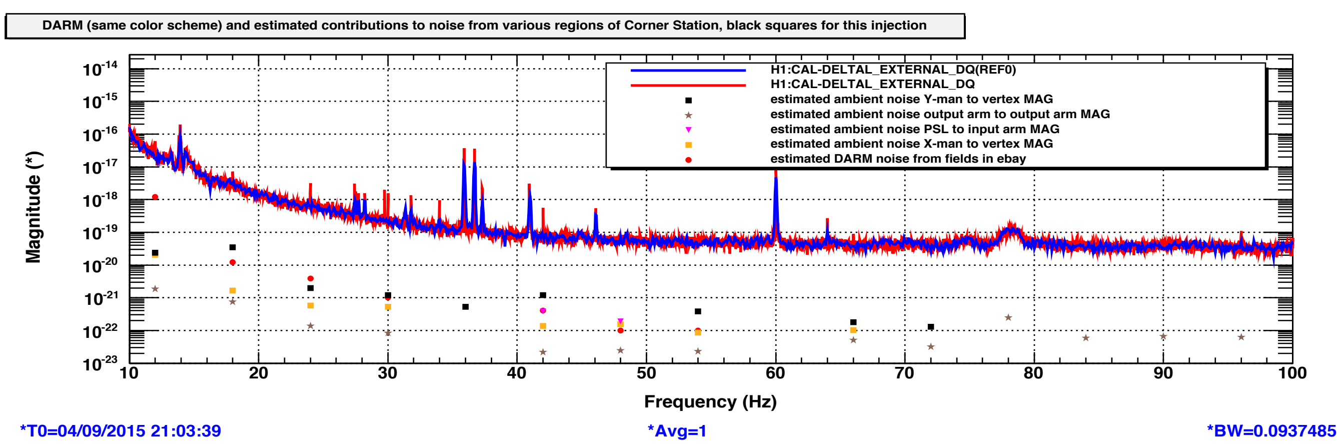
Coupling function (CF) is injection peak value in DARM over injection peak value in sensor (e.g m/T)

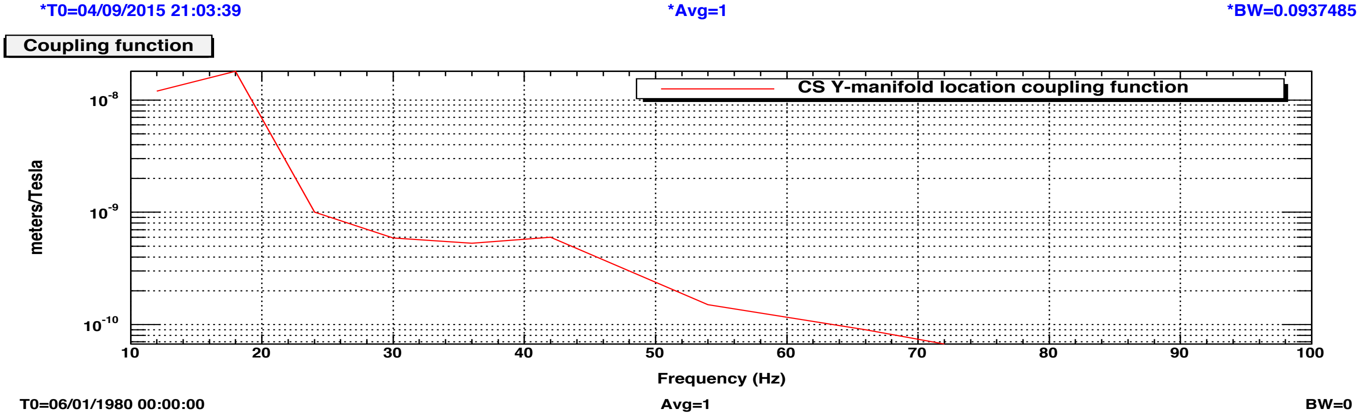
- Used for linear projections
- Used for comparing instrument performance, independent of ambient

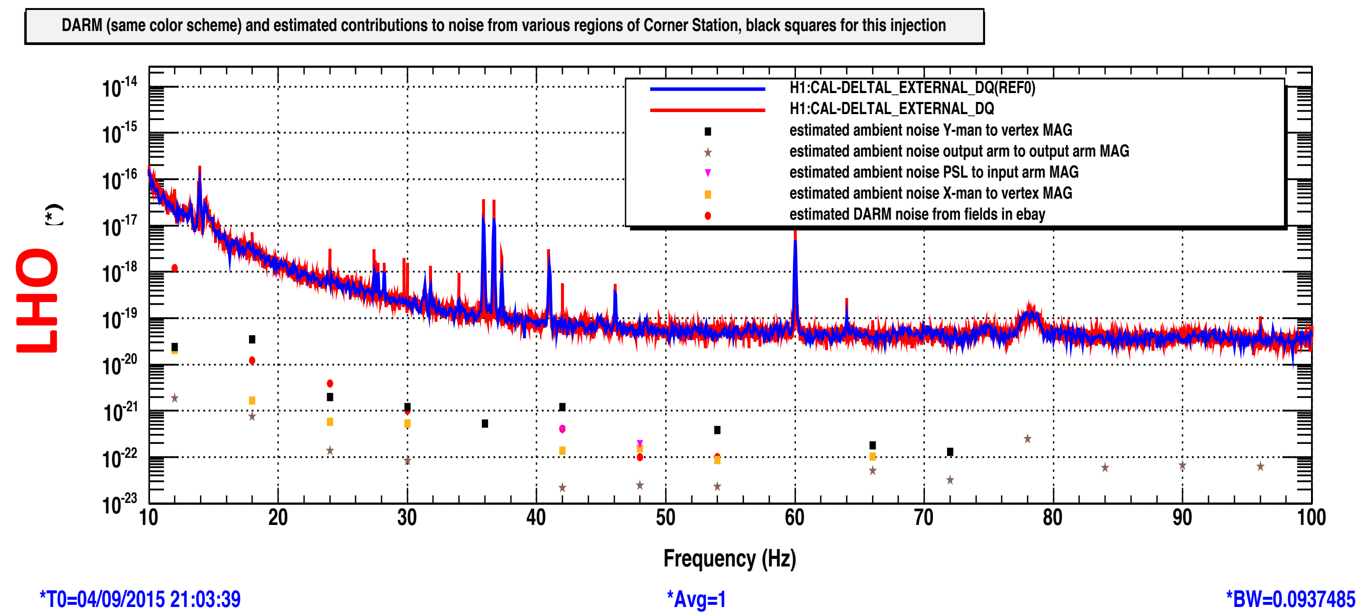
Estimated ambient (EA): coupling function multiplied by the ambient level gives the estimated contribution to DARM of the ambient field assuming linearity

- Useful for answering the question of whether an event seen in a PEM channel was strong enough to produce a given SNR in DARM
- Useful for planning what needs to be done to reach sensitivity goal

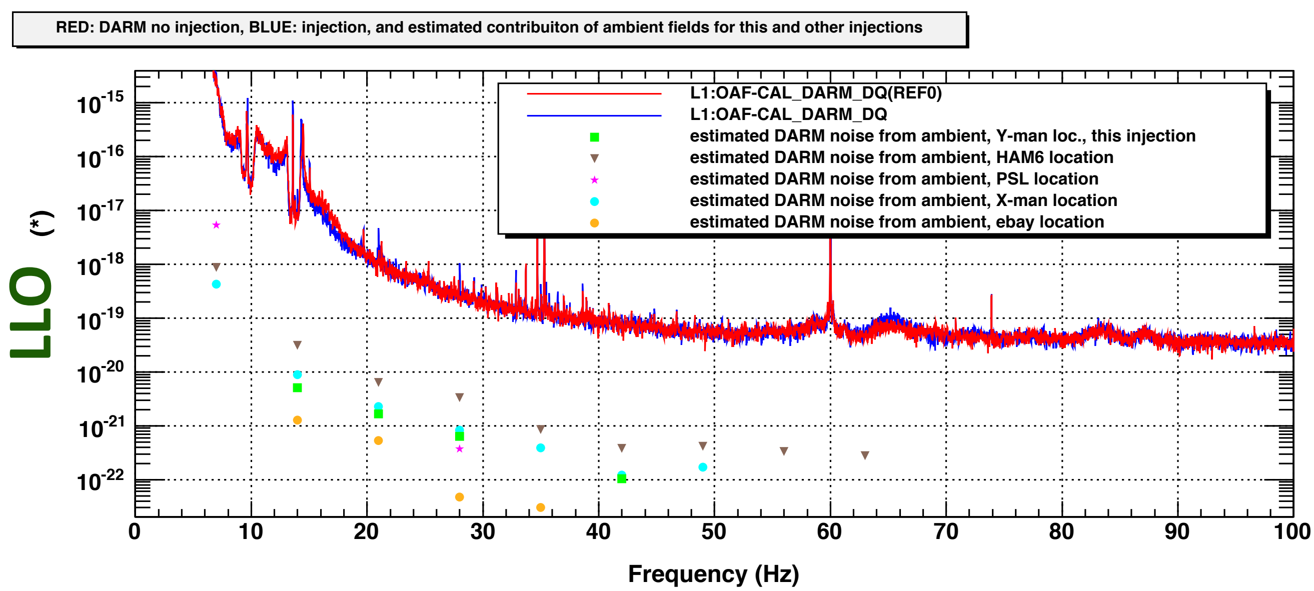








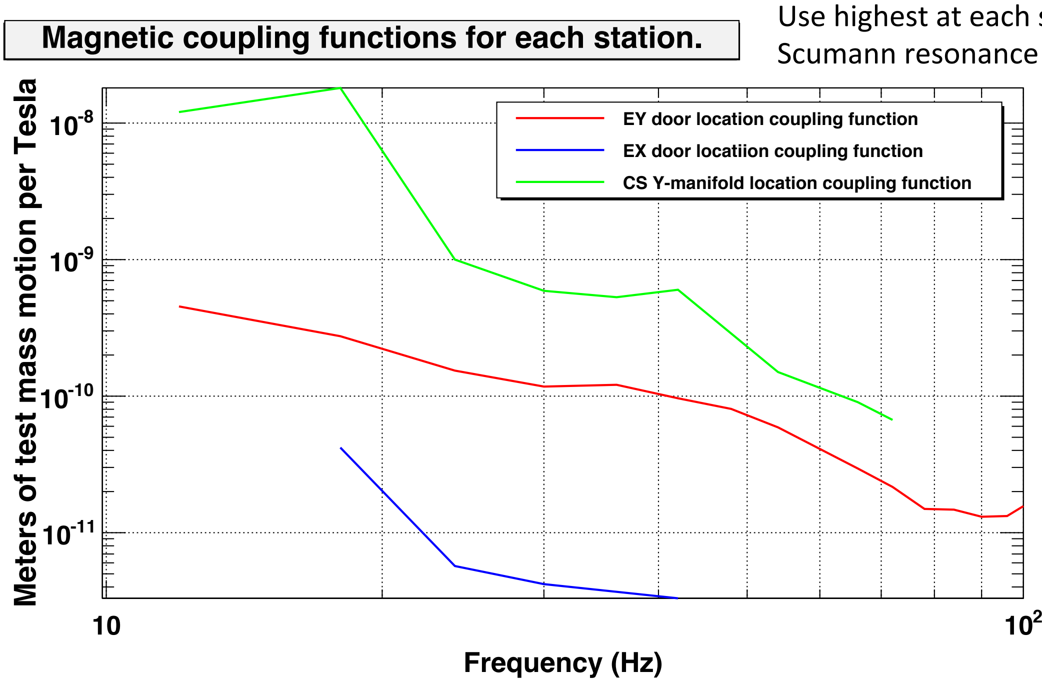
DARM (same color scheme) and estimated contributions to noise from various regions of Corner Station, black squares for this injection
LHO
H1:CAL-DELTAL_EXTERNAL_DQ(REF0)
H1:CAL-DELTAL_EXTERNAL_DQ
estimated ambient noise Y-man to vertex MAG
estimated ambient noise output arm to output arm MAG
estimated ambient noise PSL to input arm MAG
estimated ambient noise X-man to vertex MAG
estimated DARM noise from fields in ebay
Frequency (Hz)
*T0=04/09/2015 21:03:39
*Avg=1
*BW=0.0937485



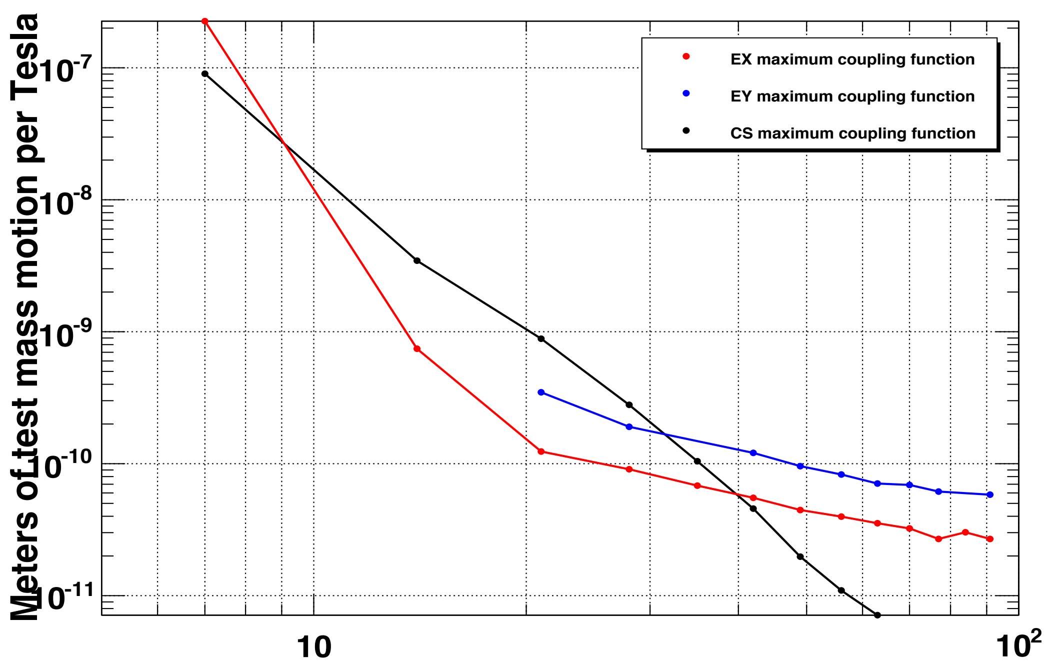
RED: DARM no injection, BLUE: injection, and estimated contribuiton of ambient fields for this and other injections
LLO
L1:OAF-CAL_DARM_DQ(REF0)
L1:OAF-CAL_DARM_DQ
estimated DARM noise from ambient, Y-man loc., this injection
estimated DARM noise from ambient, HAM6 location
estimated DARM noise from ambient, PSL location
estimated DARM noise from ambient, X-man location
estimated DARM noise from ambient, ebay location
Frequency (Hz)

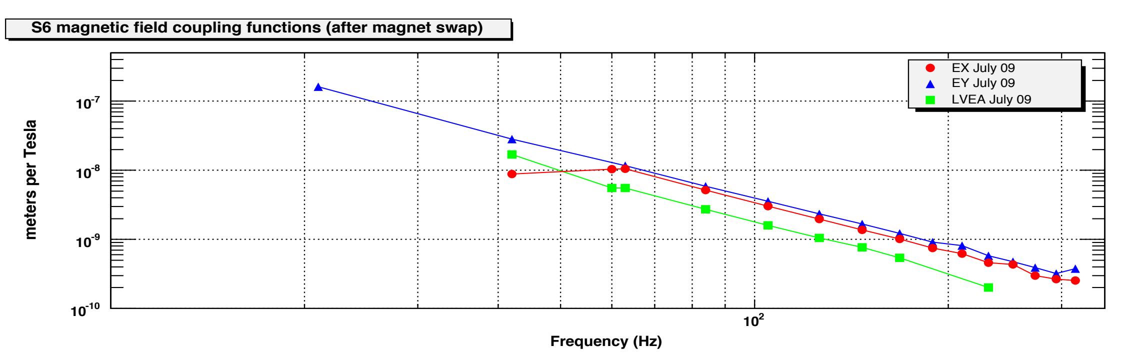
Use highest at each site for
Scumann resonance calculation

LHO



LLO





Vibration Coupling

LHO summary:

Above 50 Hz

At the corner station there are three sites that strongly couple ground or acoustically induced vibrations into DARM: HAM6, HAM2 and the PSL table. The most important vibration sensors for monitoring these couplings are the PSL periscope accelerometer and the GS13s in HAMs 2 and 6. We think that the PSL table vibrations couple mainly by causing beam jitter. Our best guess is that the coupling at HAM2 is similarly produced by jitter. The two steering mirrors and the periscope just upstream of the IMC are not suspended and so are good candidates. At HAM6, sound shakes the blue cross beam, which would shake the table top, especially at ISI suspension resonances. More speculatively, this HAM6 table top motion may couple through the OM or OMC suspensions. The motion of these mirrors would modulate the light, which results in intermodulation with the 4100 Hz OMC dither frequency, producing up and down-converted features as well as direct coupling.

At the end stations, we have not narrowed down the coupling sites or mechanisms. There is high coupling in the EX VEA and the large sidebands that Sheila saw suggest that coupling is via scattering.

Below 50 Hz

At the corner station there is high coupling at certain frequencies between 10 and 50 Hz, but we were shaking the whole building and so we have not narrowed down the coupling sites. At the end stations we did not see coupling in this band. We also found that ground motion at the corner station in the 10-50 Hz band produced noise in at least the 82-100 Hz band of DARM.

LLO Summary:

In the corner station there are a few sites which strongly couple ambient vibration/acoustics above 30 Hz to DARM:

a) The PSL periscope around 490 Hz and 3.3kHz is within a factor of 3 of DARM, likely through input beam jitter.

b) HAM6 ISI couples strongly, where most of the acoustic coupling can be explained through ISI motion. The hypothesis here is that it is coupling either through beam jitter of the OMs and/or OMC suspension. High frequency motion then would couple to the OMC dither line (4.8kHz at LLO, 4.1kHz at LHO) and produce bilinear effects such as down/upconversion to ~100 Hz, 1kHz and 2 kHz. Regression algorythm subtraction (see Filipe's work here) suggest such a mechanism.

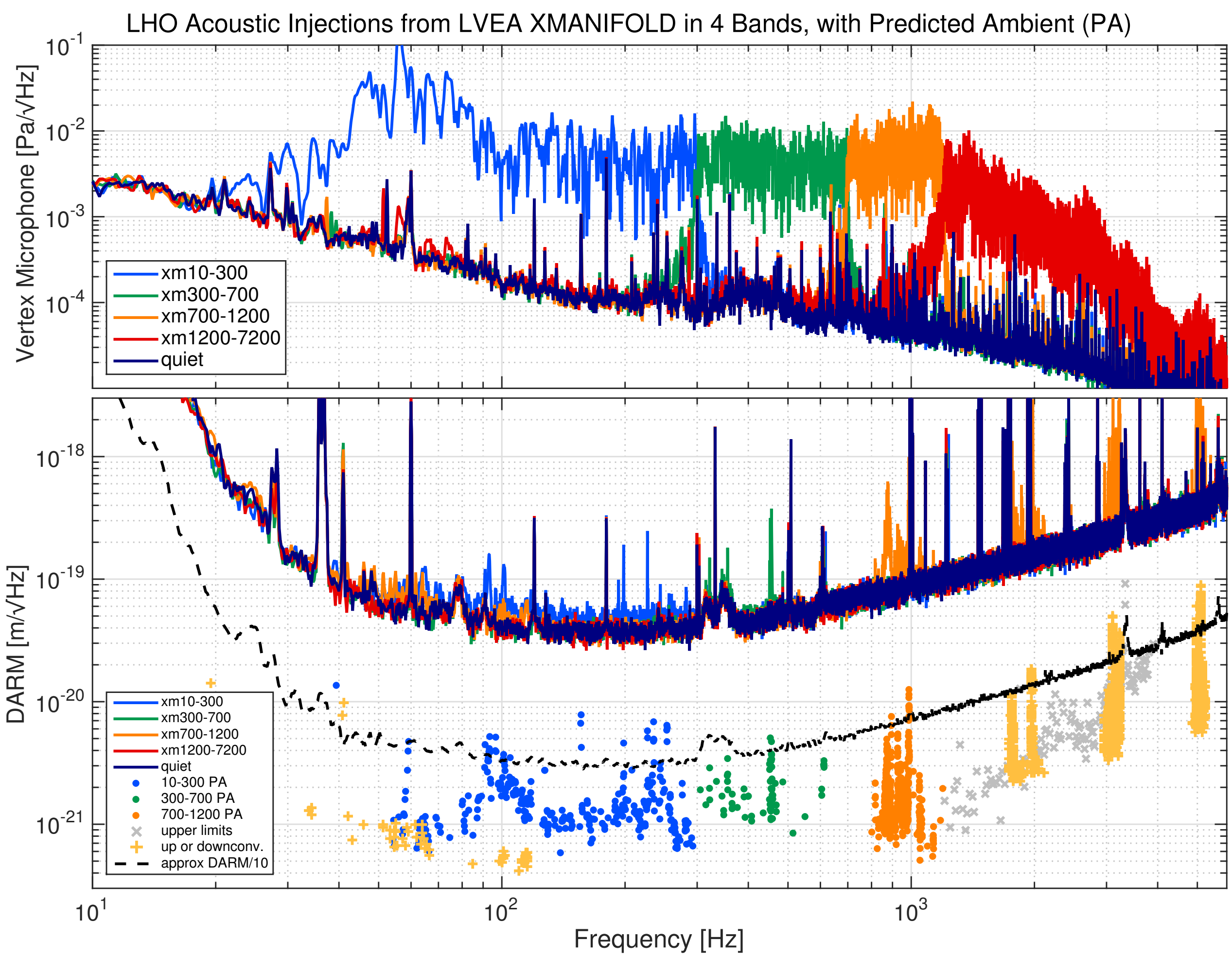
c) There is low frequency acoustic coupling (80-90Hz) within a factor of 3 in DARM where we have not pinpointed a location. If linear, this coupling is likely to be in the output optics area. We should also shake HAM5 for OFI reasons.

d) Last but not least there is a sharp resonance at 455 Hz that we have not located and is not easy to triangulate with current measurements. There are sharper resonances very close to this frequency in HAM3, HAM4 and HAM5 GS13s, so maybe it could be an intermodulation of these three (though no coherence was found).

An EM shaker was used to inject a couple of low frequency points on the floor near the PSL. The signal in DARM was large, one to one depending on which sensor is used (i.e. where the coupling point is). ***We must do more low frequency injection studies****, either with various locations with these EM shakers or renting a tamper like Robert did at LHO (section on "global shaking").* The speakers we have cannot inject much lower than 30-40 Hz, so that region remains untested.

Not all mechanisms are known and the coupling functions calculated may have up to factors of 2 systematics. We propose further tests to clarify.

Vibration coupling, acoustic, injection in bands because of nonlinearity



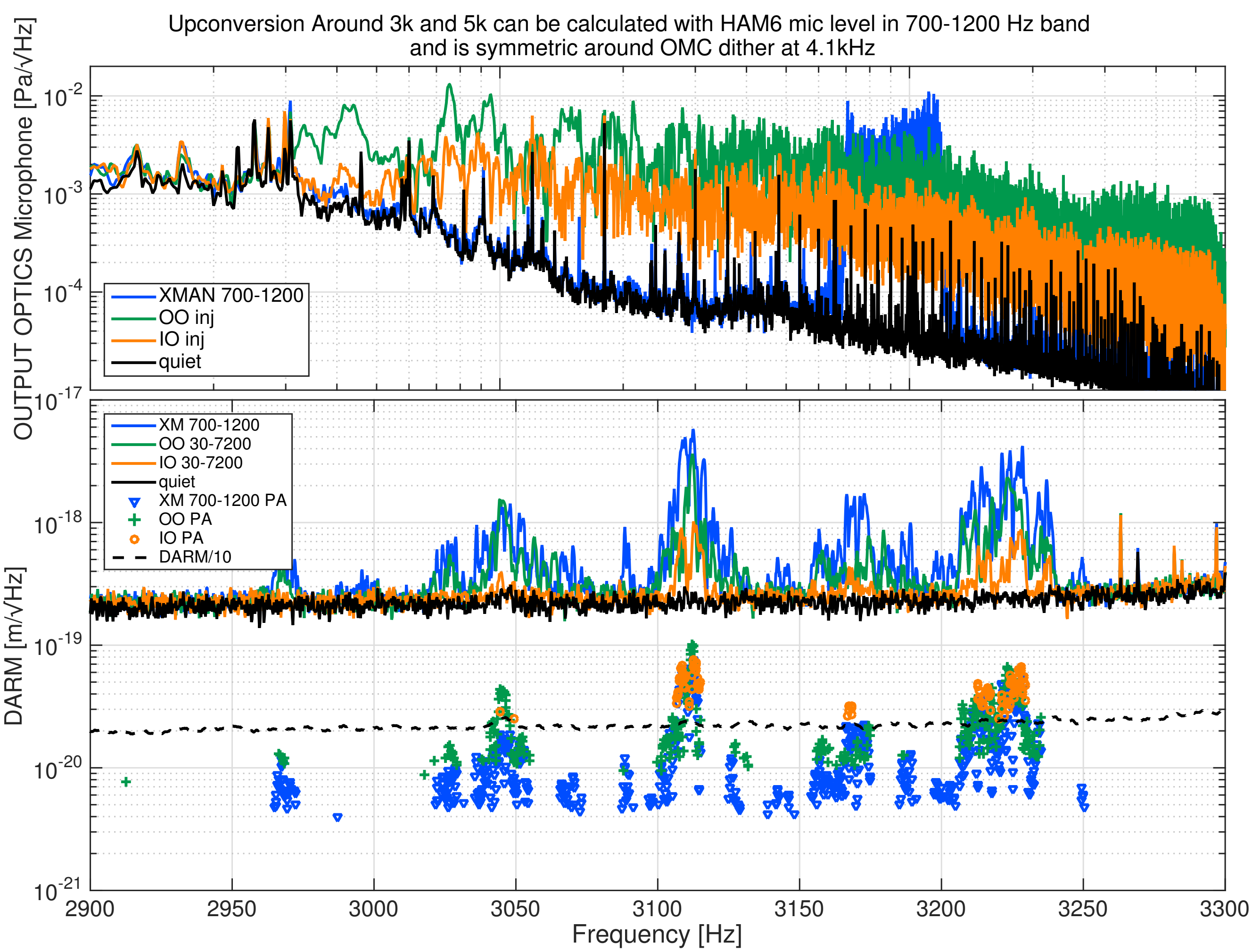
Global injection (e.g. constant amplitude in building)

- Gives approximately what you would expect from distant sources
- Equal field works to factor of 2, scattering

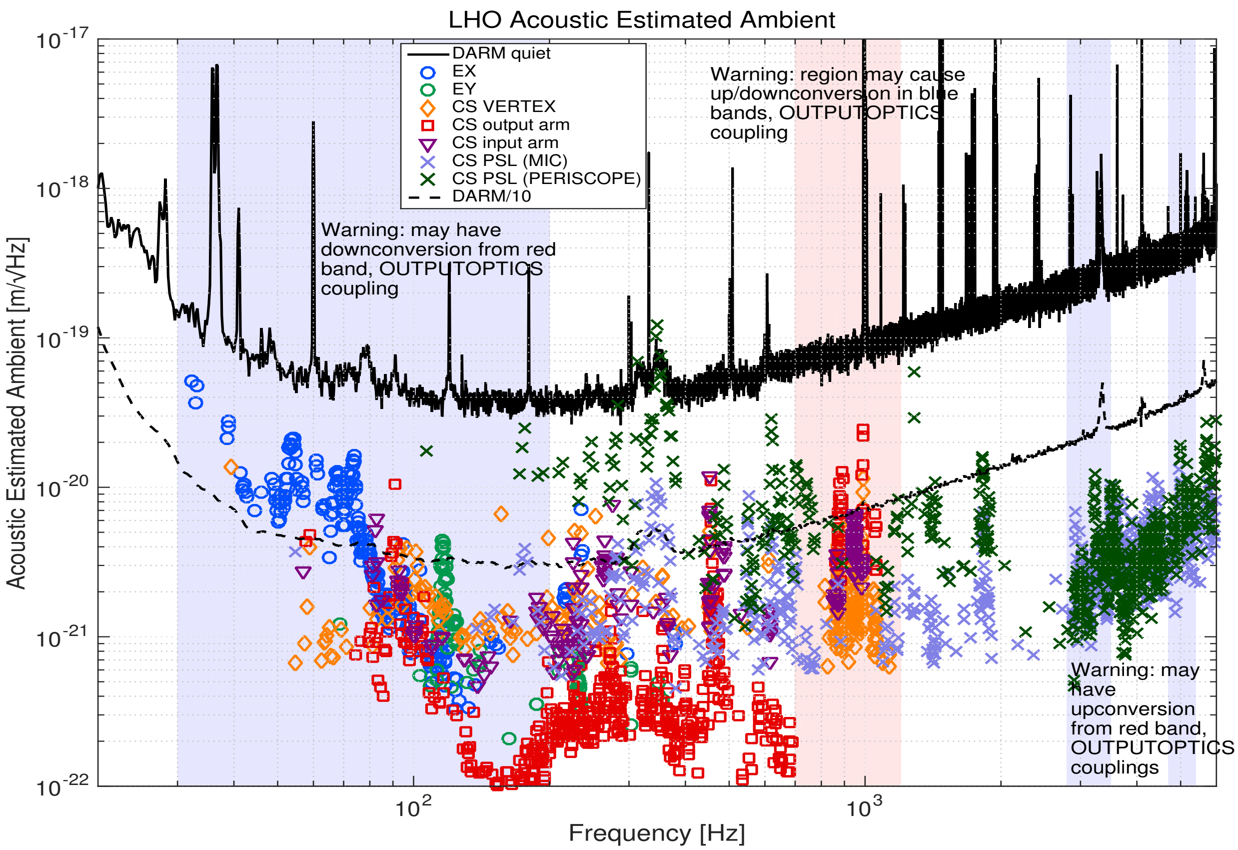
Local injections

- Useful for more local (self-inflicted) sources
- Can be used to locate dominant coupling sites (propagation delays for vibrations are also sometimes used)
- Also used when injectors not strong enough

A sensor at the dominant coupling site will give the same Estimated Ambient level for injections from multiple locations (following example is for upconversion).

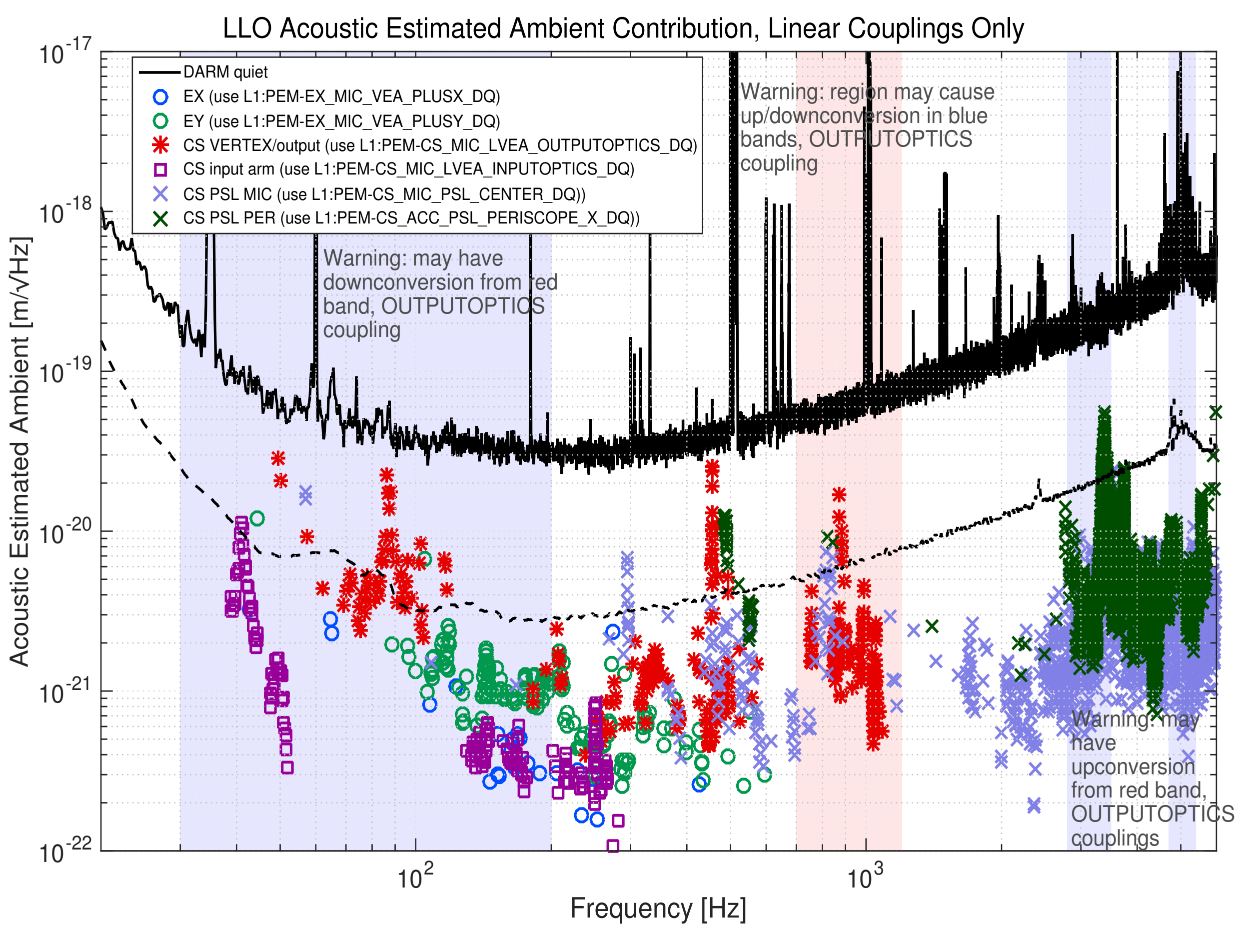


LHO



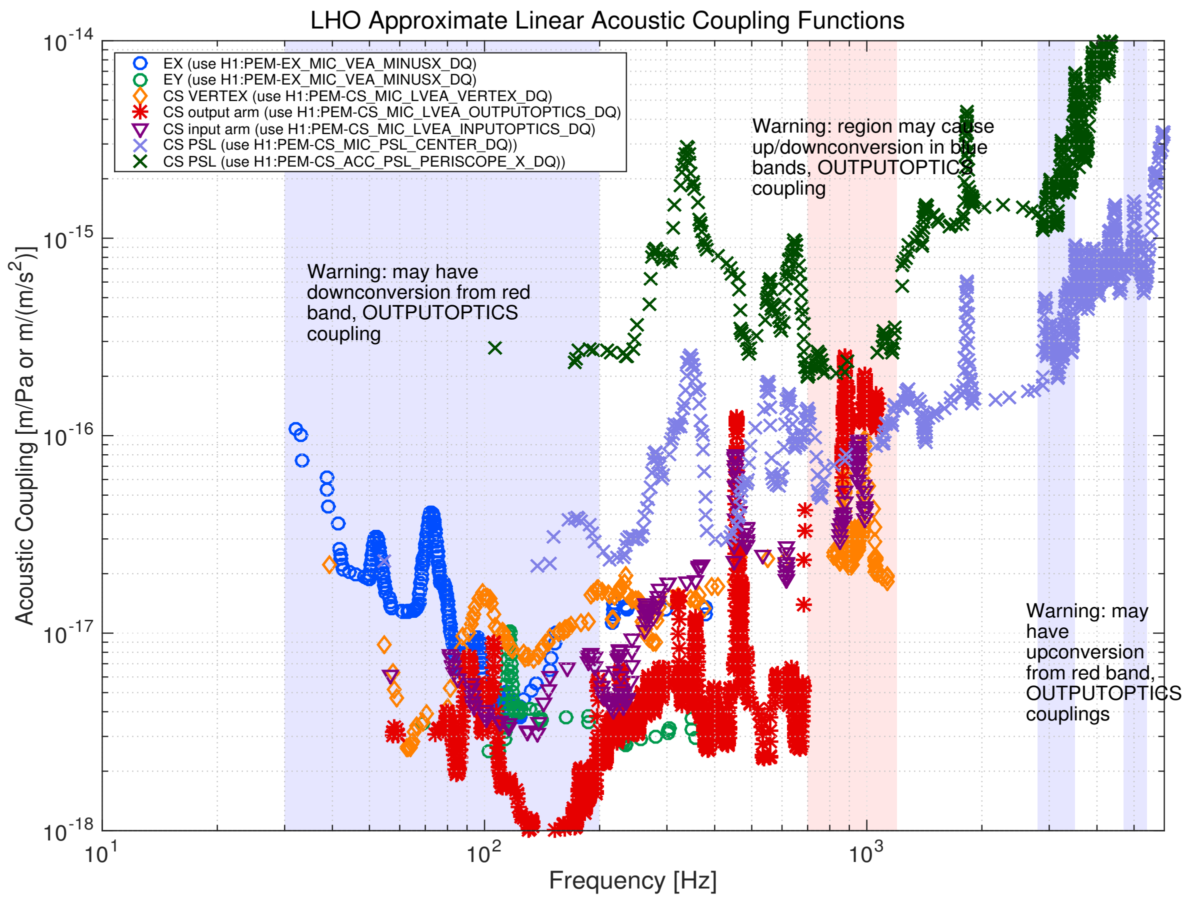
LHO Acoustic Estimated Ambient
DARM quiet
EX
EY
CS VERTEX
CS output arm
CS input arm
CS PSL (MIC)
CS PSL (PERISCOPE)
DARM/10
Warning: region may cause up/downconversion in blue bands, OUTPUTOPTICS coupling
Warning: may have downconversion from red band, OUTPUTOPTICS coupling
Warning: may have upconversion from red band, OUTPUTOPTICS couplings
Acoustic Estimated Ambient [m/√Hz]
Frequency [Hz]

LLO



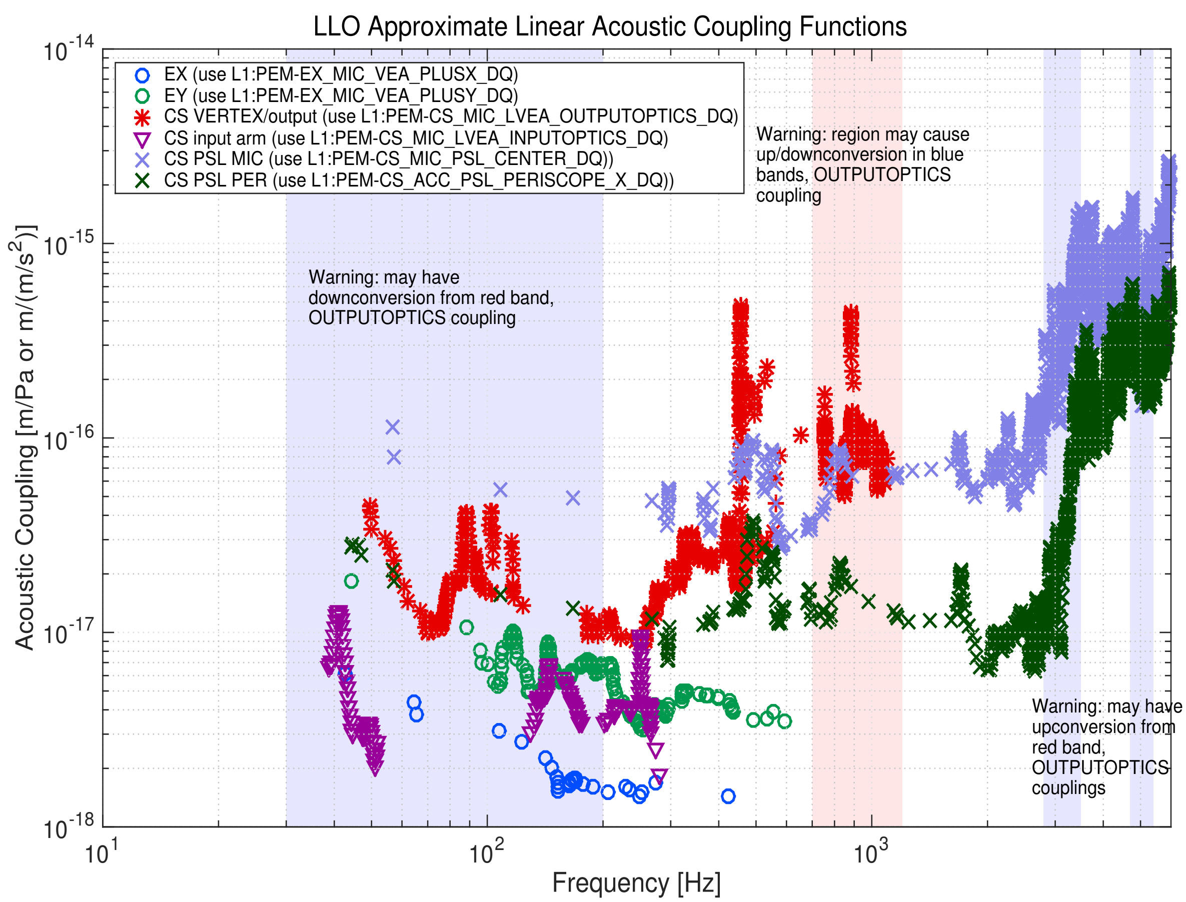
LLO Acoustic Estimated Ambient Contribution, Linear Couplings Only
DARM quiet
EX (use L1:PEM-EX_MIC_VEA_PLUSX_DQ)
EY (use L1:PEM-EX_MIC_VEA_PLUSY_DQ)
CS VERTEX/output (use L1:PEM-CS_MIC_LVEA_OUTPUTOPTICS_DQ)
CS input arm (use L1:PEM-CS_MIC_LVEA_INPUTOPTICS_DQ)
CS PSL MIC (use L1:PEM-CS_MIC_PSL_CENTER_DQ))
CS PSL PER (use L1:PEM-CS_ACC_PSL_PERISCOPE_X_DQ))
Warning: region may cause up/downconversion in blue bands, OUTPUTOPTICS coupling
Warning: may have downconversion from red band, OUTPUTOPTICS coupling
Warning: may have upconversion from red band, OUTPUTOPTICS couplings
Acoustic Estimated Ambient [m/√Hz]
Frequency [Hz]

LHO



LHO Approximate Linear Acoustic Coupling Functions
EX (use H1:PEM-EX_MIC_VEA_MINUSX_DQ)
EY (use H1:PEM-EX_MIC_VEA_MINUSX_DQ)
CS VERTEX (use H1:PEM-CS_MIC_LVEA_VERTEX_DQ)
CS output arm (use H1:PEM-CS_MIC_LVEA_OUTPUTOPTICS_DQ)
CS input arm (use H1:PEM-CS_MIC_LVEA_INPUTOPTICS_DQ)
CS PSL (use H1:PEM-CS_MIC_PSL_CENTER_DQ))
CS PSL (use H1:PEM-CS_ACC_PSL_PERISCOPE_X_DQ))
Warning: region may cause up/downconversion in blue bands, OUTPUTOPTICS coupling
Warning: may have downconversion from red band, OUTPUTOPTICS coupling
Warning: may have upconversion from red band, OUTPUTOPTICS couplings
Acoustic Coupling [m/Pa or m/(m/s^2)]
Frequency [Hz]

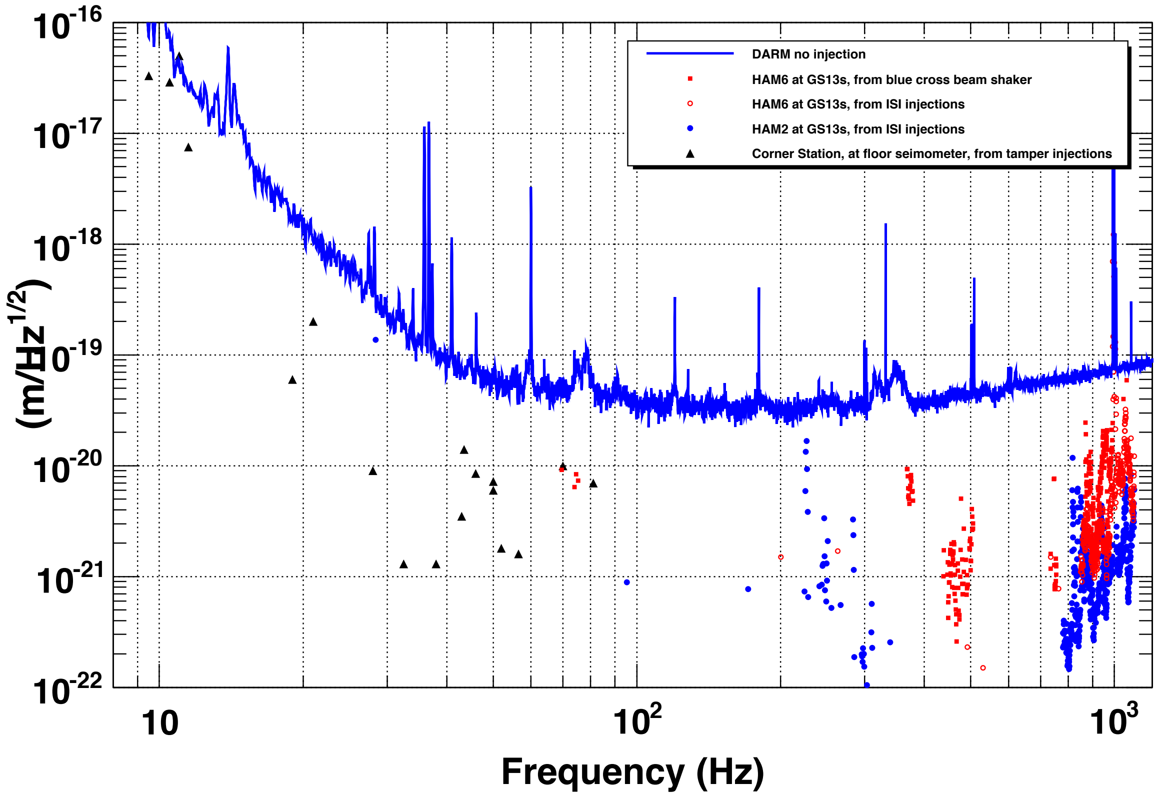
LLO



LLO Approximate Linear Acoustic Coupling Functions
EX (use L1:PEM-EX_MIC_VEA_PLUSX_DQ)
EY (use L1:PEM-EX_MIC_VEA_PLUSY_DQ)
CS VERTEX/output (use L1:PEM-CS_MIC_LVEA_OUTPUTOPTICS_DQ)
CS input arm (use L1:PEM-CS_MIC_LVEA_INPUTOPTICS_DQ)
CS PSL MIC (use L1:PEM-CS_MIC_PSL_CENTER_DQ))
CS PSL PER (use L1:PEM-CS_ACC_PSL_PERISCOPE_X_DQ))
Warning: region may cause up/downconversion in blue bands, OUTPUTOPTICS coupling
Warning: may have downconversion from red band, OUTPUTOPTICS coupling
Warning: may have upconversion from red band, OUTPUTOPTICS couplings
Acoustic Coupling [m/Pa or m/(m/s^2)]
Frequency [Hz]

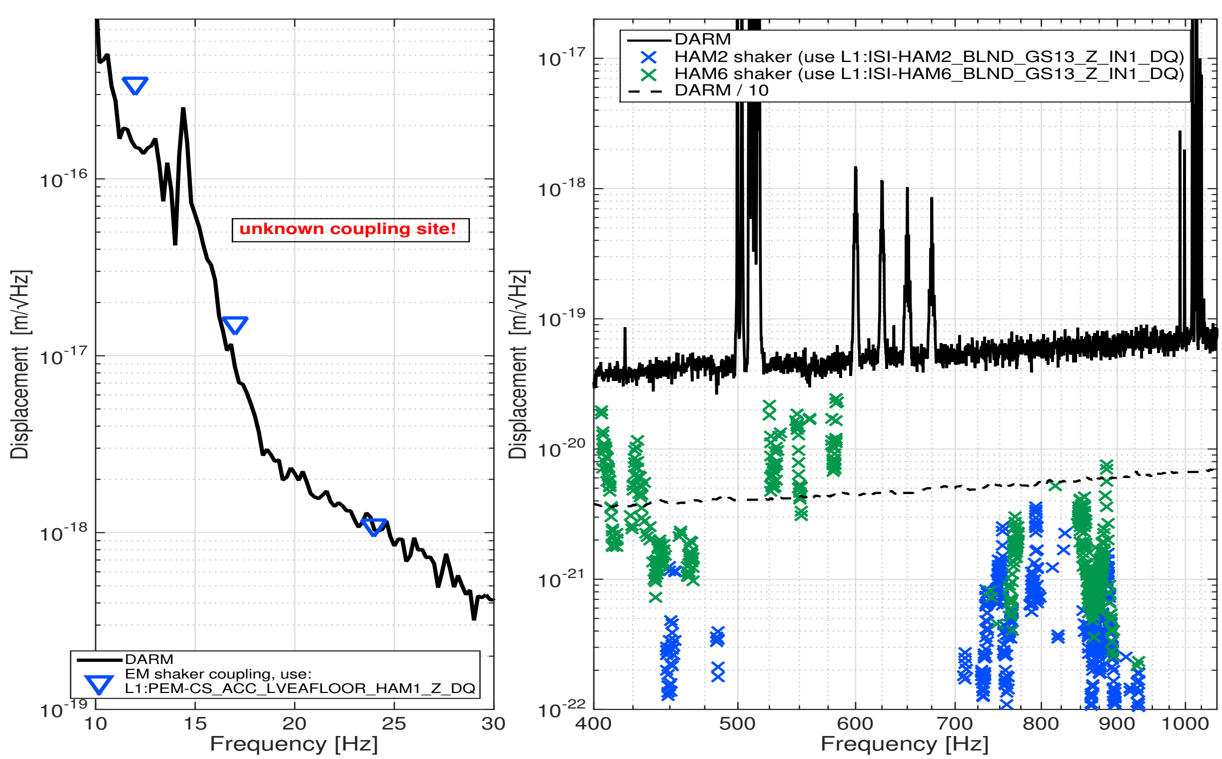
Estimated noise contribution from ambient at indicated sensors, shaker injections

LHO

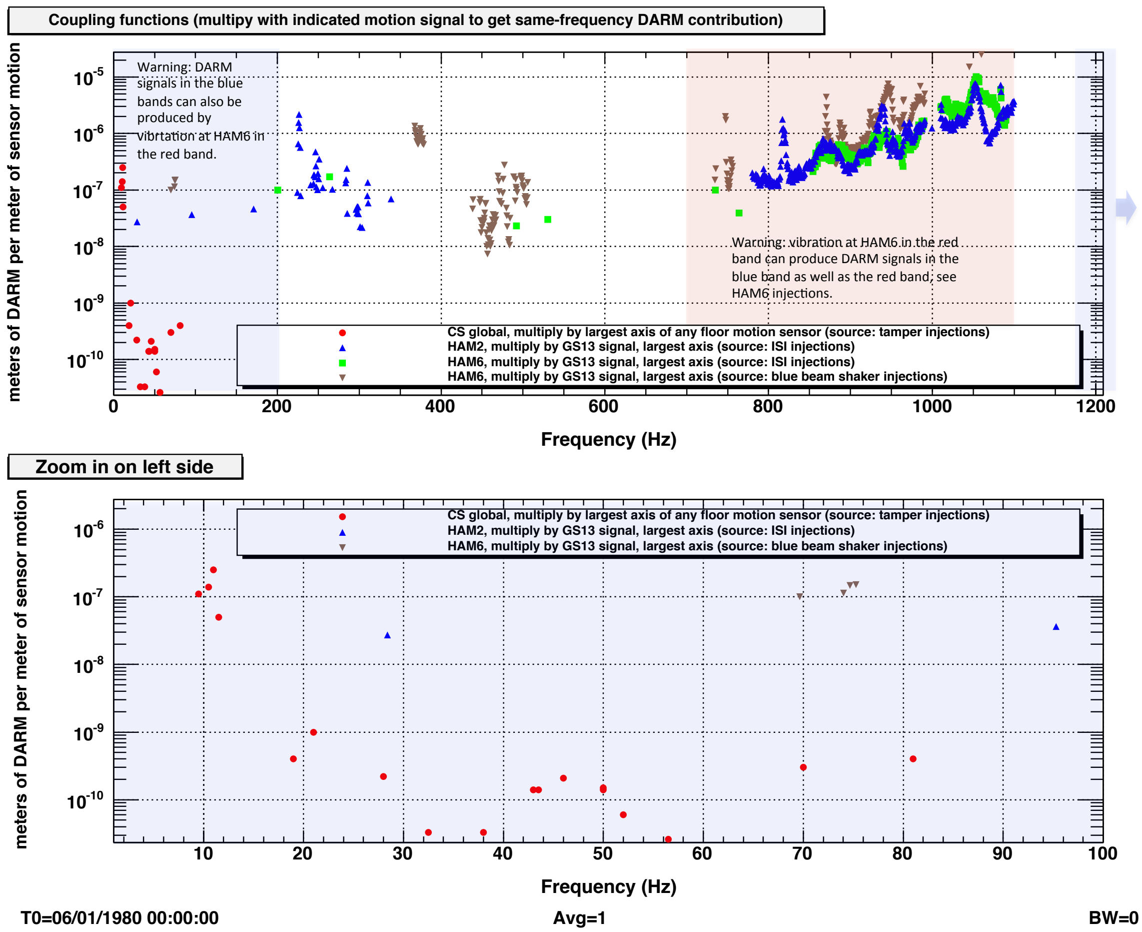


*T0=03/09/2015 22:02:43 *Avg=1/Bin=2L *BW=0.0937485

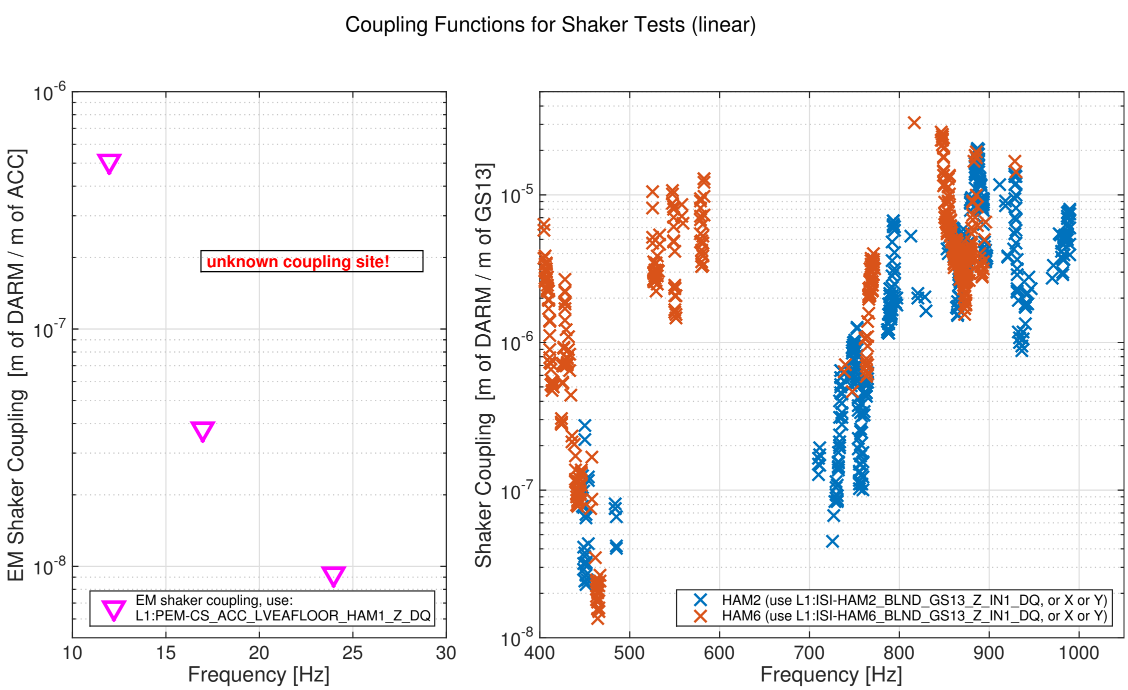
LLO



LHO


Coupling functions (multipy with indicated motion signal to get same-frequency DARM contribution)
Warning: DARM signals in the blue bands can also be produced by vibration at HAM6 in the red band.
Warning: vibration at HAM6 in the red band can produce DARM signals in the blue band as well as the red band; see HAM6 injections.
CS global, multiply by largest axis of any floor motion sensor (source: tamper injections)
HAM2, multiply by GS13 signal, largest axis (source: ISI injections)
HAM6, multiply by GS13 signal, largest axis (source: ISI injections)
HAM6, multiply by GS13 signal, largest axis (source: blue beam shaker injections)
meters of DARM per meter of sensor motion
Frequency (Hz)
Zoom in on left side
CS global, multiply by largest axis of any floor motion sensor (source: tamper injections)
HAM2, multiply by GS13 signal, largest axis (source: ISI injections)
HAM6, multiply by GS13 signal, largest axis (source: blue beam shaker injections)
meters of DARM per meter of sensor motion
Frequency (Hz)
T0=06/01/1980 00:00:00
Avg=1
BW=0

LLO


Coupling Functions for Shaker Tests (linear)
unknown coupling site!
EM shaker coupling, use:
L1:PEM-CS_ACC_LVEAFLOOR_HAM1_Z_DQ
EM Shaker Coupling [m of DARM / m of ACC]
Frequency [Hz]
HAM2 (use L1:ISI-HAM2_BLND_GS13_Z_IN1_DQ, or X or Y)
HAM6 (use L1:ISI-HAM6_BLND_GS13_Z_IN1_DQ, or X or Y)
Shaker Coupling [m of DARM / m of GS13]
Frequency [Hz]

Summary comparison of Hanford and Livingston

Coupling location	Max LHO coupling factor 30-1000 Hz unless indicated	Max LLO coupling factor 30-1000 Hz unless indicated	Ratio LHO/LLO (approx.)
PSL periscope accelerometer	3e-15 m/(m/s^2)	4e-17 m/(m/s^2)	100 (probably about 10 after fix)
Output optics mic	3e-16 m/Pa	6e-16 m/Pa	0.5
EX VEA mic, either	1e-16 m/Pa	4e-18 m/Pa	25
EY VEA mic, either	1e-17 m/Pa	1e-17 m/Pa	1
HAM2 GS13s	3e-6 m/m		
HAM6 GS 13s	9e-6 m/m		
Any floor seismometer	1e-7 m/m, 10 Hz		
Largest magnetic coupling at 12 Hz	1e-8 m/T - vertex magnetometer	7e-9 m/T -output arm magnetometer	1.4
Largest magnetic coupling at 100 Hz	8e-11 m/T vertex magnetometer	8e-11 m/T EY VEA magnetometer	1

List of suggested PEM-related improvements for O2

1) Reduce jitter coupling at LHO. TCS?

2) Damp HAM6 blade springs and flexures. This may expand to other HAMs depending on results of jitter coupling reduction at LHO and 80-90, 455 Hz coupling investigations at LLO.

3) More injections to better understand 80-90 and 455 Hz coupling at LLO

4) Find and fix the high acoustic coupling at LHO EX, scattering?

5) Find and mitigate the source of high magnetic fields around 10 Hz in the LHO ebay.

6) Find coupling site and mechanism for 10-50 Hz ground motion producing up-conversion at CS (using shakers). Why 10-50 Hz? Microseism is too variable, so is 1-10 Hz (diurnal anthropogenic variation). Also 1, 2 Hz injections at LHO low coupling, and HVAC consistent with 10-50.

7) Use buried external seismometers to reduce wind tilt problems

8) Check transfer function of OMC suspension at 900 Hz

9) Monitor beam tube stick slips that could produce particulate glitches.