LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T1500062-v21** 2025/09/30

Pcal End Station Power Sensor Responsivity Ratio Measurements: Procedures and Log

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End Station: ......EX.............................. Date: ....10/02/2026...............................
Sphere Name and Number: ....PS4........
Measurements Performed By: ....Tony/Dripta...

Items to take to the end station for the measurements:

- ✓ Working Standard (in protective case)
- CDS Laptop including the power chord
- ✓ PD Satellite Box (blue box), D1300368
- ✓ Long (25') DB9 cable
- ✓ DB9/BNC male to DB9 female temperature cable
- ✓ BNC cable
- ✓ A Fluke handheld digital voltmeter
- ✓ Martel calibrated voltage source, banana-to-BNC adapter cable, and charger/AC adapter
- IR-only laser glasses (for use ONLY if work in the ALS laser enclosure, which could expose the VEA to green laser light, will not be ongoing in parallel)
- ✓ IR viewing cards: high-power (white) and low power (orange)
- ✓ 1.5 mm allen key to remove input aperture cover from Working Standard
- ✓ Handheld IR Viewer
- we are also taking an empty pelican case to bring back Rx sensor for its temperature characterization

Before (or after) going to the End Station

- Check the calibration of the Keithley Model 2100 voltmeter using the Martel Calibrated Voltage source at following three different voltages (the same one that will be taken to the end station). Note: use negative polarity.

  1. (**-4 V**): with Martel = ... V on Keithley 2100 DVM
  2. (**-2 V**): with Martel = ... V on Keithley 2100 DVM
  3. (**0 V**):with Martel = ... V on Keithley 2100 DVM

1 Before starting Pcal work in VEA

- ✓ Call the Control Room (ext. 202) to notify them of the laser status change.
- ✓ Transition VEA to **LASER HAZARD** status.

- Plug in the Blue Satelite Box to the WS_PD connector on the PCAL Chassis, using the DB9/BNC male to DB9 female to power the Blue box. Ensure the Power Source switch on the back is in the proper setting. Plug the BNC cable into the FLuke Voltmeter for now. Plug in the integrating sphere while it is sitting in a safe location. Power on the power sensor and take note of the current temperature of the on-board AD590 using the Fluke Voltmeter.
  WS on-board temperature: ....297.5.......... K
- Make sure that the IFO's ISC LOCK Gaurdian is in a down or idle state, and that it will not try to auto lock. (sitemap / GRD / ISC OVERVIEW)
  DO NOT CHANGE STATE OF GUARDIAN UNLESS APPROVED BY THE ON-SHIFT OPERATOR
- Close the ALS laser shutter via the MEDM screen (sitemap/LSC/Shutters/ISCTX(Y) green beam.) This protects you from the 50 mW ALS green lasers
- Check that SEI ENV is set to Maintenance Mode to Shut Off Sensor correction (The Operator should have done this for Tuesday Maintenance but check anyways.) (sitemap/SEI/ISI SENSOR CONFIG)

1.1 Before starting the measurements

- Record Rx enclosure Digital Thermometer ("Outside" display) = ...19.7...... deg. C
- Record Rx enclosure Digital Thermometer (" Inside" display) = ...19.1...... deg. C
- Turn PCAL Interlock bypass to the ON position.
- Set shutter to local
- Disable all three excitations on the Pcal MEDM screen (sitemap/Cal/PcalX(Y)/Excitation):
  1. H(L)1:CAL-PCALX(Y)_SWEPT_SINE
  2. H(L)1:CAL-PCALX(Y)_OSC_SUM
  3. H(L)1:CAL-INJ_MASTER_SW
- Ensure that the ETM pointing is in the "aligned" state, If you cannot tell from the medm screen call the operator and ask them. SUS → Guardians → ETX(Y)
- Remove cover from Rx enclosure and verify that Pcal beam spots are close to their nominal locations (centered on the Rx sensor input aperture). If they are not, adjust their positions using the final steering mirrors inside the output section of the Tx module enclosure.
- Open a GPS Clock window (type `gpsclock &` in a terminal window).

- Open **StripTool** (type `StripTool &` in a terminal window) and display the following four sensor outputs (choose the appropriate interferometer and arm). Always verify that signals are stable before recording time series.

  1. **H(L)1:CAL-PCALX(Y)_TX_PD_WATTS_OUTMON**
  2. **H(L)1:CAL-PCALX(Y)_RX_PD_WATTS_OUTMON**
  3. **H(L)1:CAL-PCALX(Y)_WS_PD_OUTM16**
  4. **H(L)1:CAL-PCALX(Y)_OFS_PD_OUT16**

- Make sure the OFS is not railed, if it is turn the loop off and back on.

2 Calibration measurements

Optional Procedure

Prior to starting the measurements, use the shell script below to automatically acquire and save GPS times and parameters required for the procedure. These values are used to populate `config.py`. The shell can be found here:

`pcal/O4/ES/scripts/pcalEndstationPy/es_meas.sh`

If using this shell, skip Section 2.1 and 2.2 entirely. Once the script has finished running, proceed directly to Section 2.2.10.

Motivation

- This shell populates lines 6–9 and 13–28 of `config.py`.
- Save time and reduce user error by automating the recording of GPS times, eliminating manual transcription between computer, paper, and script. Automatically records data for measurements described in Sections 2.1 and 2.2.
- The shell is designed to run concurrently with the end station (ES) measurements. Once completed, the data is updated in `config.py`, which enables the report and trend scripts described in Section 3.1 to be executed.

Usage

1. Navigate to the directory mentioned above to find **`es_meash.sh`**. In the terminal run:

   ```
   ./es_meas.sh
   ```

2. The initial prompt requests a choice between an EMPTY or a POPULATED `config.py`. By default, `config.py` is populated with measurements from the most recent ES measurement.

- **EMPTY** `config.py`: All data in lines 6–9 and 13–28 will be cleared. During measurement, selecting **`quit`** saves completed entries to `config.py` and exits the shell; remaining measurements will remain empty. If **`skip`** is used, only the skipped measurement are left empty while the shell continues with subsequent prompts.
- **POPULATED** `config.py`: Data in lines 6–9 and 13–28 from the most recent `config.py` is retained. Using **`quit`** saves new data up to that point; remaining fields are preserved from the previous file. If **`skip`** is used, existing data for the skipped measurement is kept, and the shell proceeds to the next prompt

3. After that, a series of questions that are needed for populating `config.py` would be asked (interferometer and arm where measurement is being taken, Working Standard (WS) being used, WS temperature). The date is automatically recorded as the current day.

4. Instructions and required button selections for shell usage are displayed in the terminal during use. Additionally, setup procedures, step-by-step instructions, and timing information for measurements described in Sections 2.1.2 and 2.2 are provided in the terminal during each measurement.

5. Upon completion of all measurements, a prompt is displayed indicating that the process of acquiring the GPS times is finished. The shell updates `config.py` with the new GPS times. Additionally, a new log file named **`shell.txt`** is created in the same directory as **`es_meas.sh`**. This log contains a copy of the terminal output and is intended to be posted in the alog for the ES measurement, after that, **`shell.txt`** may be deleted.

6. Once all measurements have been completed, proceed directly to Section 2.2.10. Furthermore, in Section 3.1, you can skip to step 7. By following this optional procedure, steps 1 to 6 are already fulfilled.

2.1 Preliminary measurements

2.1.1 Record Optical Follower Servo (OFS) settings

Using **`caget`** in a terminal window, display the following three sensor outputs and record them accordingly.

1. **H(L)1:CAL-PCALX(Y)_OPTICALFOLLOWERSERVOOFFSET**
2. **H(L)1:CAL-PCALX(Y)_OPTICALFOLLOWERSERVOGAIN**
3. **H(L)1:CAL-PCALX(Y)_OFS_PD_OUT16**

- Offset: ....3.68.... V
- Gain: ....39.79.... dB
- OFS PD: ....-3.663.... V

2.1.2 Calibrate the Working standard channel

- Connect **Martel Calibrated Voltage Source** to INPUT 1 on the ***BNC to DB9*** interface module mounted in the Pcal transmitter pylon. Note: use negative polarity, and adjust Range to 0.000 to allow up to 4V.

- Inject the three following input voltages for 15 seconds each and record the GPS time and the output level displayed on `StripTool` for each 15 second interval.

  1. **(-4 V)**: GPS Start Time 1454 784 470; Voltage = -3.9958 V
  2. **(-2 V)**: GPS Start Time 1454 784 525; Voltage = -1.9975 V
  3. **(0 V)**: GPS Start Time 1454 784 565; Voltage = 0.00022 V

2.1.3 Record Working Standard temperature

- Measure the Working Standard on-board temperature using at DVM at the BNC output of the DB9/BNC to DB9 cable. Multiply the voltage by 100 to obtain the temperature in K.
  - GPS time: 1454 784 600
  - WS on-board temperature: 299.7 K

2.2 Power sensor measurements

- Connect the Pcal Satellite Box PD MON output to INPUT 1 on the ***BNC to DB9*** interface module mounted in the Pcal transmitter pylon.

- Record GPS start and end times and nominal `StripTool` output levels during the measurements.

2.2.1 Measurement 1:

- Block the OUTER beam with a razor blade beam block in the Tx module.

- Loop cable around something to ensure that the sphere doesn't fall when the cable is stepped on.

- Place the WS in the INNER beam in the Tx module.

WS in the INNER beam in the Tx module.				
GPS times		StripTool outputs		
Start Time #1	1454 784 870	TxPD	0.500245	W
Duration	300 seconds	WSPD	-1.16271	V
End Time #1	1454 785 170	OFSPD	-3.6628	V

2.2.2 Measurement 2:

- Move the beam block to the INNER beam in the Tx module.
- Move the WS to the OUTER beam in the Tx module.

WS in the OUTER beam in the Tx module.				
GPS times		StripTool outputs		
Start Time #2	1454 785 410	TxPD	0.4999	W
Duration	300 seconds	WSPD	-1.1785	V
End Time #2	1454 785 710	OFSPD	-3.6628	V

2.2.3 Measurement 3:

- Leave the WS in the OUTER beam in the Tx module with the INNER beam blocked.
- Close the shutter in the Tx module.

WS in the OUTER beam in the Tx module. Shutter CLOSED.				
GPS times		StripTool outputs		
Start Time #3	1454 785 815	TxPD	0.000205	W
Duration	60 seconds	WSPD	0.00268	V
End Time #3	1454 785 875	OFSPD	-0.0101	V

2.2.4 Measurement 4:

- ✓ Leave the block in the INNER beam in the Tx module.
- ✓ Leave shutter closed in the TX module.
- ✓ Replace the Rx sensor with the WS in the Rx module.
- ✓ Open the shutter in the Tx module.
- ✓ Check if OFS is railed.

WS in the Rx module. INNER beam blocked in the Tx module.				
GPS times		StripTool outputs		
Start Time #4	1454 786 310	TxPD	0.5002	W
Duration	300 seconds	WSPD	-1.16497	V
End Time #4	1454 786 610	OFSPD	-3.663	V

2.2.5 Measurement 5:

- Move the block to the OUTER beam in the Tx module.

WS in the Rx module. OUTER beam blocked in the Tx module.				
GPS times		StripTool outputs		
Start Time #5	1454 786 835	TxPD	0.500	W
Duration	300 seconds	WSPD	-1.14921	V
End Time #5	1484 787 135	OFSPD	-3.66271	V

2.2.6 Measurement 6:

- CLOSE the shutter in the Tx module.

WS in the Rx module. Shutter CLOSED in the Tx module.				
GPS times		StripTool outputs		
Start Time #6	1454 787 210	TxPD	2.9118e-5	W
Duration	60 seconds	WSPD	0.002675	V
End Time #6	1454 787 270	OFSPD	-0.01015	V

2.2.7 Measurement 7:

- ~~Open Shutter.~~
- REMOVE the beam block from the OUTER beam in the Tx module.
- Open the shutter in the Tx module.

WS sensor in the Rx module, both Inner and Outer beams on it				
GPS times		StripTool outputs		
Start Time #7	1454 787 ~~320~~ 660	TxPD	0.5002	W
Duration	300 seconds	WsPD	-2.3179	W
End Time #7	1454 787 ~~620~~	OFSPD	-3.6629	V

2.2.8 Measurement 8:

- CLOSE the shutter in the Tx module
- Replace WS sphere with the Rx sphere at the Rx Module.

- Open the shutter in the Tx module
- Verify that the Pcal beam spots are centered on the input aperture of the Rx sensor (photograph spot locations on white card).

Both Inner and Outer beams on Rx sensor in the Rx module.				
GPS times		StripTool outputs		
Start Time #8	1454 788 220	TxPD	0.49985	W
Duration	300 seconds	RxPD	0.49414	W
End Time #8	1454788520	OFSPD	-3.66275	V

2.2.9 Measurement 9:

- CLOSE the shutter in the Tx module.

Shutter CLOSED in the Tx module.				
GPS times		StripTool outputs		
Start Time #9	1454 788 740	TxPD	0.000157	W
Duration	60 seconds	RxPD	6.5403e-5	W
End Time #9	1454788 800	OFSPD	-0.01012	V

2.2.10 Before leaving VEA

These 2 steps were not done bcz we took out Rx sensor

1. OPEN the shutter in the Tx module.
2. Set the shutter control to **Remote** on interface module.
3. ✓ Replace the enclosure covers on both the Tx & Rx modules.
4. Re-enable the three excitations on the Pcal MEDM screen (if applicable).
5. ✓ Make sure **ALL** covers are back on before turning the interlock bypass to **OFF**.
6. Transition VEA back **LASER SAFE** status.
7. Call the Control Room (ext. 202) to notify them of the laser status change and that they may unshutter ALS and take the SEI ENV to CALM if they wish to start Locking.

"EXC-SUM-MON" switch was on 1454787583 came through till 1454789662 But no exc.

2.2.11 To complete the end station measurement effort

- Analyze the data (see Section 3) and upload results to the Pcal Git.
- Make an alog entry; append images of the beam spots at the Rx power sensor aperture.

3 Data Retrieval and calculations

3.1 Data Acquisition, Plots and Report

1. Log in to the CDS laptop as yourself to avoid username and permissions issues. If you are already logged in as controls you can use the terminal command `su albert.einstein` to log in to the terminal as yourself, but you will only be logged into the terminal so you will have to use terminal editors like nano or VIM.

2. Make sure that the Local Pcal Git Repo on CDS machines is up to date with the latest version of the `master` branch. At LHO navigate to: `/ligo/gitcommon/Calibration/pcal`, at LLO go to: `/ligo/groups/cal/pcal`. Now, in a terminal run `git status` and `git pull` commands. If you run into any issues, refer to the README.md file on the Remote Git lab Repo found here: https://git.ligo.org/Calibration/pcal .

3. If working from LHO open:

   `/ligo/gitcommon/Calibration/pcal/O4/ES/scripts/pcalEndstationPy/config.py.`

   If working from LLO open:

   `/ligo/groups/cal/pcal/O4/ES/scripts/pcalEndstationPy/config.py`

4. Edit lines 6, 7, 8 and 9 with the values from the procedure. The entry `ifo_string` specifies the interferometer and arm where the measurements were performed, typically in a format such as `LLO_EndY`. The variable `date_code` should follow the convention `DYYYYMMDD`. The field `WS` indicates the Working Standard employed, and `temp` corresponds to the temperature value recorded in Section 2.1.3.

5. Edit lines 13, 15, and 16 with the GPS values from the procedure during the start of each Martel Voltage injections as recorded in Section 2.1.2.

6. Edit lines 20–28 with the GPS start times for each measurement as written in the procedure in section 2.2, then save the document.

7. Get the date of the latest WS_GS lab measurement that was considered to be a good measurement from the directory:

   `pcal/O4/lab/measurements/reviewed_measurements/`

8. Run the command:

   ```
   python generate_measurement_data.py --$WS PS# --date YYYY-MM-DD
   ```

   Where `WS` denotes the PS# of the Working Standard that was taken to the End Station, and `date` corresponds to the latest date of the most recent reviewed `WS_GS` measurement. Once the script is running, time series plots of the Martel Voltage injections and the collected measurements will be displayed. These plots should be inspected to confirm that no obvious issues are present before closing them.

9. Then, switch directories to `pcalTrendsPy` with the the command:

```
cd ../pcalTrendsPy/
```

10. Then run:

```
python3 pcalPublishReportsV5.py LHO_EndY t[datecode]
```

where `date_code` is the date found in the `config.py` file that was opened in Step 3. In other words, the date that the measurement was done.

11. Once this is done you can push this to the `master` branch on the git repository with a

```
git commit -a -m "Notes about your Es measurement"
```

12. Once changes have been commited, run:

```
git push
```

to push the new measurement to the remote git repo.

3.2 ES data vetting instructions:

Open 2 measurements of the same arm with same WS; the previous dated measurement will serve as a reference to compare to the measurement you want to vet. To compare, look at the following 4 pngs and the trends report for vetting the data for each ES:

Note: Measurements done before July 2024 were analyzed differently. Our measurement procedure changed post-July. DO NOT use pre-July measurements as reference to vet post-July measurement.

(a) *Martel_Voltage_test.png*: Look for trends in the data for the 3 instances of -4V, -2V, 0V.

(b) *WS_at_RX.png*:
1. Look for trends and/or dropouts in the data. If dropouts happen at the beginning or end of the measurement, use judgment and see if data length can be cropped and analysis can be rerun. See the section 3.3 on how to crop data and rerun the analysis script.
2. Compare the relative variations and the mean value for each of the subplots in the png. The subplots on the last row are the ratios of the two subplots in their respective columns and hence should follow their trend.
3. Compare the backgrounds of TX and WS_PD.

(c) *WS_at_TX.png*
1. Look for trends and/or dropouts in the data. If dropouts happen at the beginning or end of the measurement, use judgement and see if data length can be cropped and analysis can be rerun. See the section 3.3 on how to crop data and rerun the analysis script.
2. Compare the relative variations and the mean value for each of the subplots in the png. The subplots on the last row are the ratios of the two subplots in their respective columns and hence should follow their trend.
3. Compare the backgrounds of TX and WS_PD.

(d) *WS_at_RX_BOTH_BEAMS.png*
1. Look for trends and/or dropouts in the data. If dropouts happen at the beginning or end of the measurement, use judgement and see if data length can be cropped and analysis can be rerun. See the section 3.3 on how to crop data and rerun the analysis script.
2. Compare the relative variations and the mean value for each of the subplots in the png. The subplots on the last row are the ratios of the two subplots in their respective columns and hence should follow their trend.
3. Compare the backgrounds of RX and WS_PD.

3.3 Cropping ES data and rerunning the analysis script

Open `/ligo/gitcommon/Calibration/pcal/O4/ES/scripts/pcalEndstationPy/config.py` and edit line 30: `data_duration = 240` to a suitable length.

Post an alog

Add the plots of the time series of the measurements, their ratios and the generated trend plots to an alog, along with a scan of this procedure and the beam alignment photo.

Note: If using the Optional Procedure in Section 2, also add the `shell.txt` that is being produced by the shell.