



# MDL Feed-Forward

## Validation and Improvements

---

Sharon Perez / FACET-II

11 January 2024

# Our approach

---

1. Rederive Glen's linear model "Nov\_22" using the same inputs that he used.
  - a. Make a covariance matrix of all the variables.
2. Compare Glen's linear model to a model that also includes Head-Tail data.
  - a. Does the Head-Tail model do better or is it redundant with other variables?
  - b. Make a covariance matrix of all the variables.
3. Compare Glen's linear model to a model that uses fewer variables.
4. Answer some basic questions and try other methods:
  - a. How repeatable are the SBST dither measurements? What is the statistical error?
  - b. Quantify MDL FF errors over short and long time periods.
  - c. Apply time-shifted correlations

## Step 1: Rederive Glen's linear model "Nov\_22" using the same inputs

Using data in same time range that Glen used for his model (Nov. 12-15, 2022) and a similar script, trained a linear model with similar outputs:

		lm{1, 5}.Coefficients			
		1	2	3	4
		Estimate	SE	tStat	pValue
	1 (Intercept)	-0.6390	0.2538	-2.5177	0.0141
Pressure	2 x1	0.2612	0.2591	1.0084	0.3168
MCC Temp	3 x2	-0.1805	0.0778	-2.3209	0.0233
MDL Temp S12	4 x3	-0.0206	0.4665	-0.0441	0.9650
MDL Temp S13	5 x4	0.4221	0.4041	1.0446	0.2999
MDL Temp S14	6 x5	-0.0707	0.4610	-0.1534	0.8785
MDL Temp S16	7 x6	0.6625	0.4002	1.6554	0.1024
MDL Temp S17	8 x7	-0.8110	1.1155	-0.7270	0.4697
MDL Temp S18	9 x8	1.3617	1.2488	1.0904	0.2793
MDL Temp S19	10 x9	0.9927	1.3204	0.7518	0.4547

Glen's model trained Nov. 2022

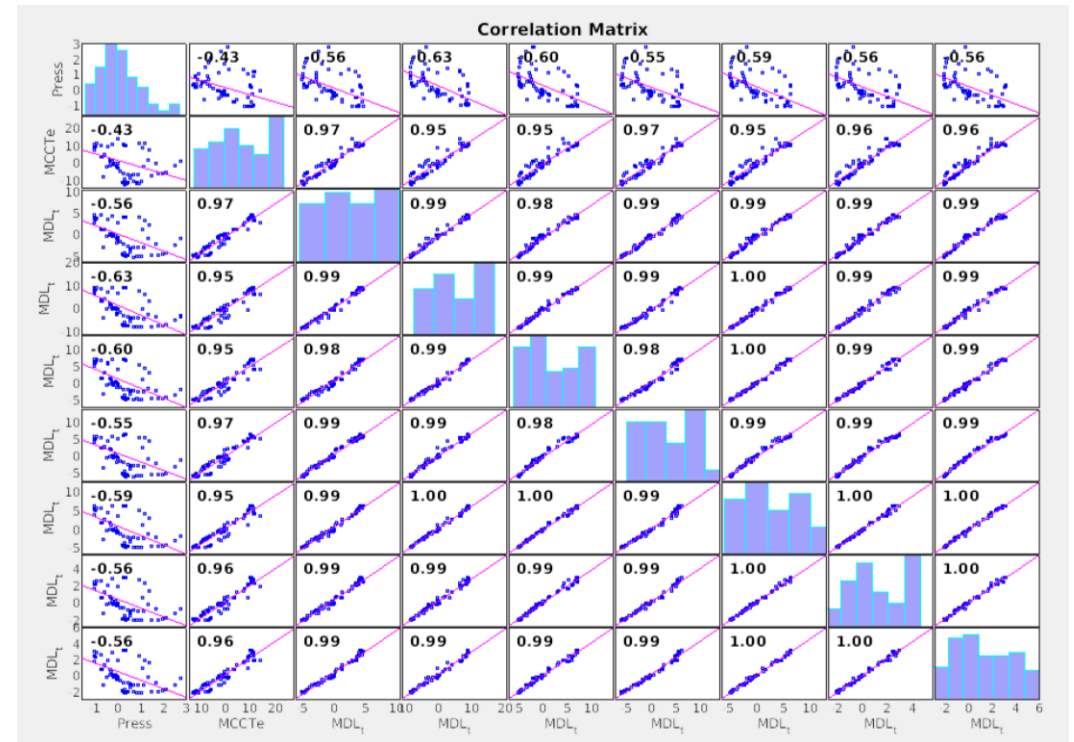
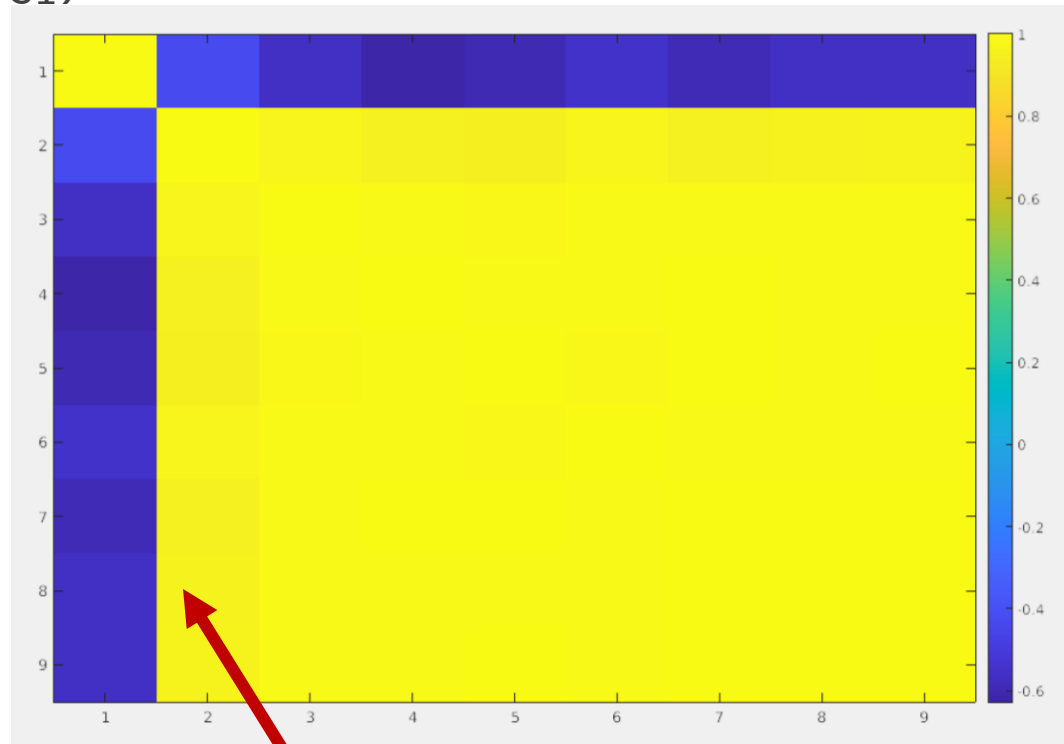
		regModel{1, 5}.Coefficients			
		1	2	3	4
		Estimate	SE	tStat	pValue
	1 (Intercept)	-0.5751	0.2635	-2.1823	0.0325
	2 x1	0.2475	0.2545	0.9726	0.3341
	3 x2	-0.1690	0.0781	-2.1639	0.0339
	4 x3	-0.0789	0.4699	-0.1678	0.8672
	5 x4	0.5113	0.4056	1.2607	0.2117
	6 x5	-0.0832	0.4682	-0.1777	0.8595
	7 x6	0.6099	0.4029	1.5139	0.1346
	8 x7	-0.7212	1.1182	-0.6449	0.5211
	9 x8	1.2479	1.2449	1.0024	0.3196
	10 x9	0.8111	1.3342	0.6079	0.5452

Model trained Nov. 2023

# Step 1: Rederive Glen's linear model "Nov\_22" using the same inputs

## Correlation matrix

Variables used to train the model are Pressure, MCC Temp, Temp at MDL S12, Temp at MDL S13, ... Temp at MDL S19



The first variable, pressure, has a negative correlation to the other variables. All other variables have a strong correlation to each other. This makes sense since they are all measuring temperature, just at different sectors. Variables are not independent!

## Step 1: Rederive Glen's linear model "Nov\_22" using the same inputs

### Fit

```
>> f = fit(phi,pred,'poly1')
```

```
f =
```

Linear model Poly1:

$$f(x) = p1*x + p2$$

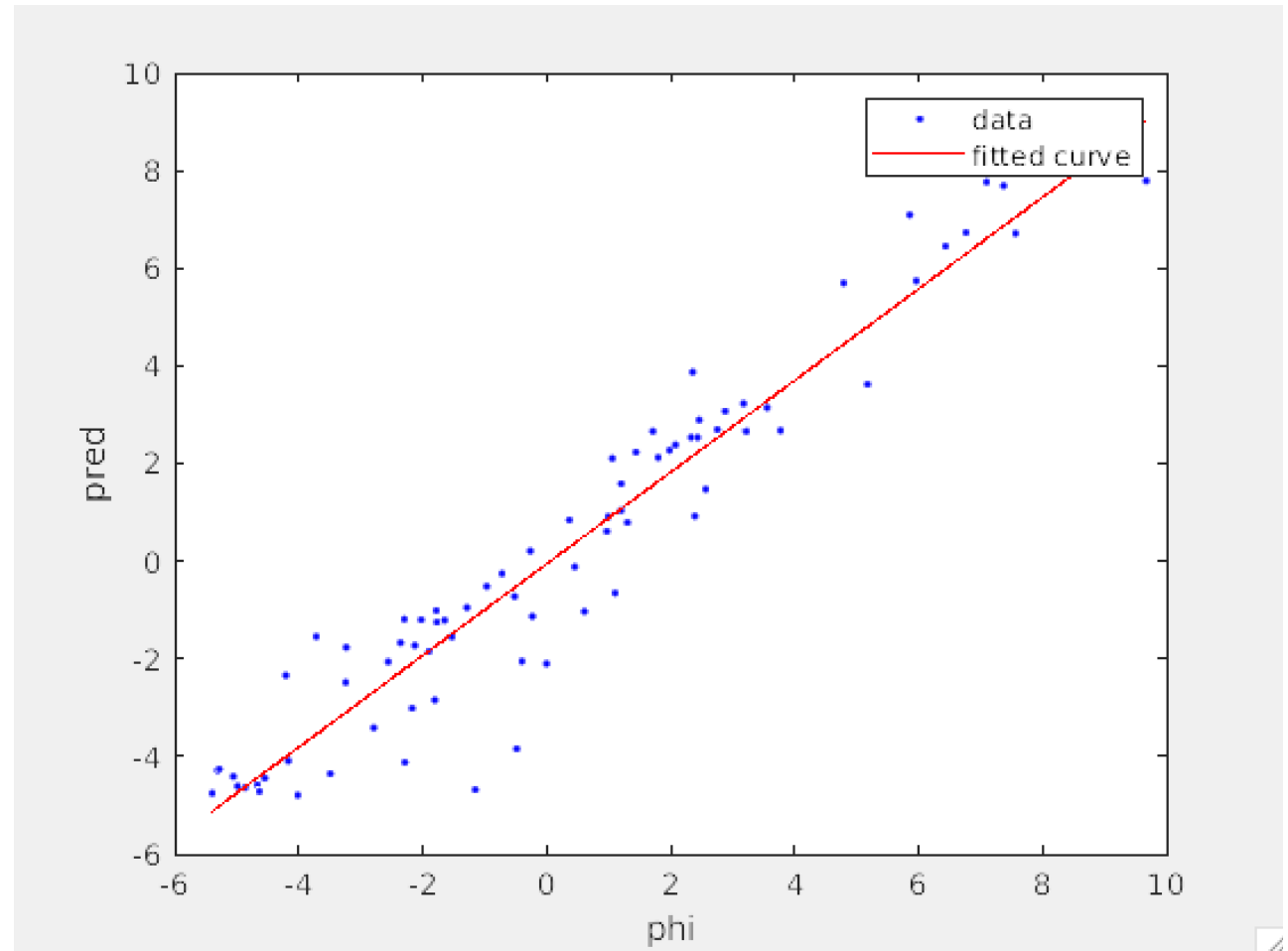
Coefficients (with 95% confidence bounds):

$$p1 = 0.9388 \quad (0.8761, 1.002)$$

$$p2 = -0.05923 \quad (-0.2902, 0.1718)$$

Where **pred** is predicted output values of linear model:

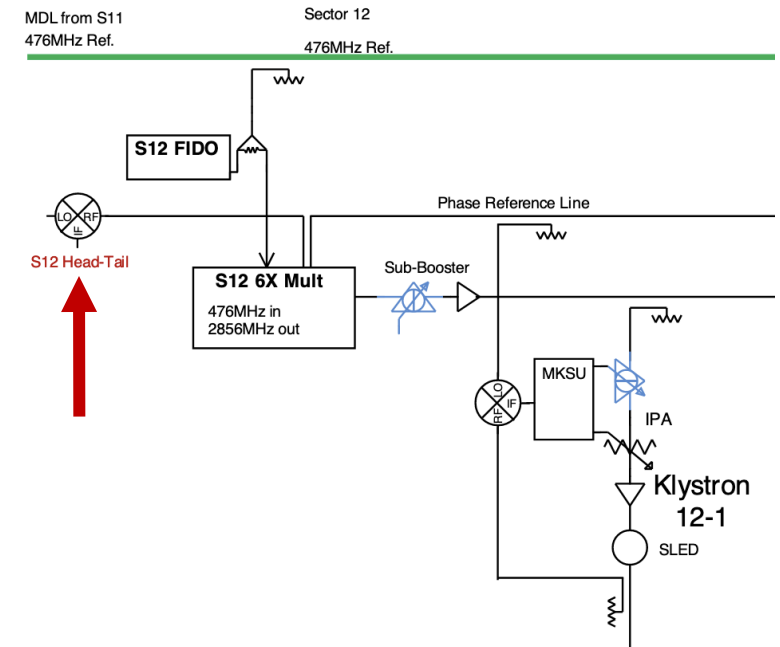
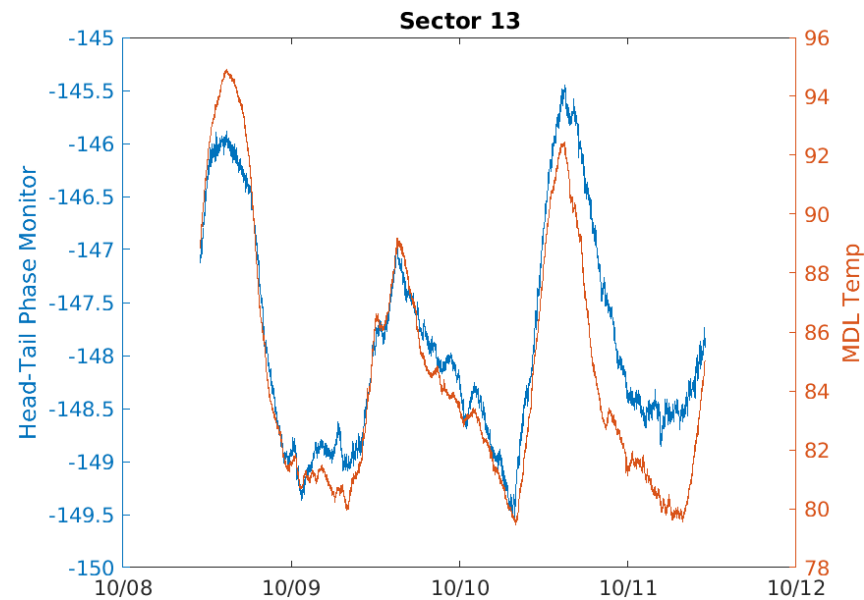
$$Y = C_1X_1 + C_2X_2 + \dots + C_nX_n + b$$



# Step 2: Add Head-Tail monitors

## Head-Tail Phase Monitors

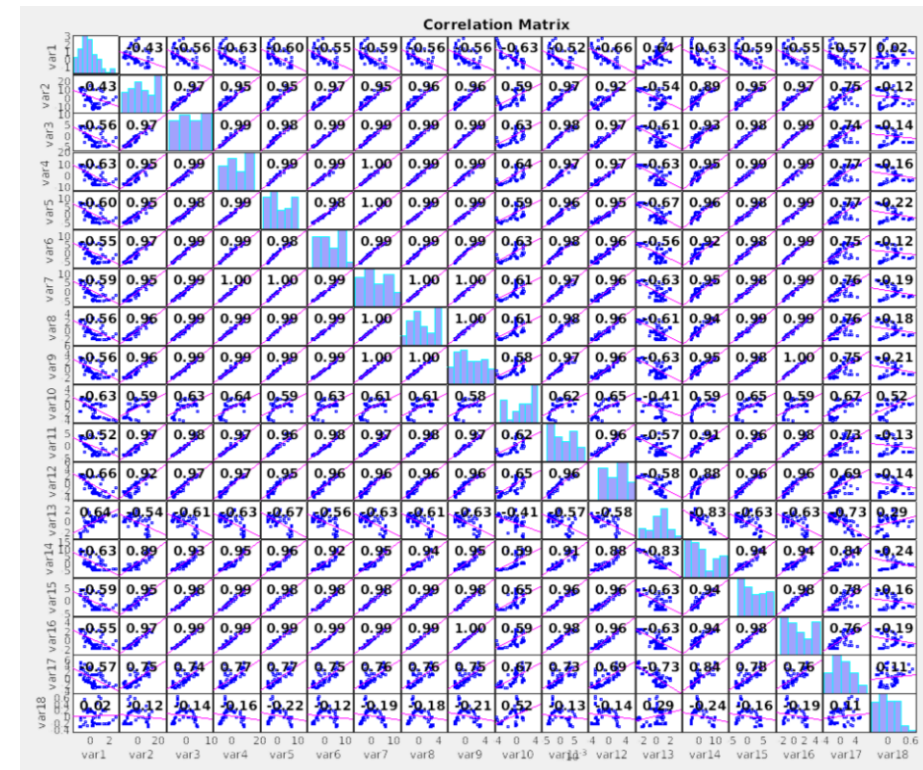
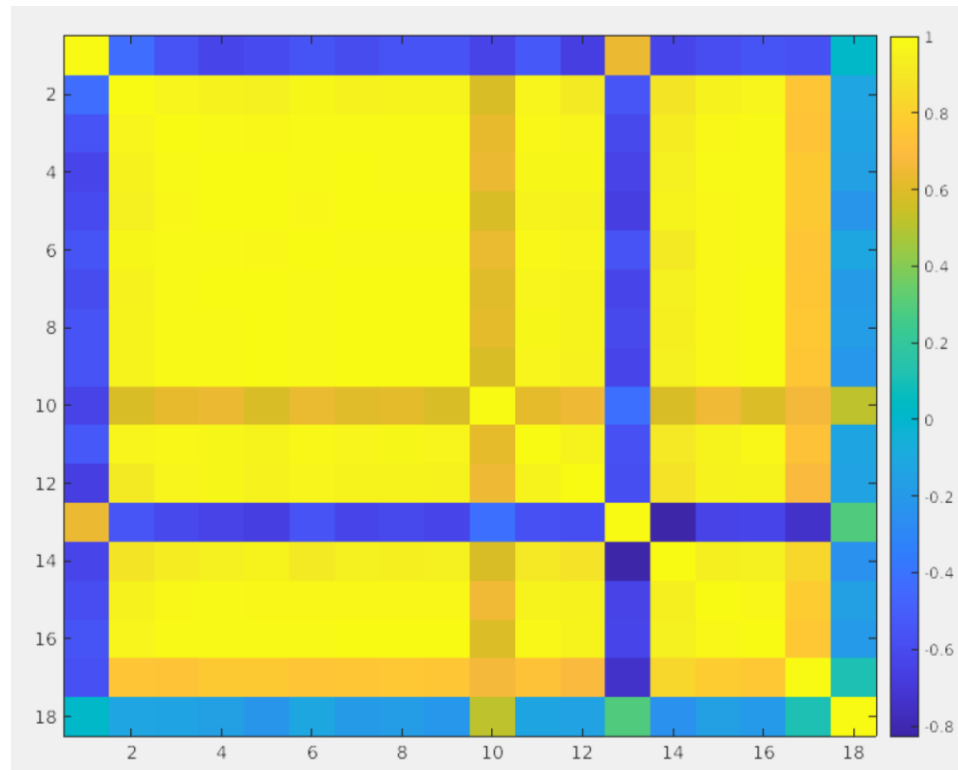
- Head-Tail Phase Monitors measure the difference between *phase reference lines* of adjacent sectors.
- They might provide information about MDL expansion/contraction, but it also could be redundant with temperature.



# Step 2: Add Head-Tail Monitors

## Correlation matrix

Including Head-Tail Monitors as variables



Head-Tail Monitors

# Step 2: Add Head-Tail Monitors

## Fit

```
>> f = fit(phi,pred,'poly1')
```

f =

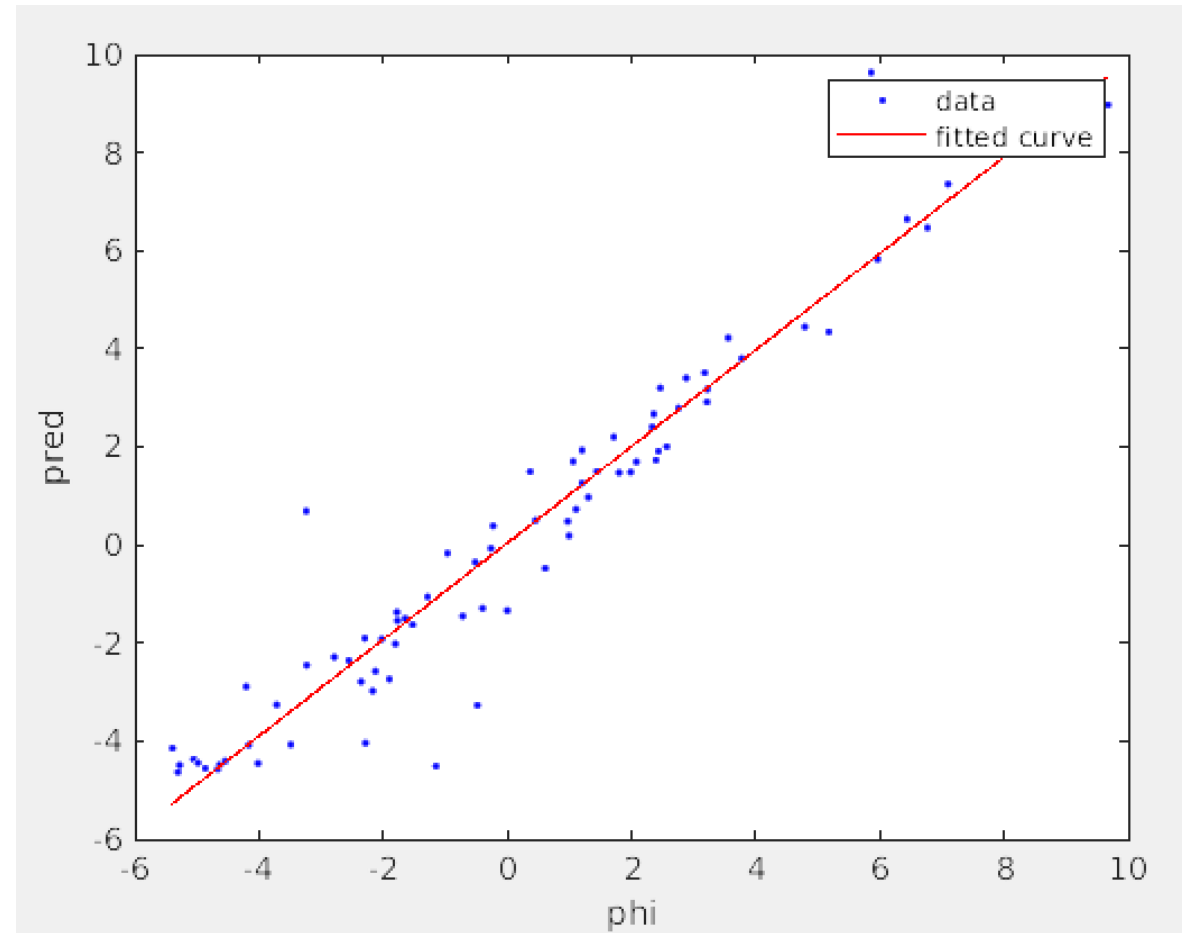
Linear model Poly1:

$$f(x) = p1*x + p2$$

Coefficients (with 95% confidence bounds):

$$p1 = 0.9838 \quad (0.9236, 1.044)$$

$$p2 = 0.03838 \quad (-0.1835, 0.2603)$$

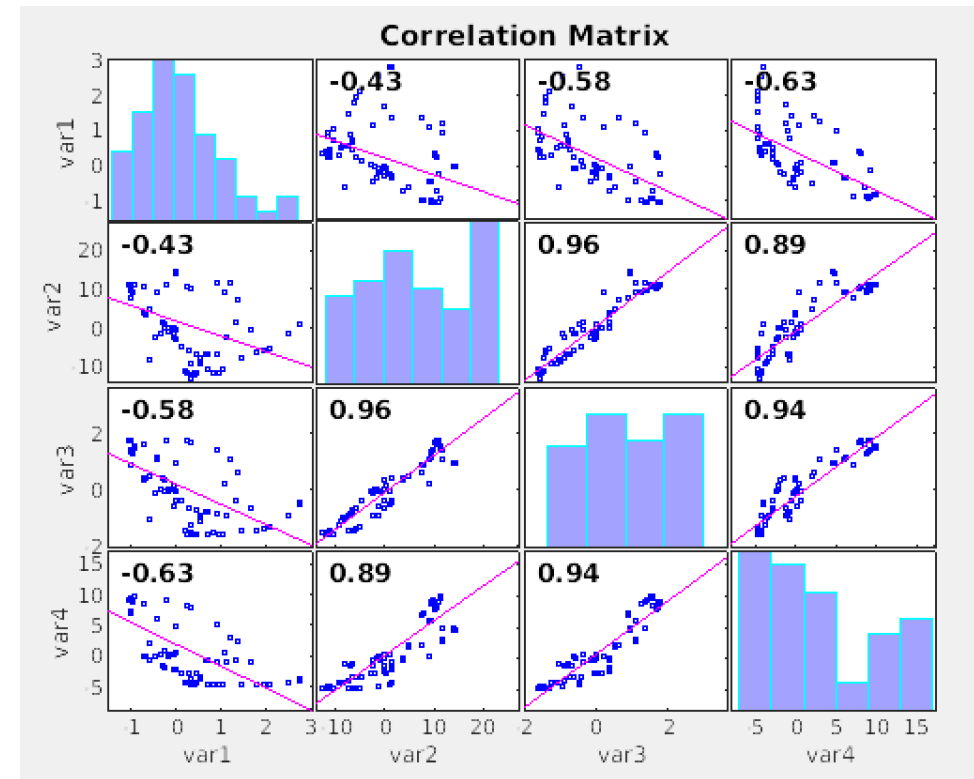
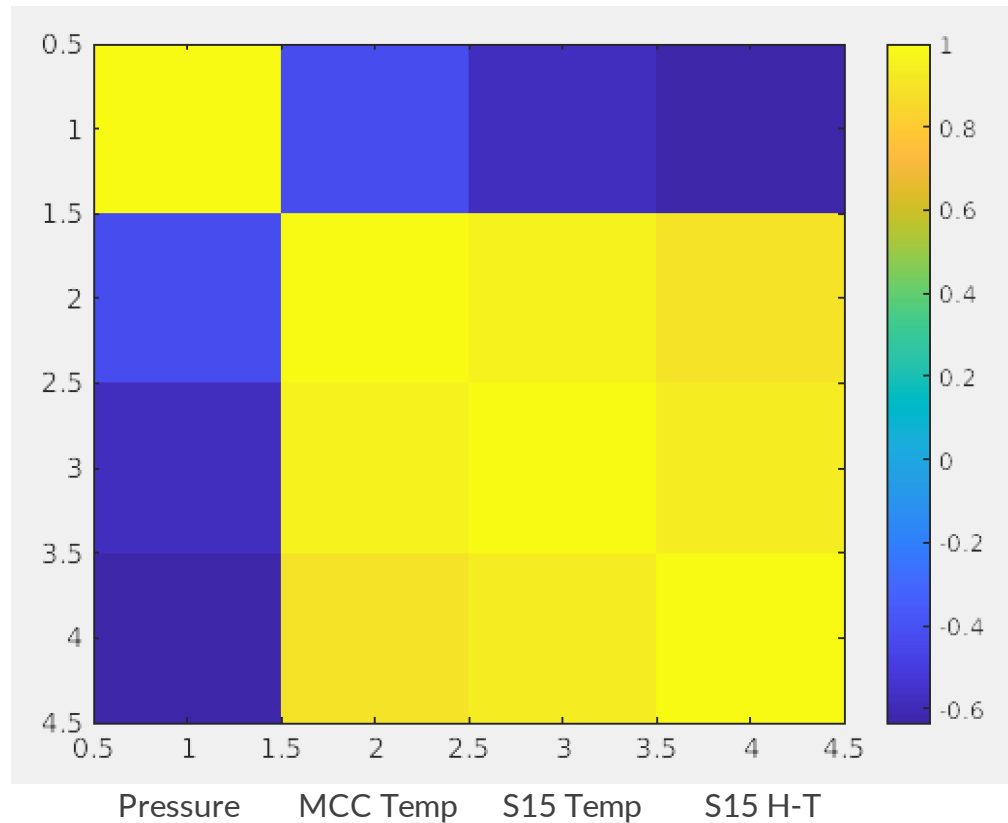




# Step 3: Reduce number of variables

## Correlation matrix

With pressure, two temperatures (one outside, one at MDL), and 1 head-tail



# Step 3: Reduce number of variables

## Fit

f =

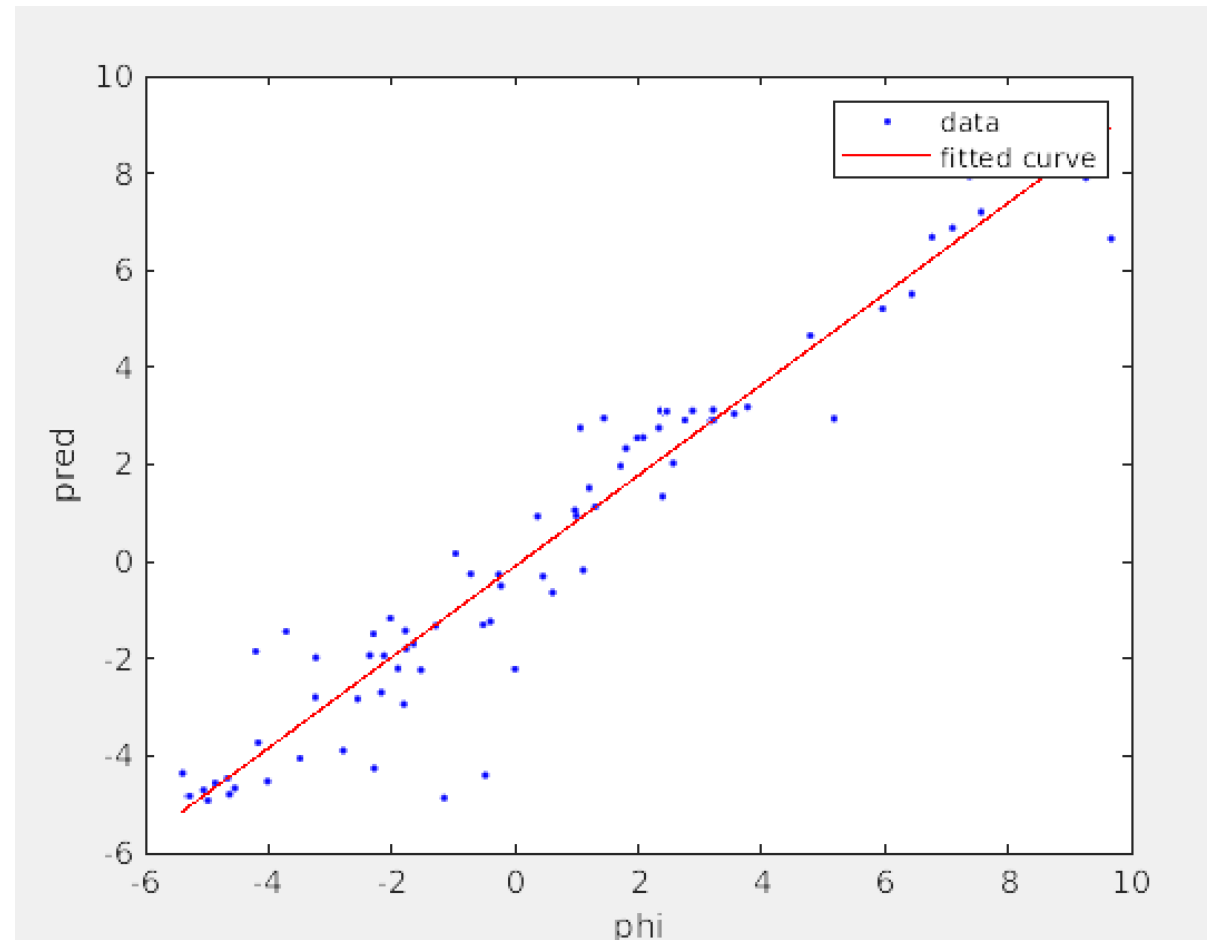
Linear model Poly1:

$$f(x) = p1*x + p2$$

Coefficients (with 95% confidence bounds):

$$p1 = 0.9355 \quad (0.8685, 1.003)$$

$$p2 = -0.09762 \quad (-0.3446, 0.1494)$$



# Comparison

---

## Summary of results

Model	Number of variables	Slope	Confidence range
Glen's	9	0.9388	(0.8761, 1.002) $\Delta = 0.1259$
Glen's + HT	18	0.9838	(0.9236, 1.044) $\Delta = 0.1204$
Few variables	4	0.9355	(0.8685, 1.003) $\Delta = 0.1345$

---

# Long- and Short-Term Error with FF on

# Long-term errors

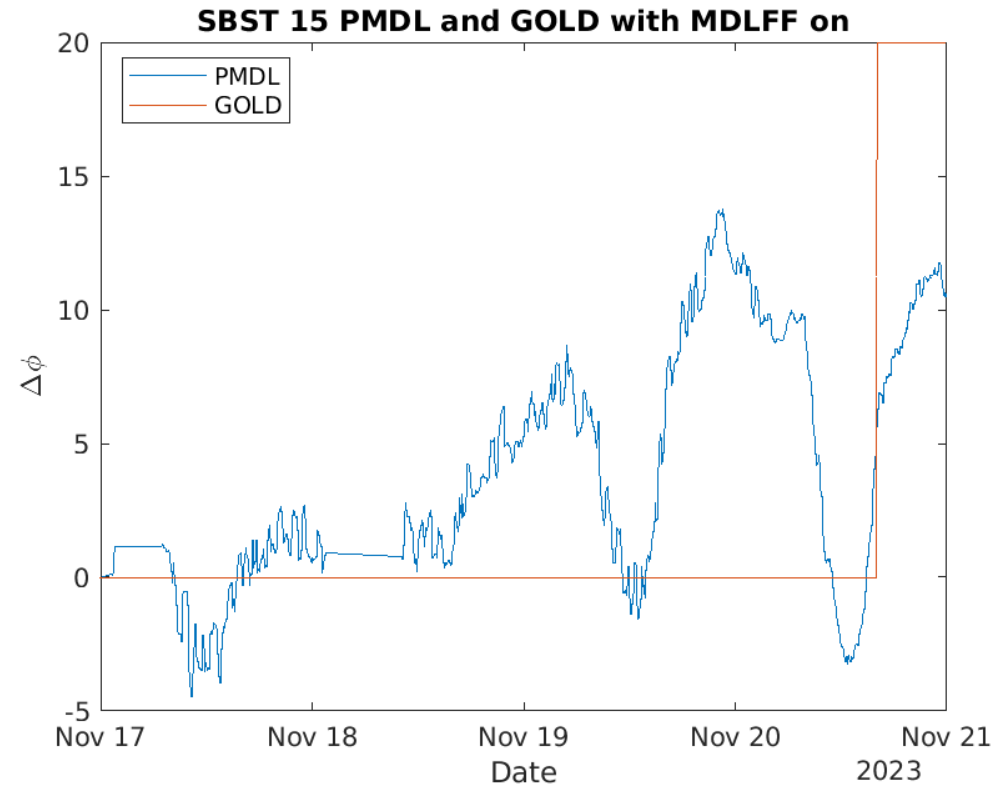
---

We tend to see a big jump in GOLD if sub-booster hasn't been phased in a while:

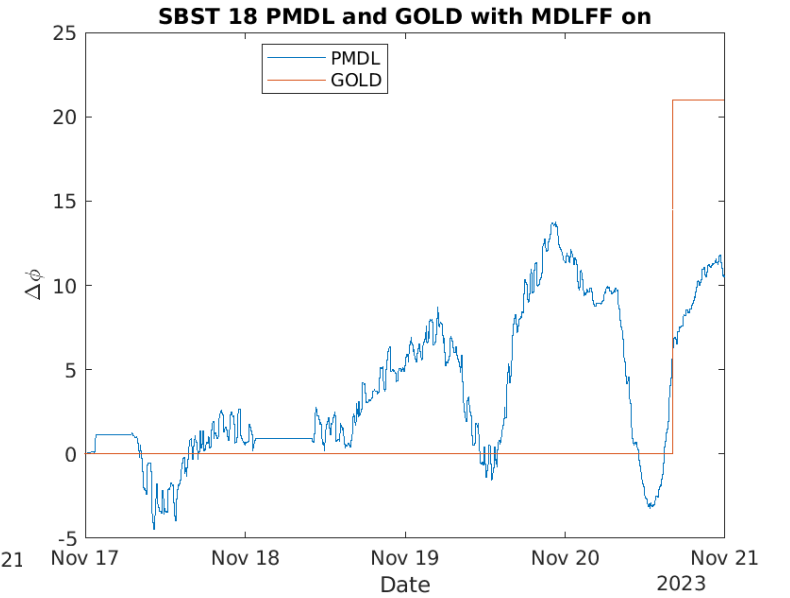
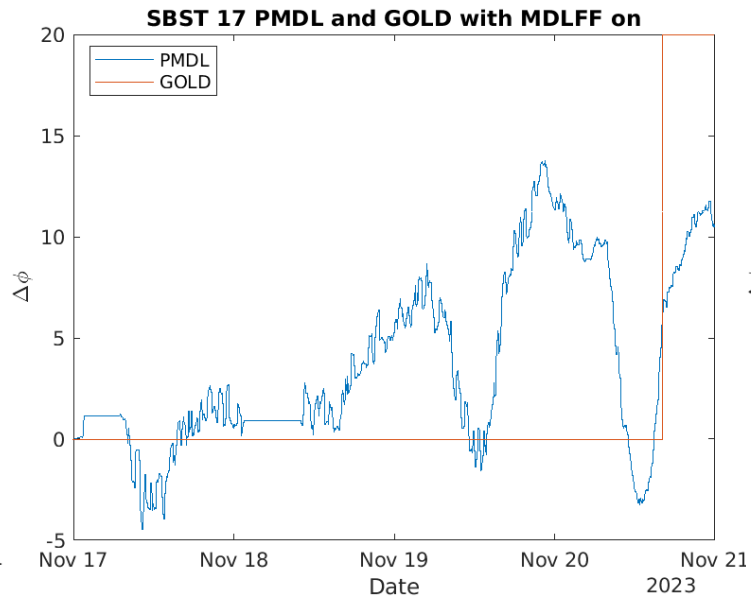
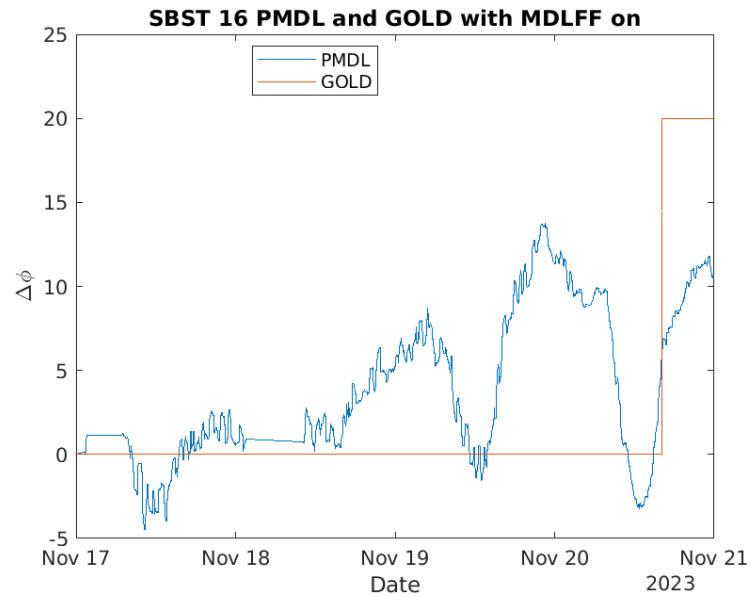
No new phasing from 11/16 to 11/20.

When sub-booster was phased on 11/20,

$\Delta \text{GOLD} = \sim 20 \text{ deg}$



# Long-term errors

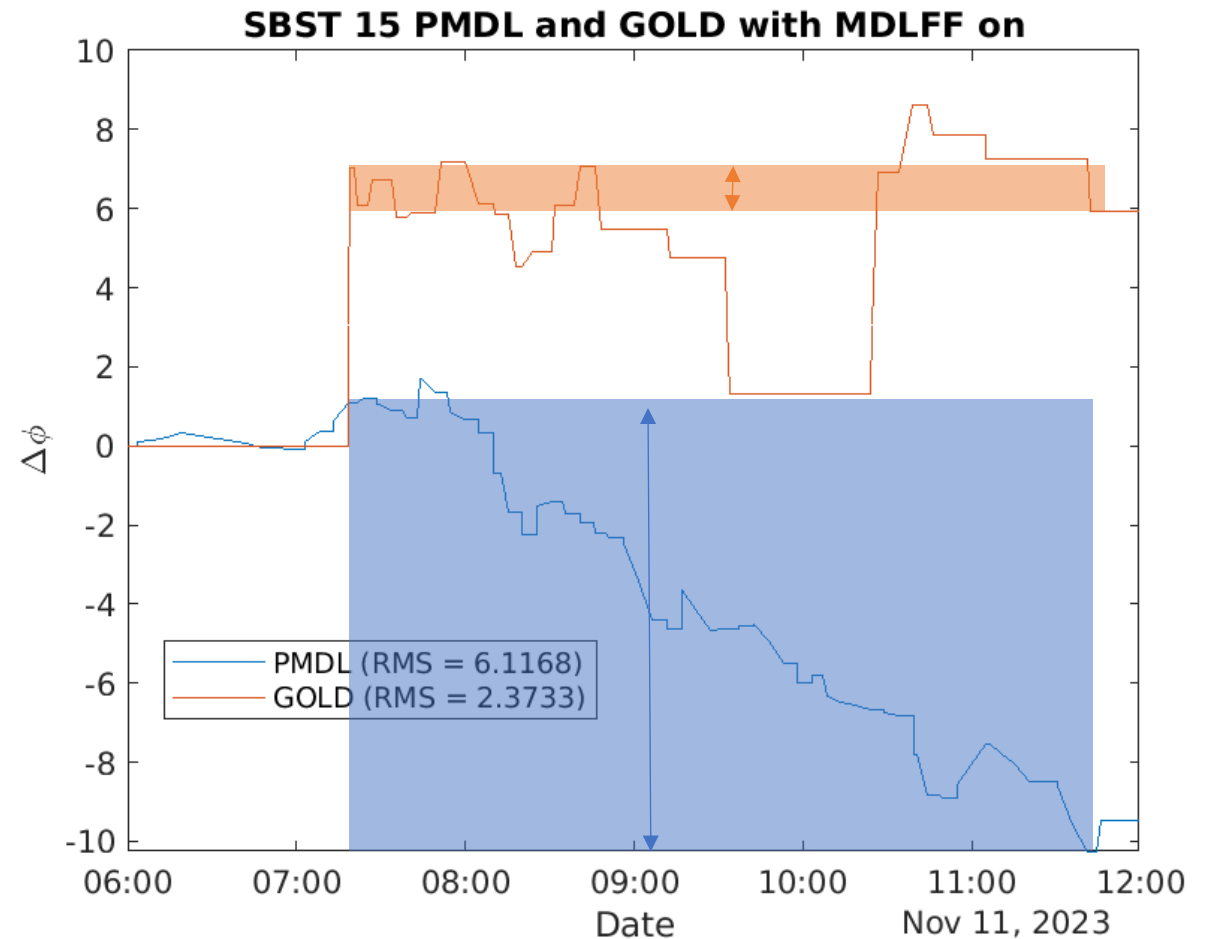


# Short-term errors

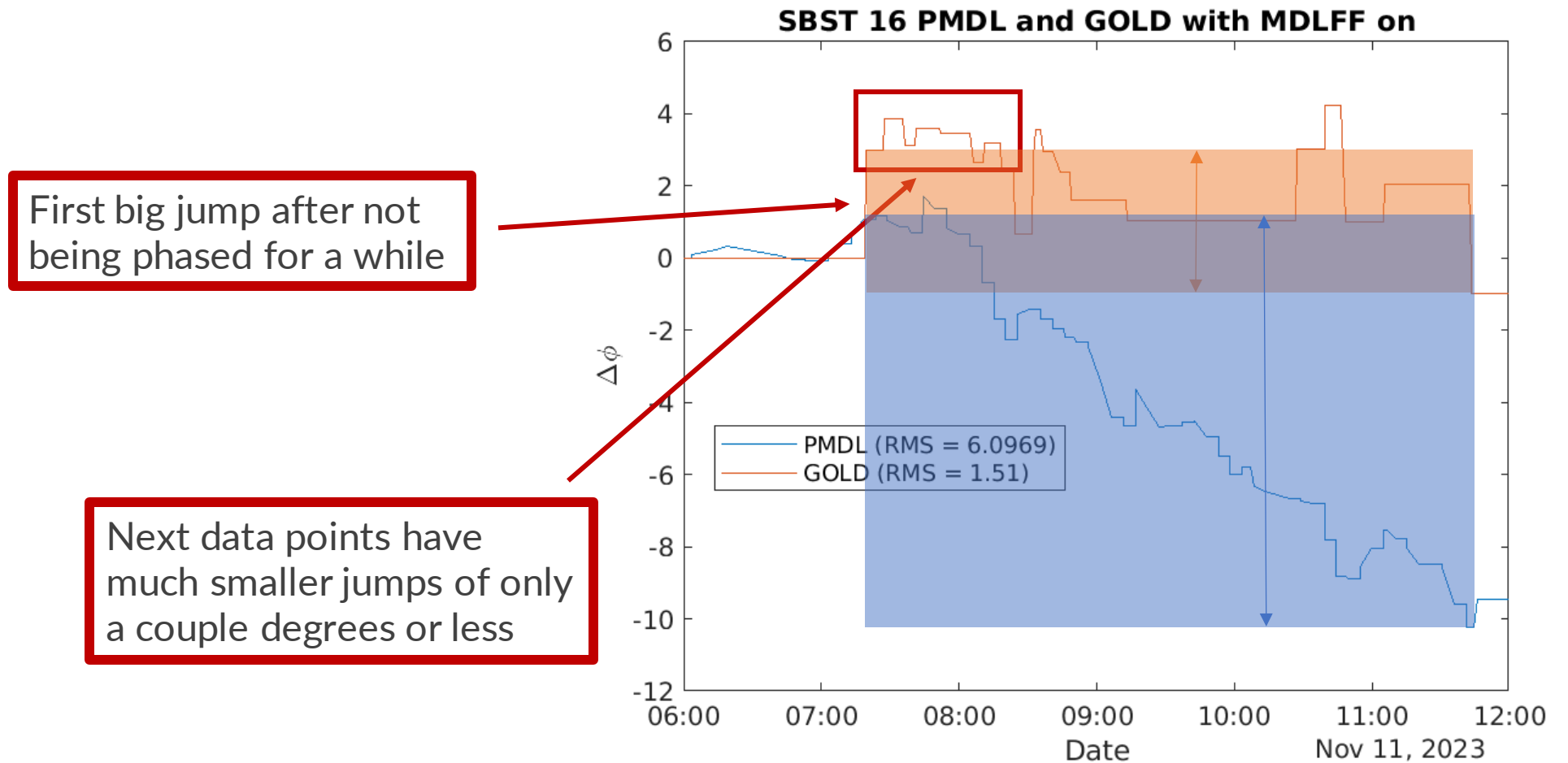
When the sub-boosters are phased frequently, the change in GOLD is small ( $\sim 1$  deg)

While the overall change in GOLD is minimal, the PMDL has changed by  $\sim 10$  degrees

Thus, the MDLFF is updating the PMDL values while keeping GOLD steady



# Short-term errors



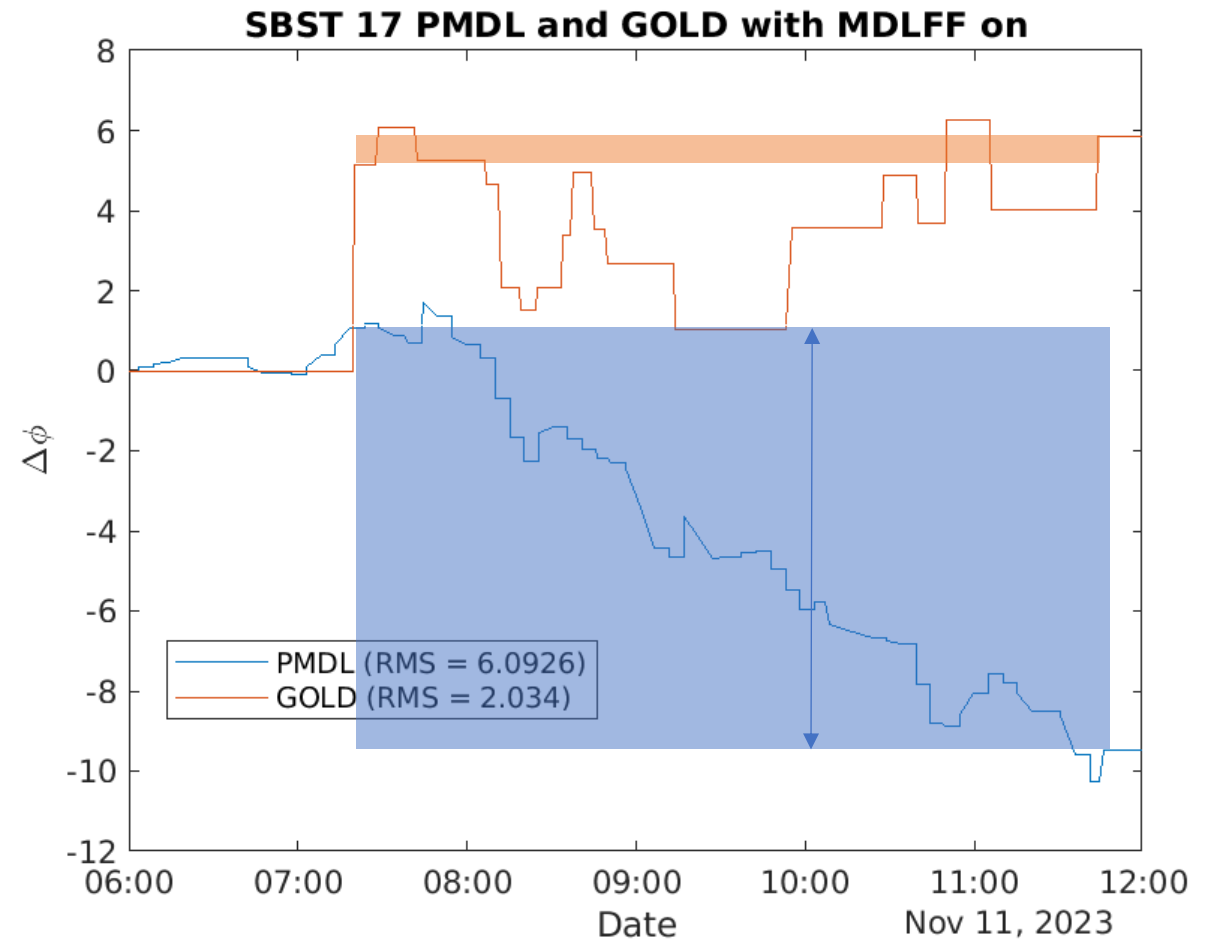


# Short-term errors

Sometimes, we still see bigger jumps of more than a couple degrees

These are caused by "random" interruptions, such as a poorly timed dither scan, a mechanical hitch in the MDL expansion joint, or something else

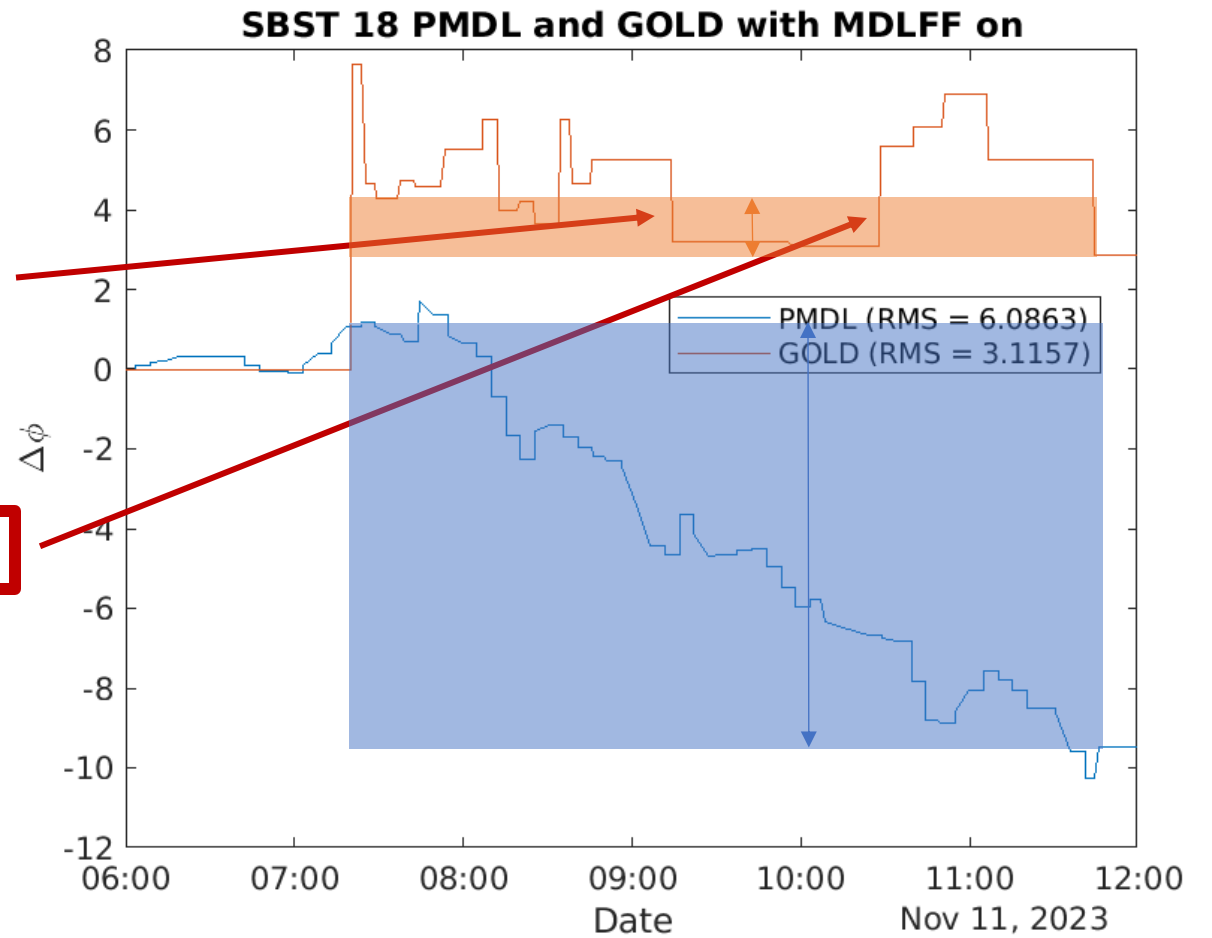
The MDLFF linear model cannot, and *should not*, account for random errors like these



# Short-term errors

Big jump (more than a couple degrees)

Big jump is "corrected" later



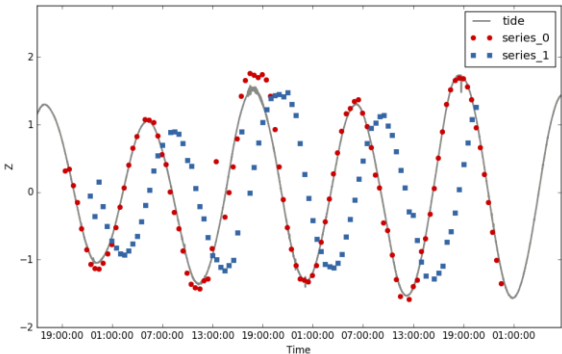
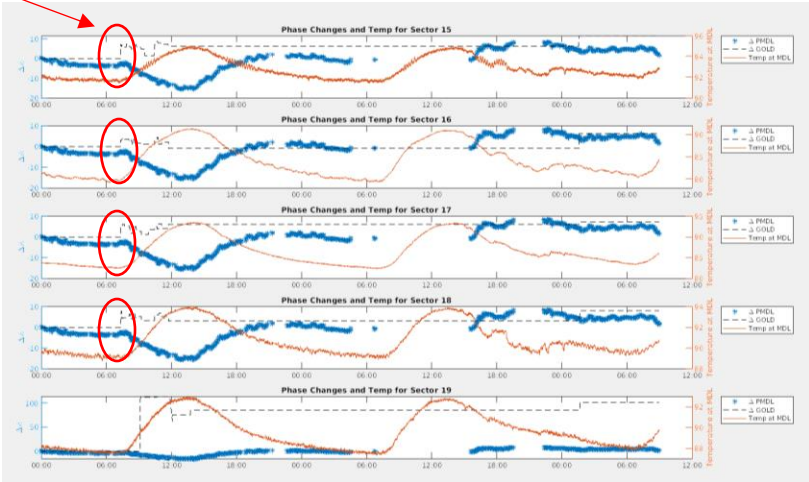
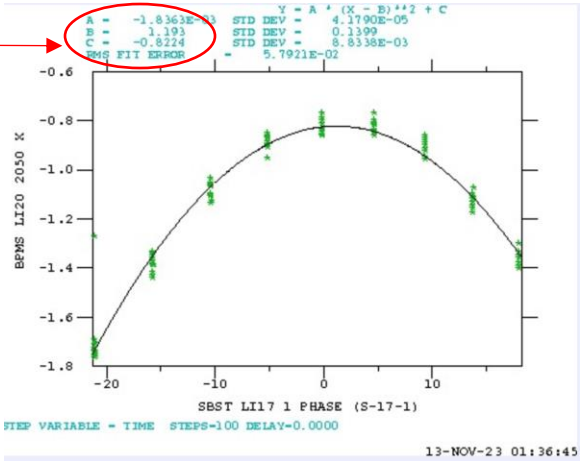
# Conclusions

---

- The MDLFF works best when paired with frequent dither scans
  - When sub-boosters are not phased at least once in a day, we see big jumps (more than a couple deg) in GOLD values
  - When sub-boosters are phased multiple times in a day, we see small GOLD changes of a couple degrees or less, and occasional bigger jumps due to random effects
- Due to random effects, it isn't possible to always keep the GOLD perfectly steady (changes less than 1 deg)
  - Even without random jumps, the accuracy of the MDLFF will be limited by repeatability of dither scan
  - Need to measure statistical error
  - e.g. Run 10 dithers of same sector in a row

# More to do

- Check repeatability of dither scans. Measure statistical error.
  - e.g. run 10 dithers of same sector in a row
- Check beam parameters are consistent
  - e.g. for 10 days in a row keep MDLFF on, phase subboosters daily
- Quantify short-term/long-term errors.
  - We tend to see big jump if sub-booster hasn't been phased in a while.
  - If jumps grow as  $\sqrt{T}$  between phasing, then it is a random effect.
- Try time-shifted correlations.
  - Perform auto-correlation on the data.
- Repeat experiment where we keep FF on but not writing PMDL values
  - Turn off +/- 1 deg limit feature

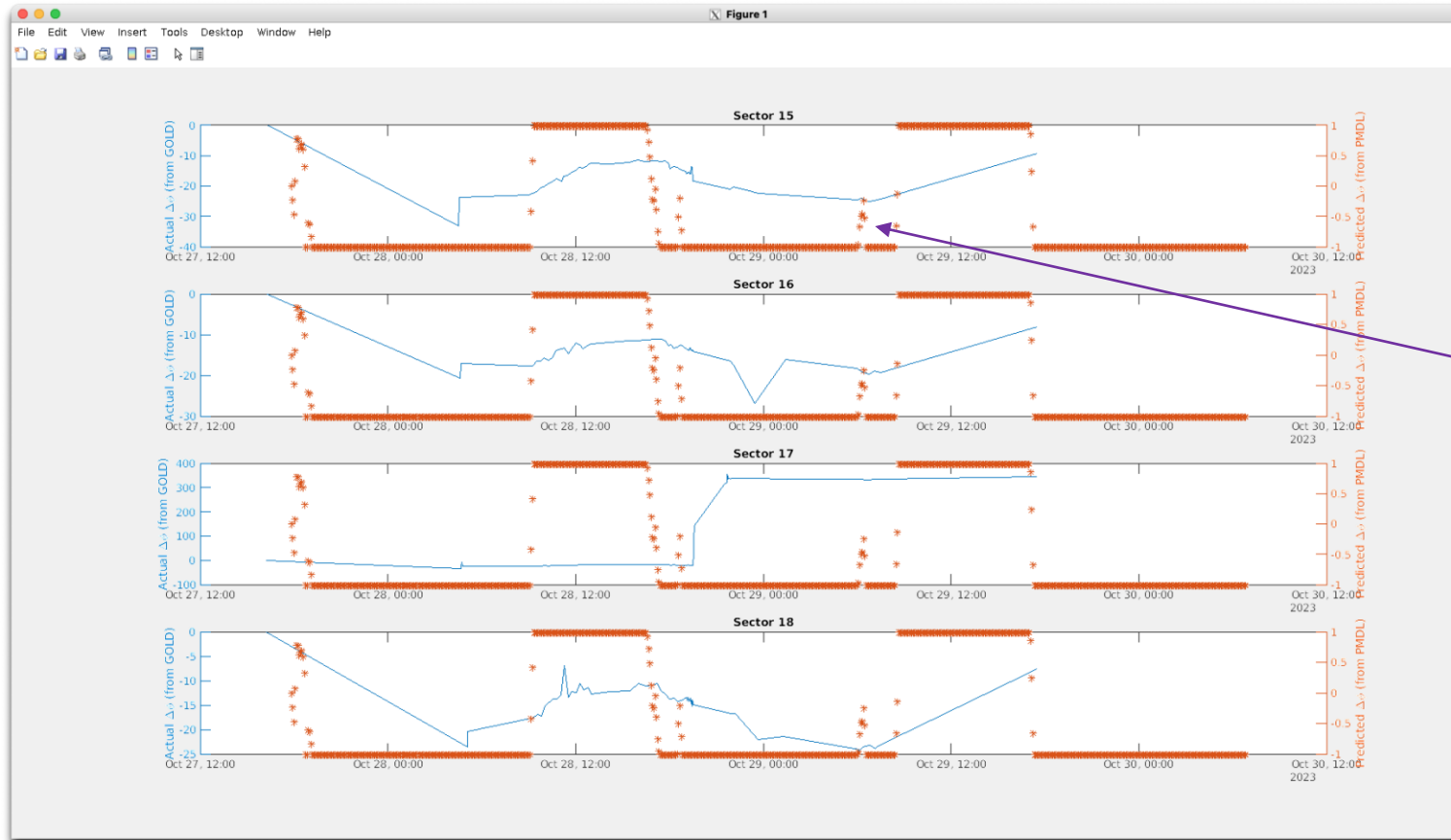


---

## Data from L3 scans over the weekend (Oct. 27 - 29)

# MDLFF on, not writing new PMDL values

Plots showing GOLD data from archiver and predicted PMDL values generated by MDLFF



- Plateaus due to +/- 1 deg limit
- Strange behavior in S17
- S19 also not working, left out of plots
- Spikes?

# Next steps

---

## Repeat with modifications in the code

Either:

1. Comment out feature that limits phase changes to +/- 1 degree per step
2. Instead of calling "caget" to get current PMDL value from EPICS, use PMDL value from last step (since we are saving this information anyways)
  - This would most closely resemble what the MDLFF does when it is on and writing PMDL values

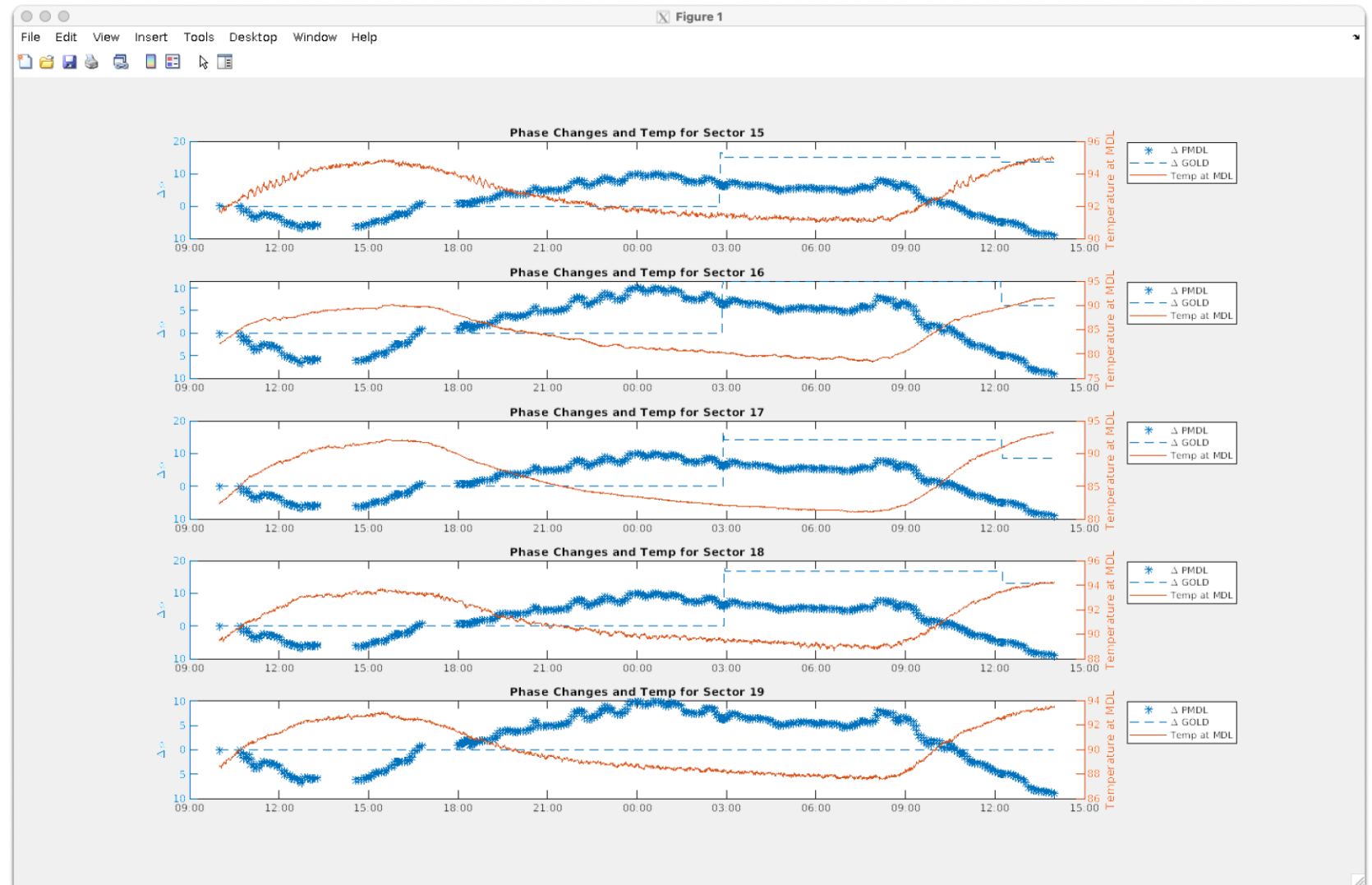
In the meantime:

- Since the FF is on (as of Wed morning) and writing PMDL values, we can alternatively evaluate the performance of the MDLFF by performing phase scans and seeing if GOLD values are constant

# MDLFF on, writing new PMDL values

GOLD still showing some changes

Will keep updating figure as more data is collected

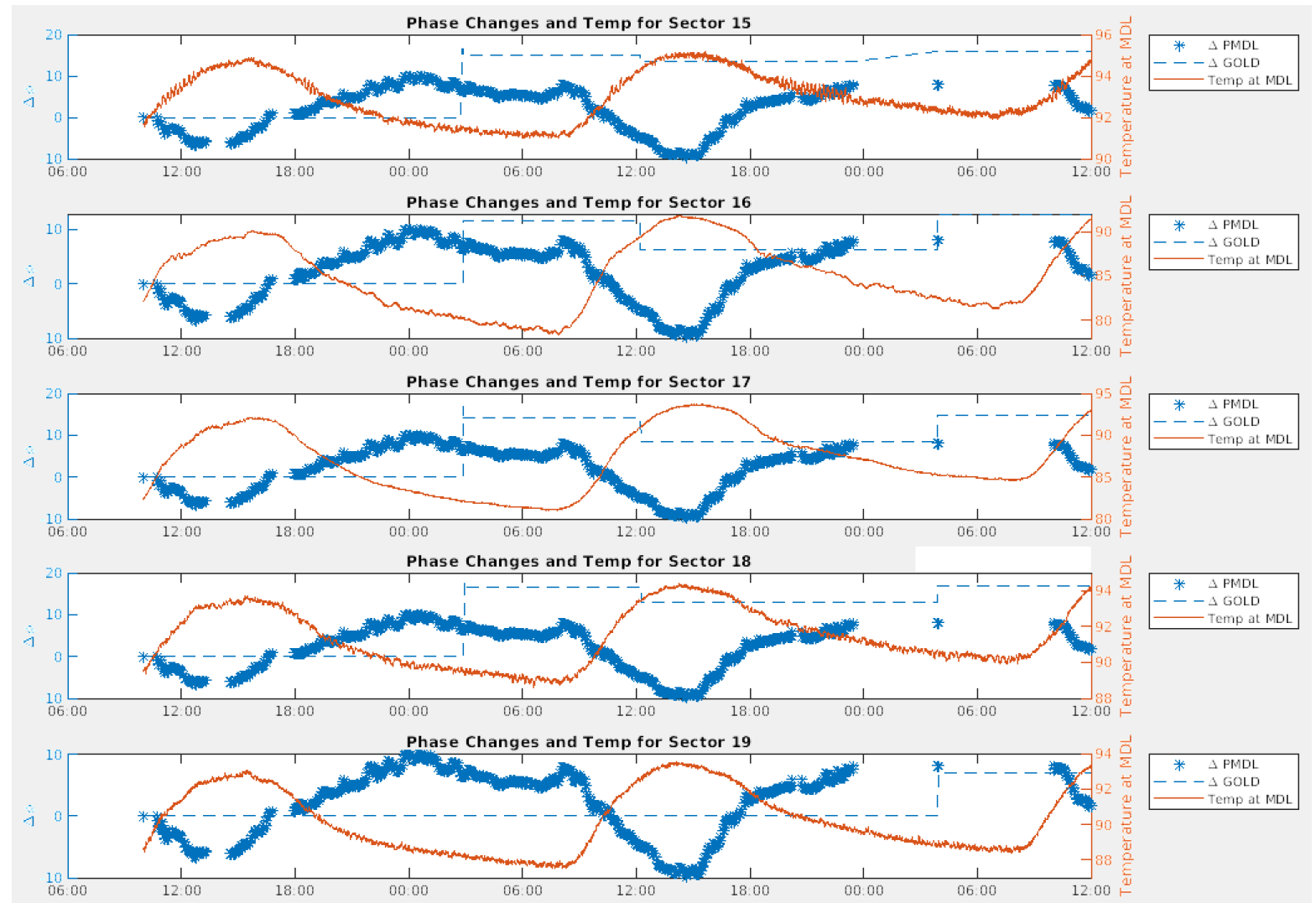




# MDLFF on, writing new PMDL values

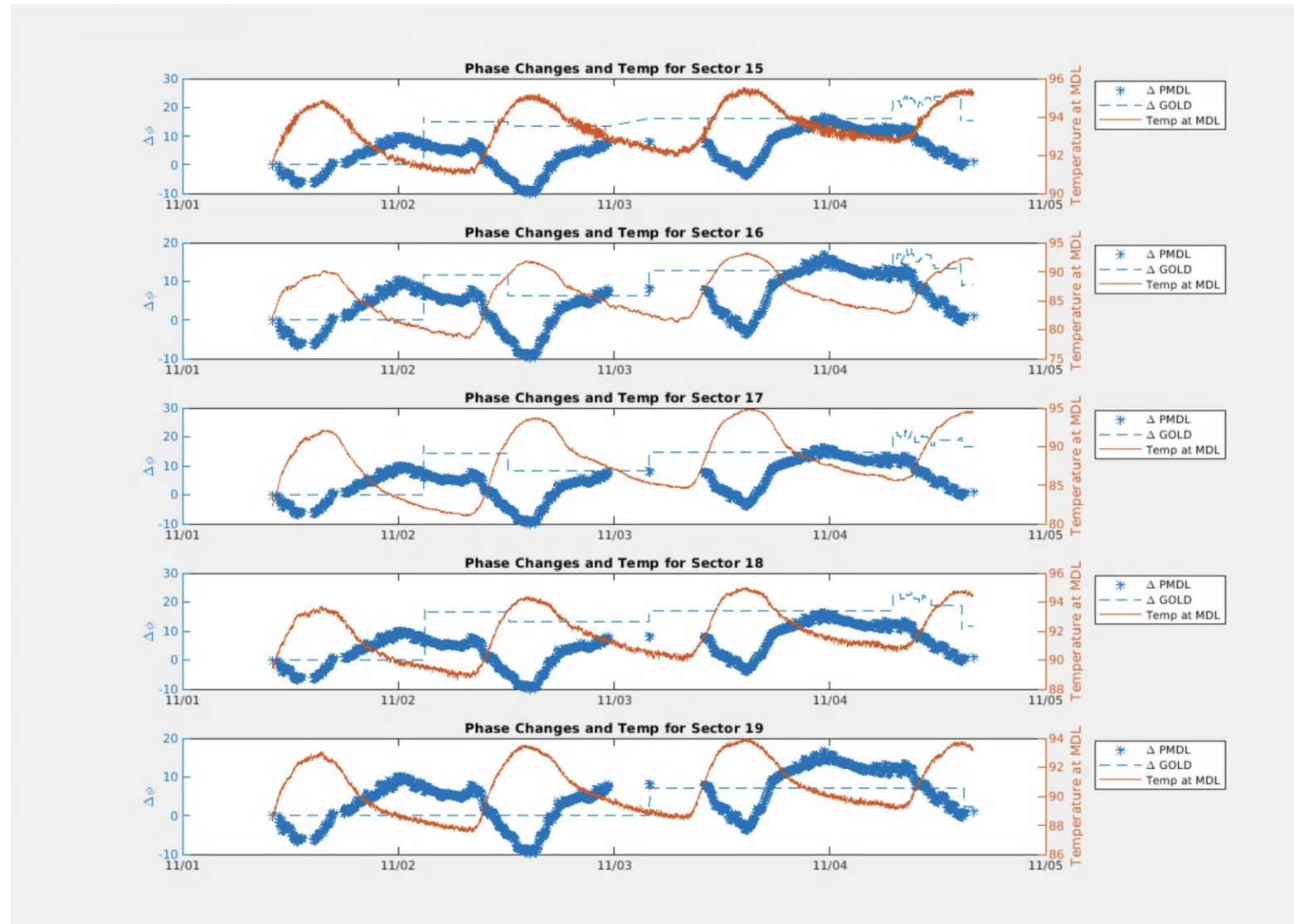
GOLD changes seem to be getting smaller

MDLFF turned off last night



# MDLFF on, writing new PMDL values

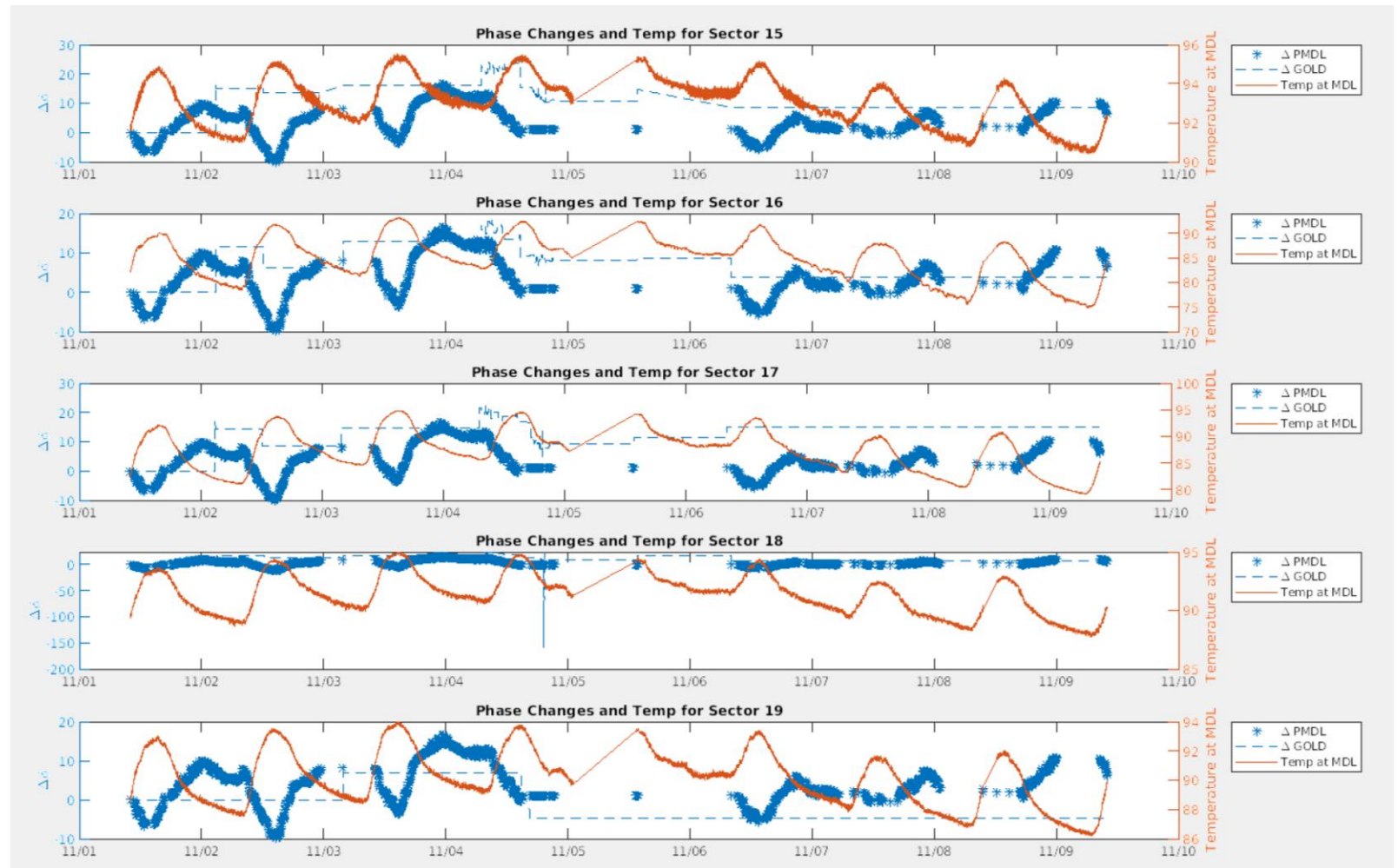
MDLFF turned off 11/4  
around 16:00



# MDLFF on, writing new PMDL values

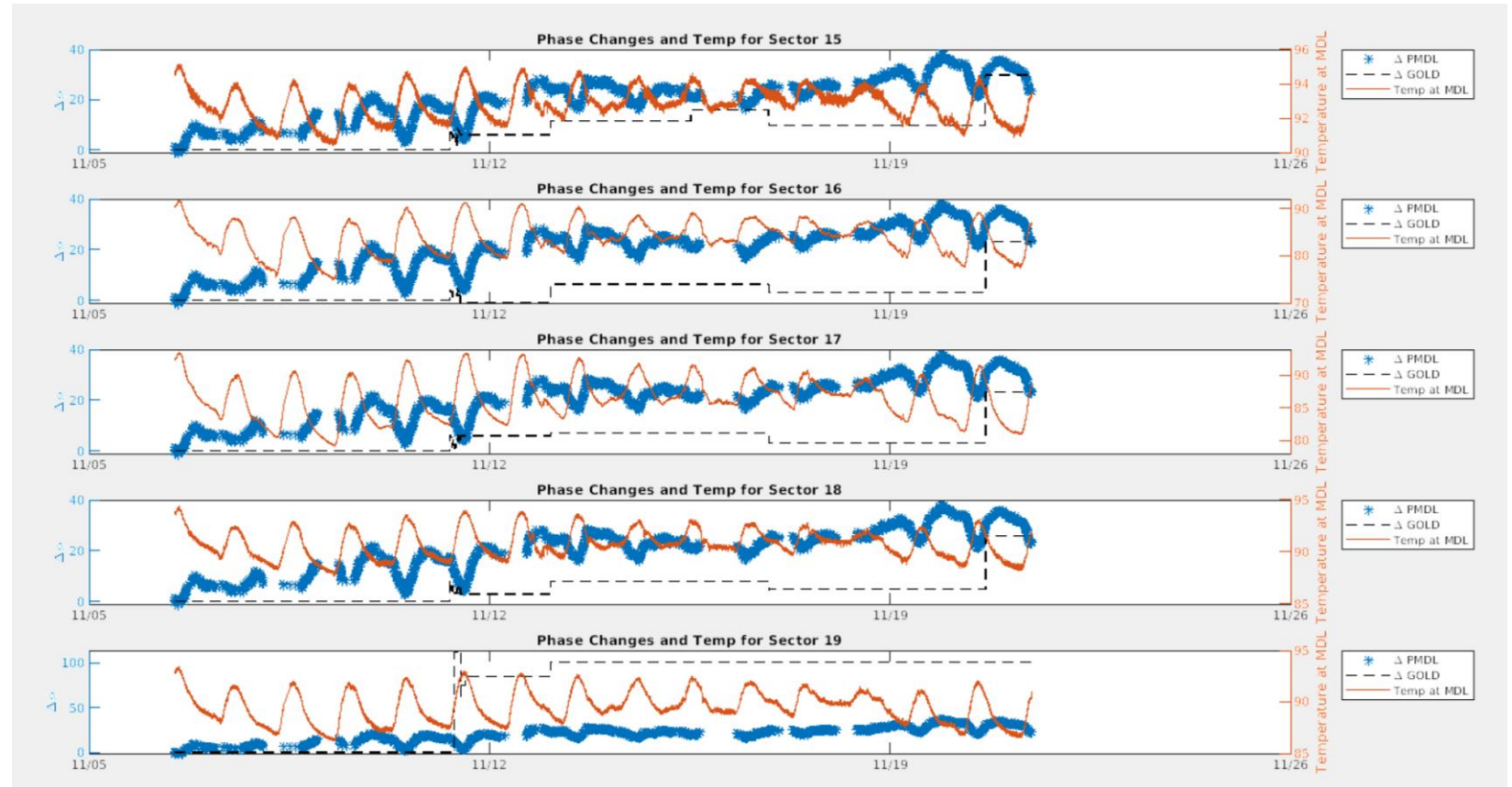
MDLFF has been on and off

No new GOLD data since 11/6



# MDLFF on, writing new PMDL values

Big jump in GOLD on 11/20



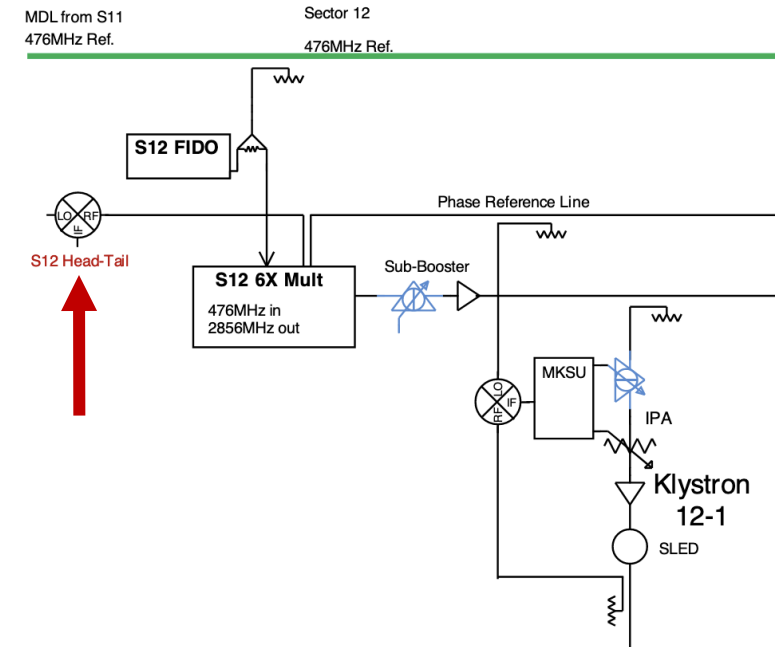
---

# Head-Tail Phase Monitor Data

# MDL Feed Forward

## Head-Tail Phase Monitors

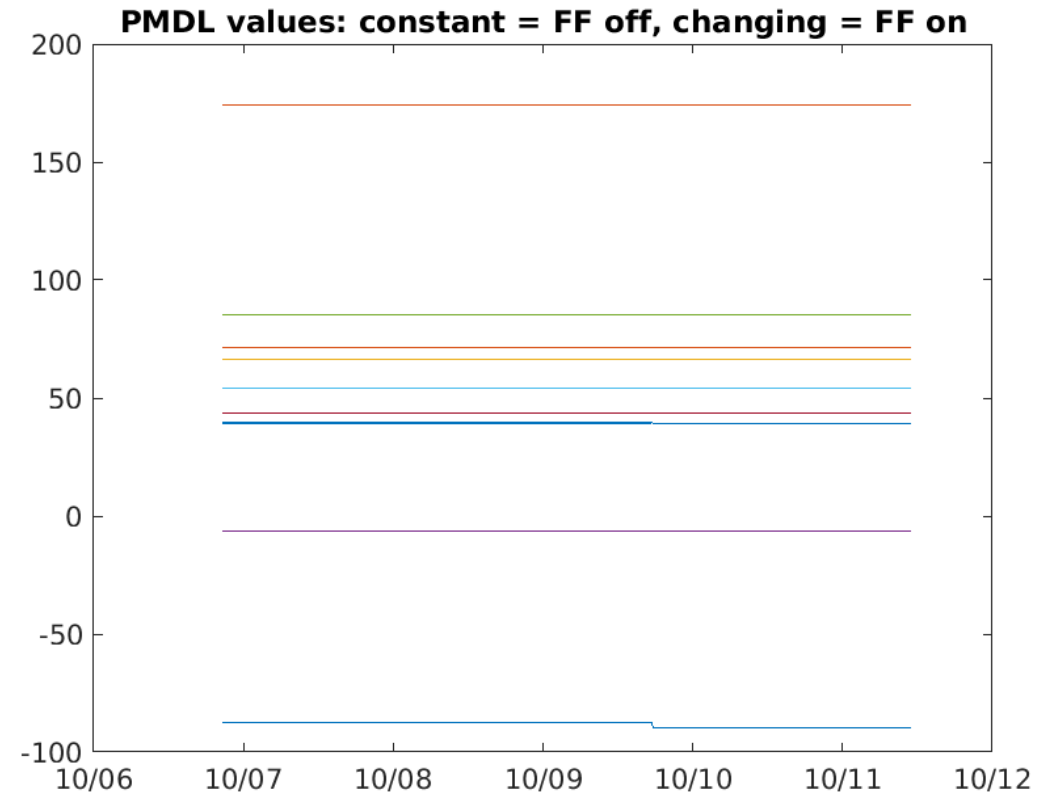
- Head-Tail Phase Monitors measure the difference between phase reference lines of adjacent sectors
- They might provide information about MDL expansion/contraction
- We think that when the Feed Forward is on, the Head-Tail will be fixed
- When Feed Forward is off, the Head-Tail will track with the temperature at the MDL at each sector



# MDL Feed Forward

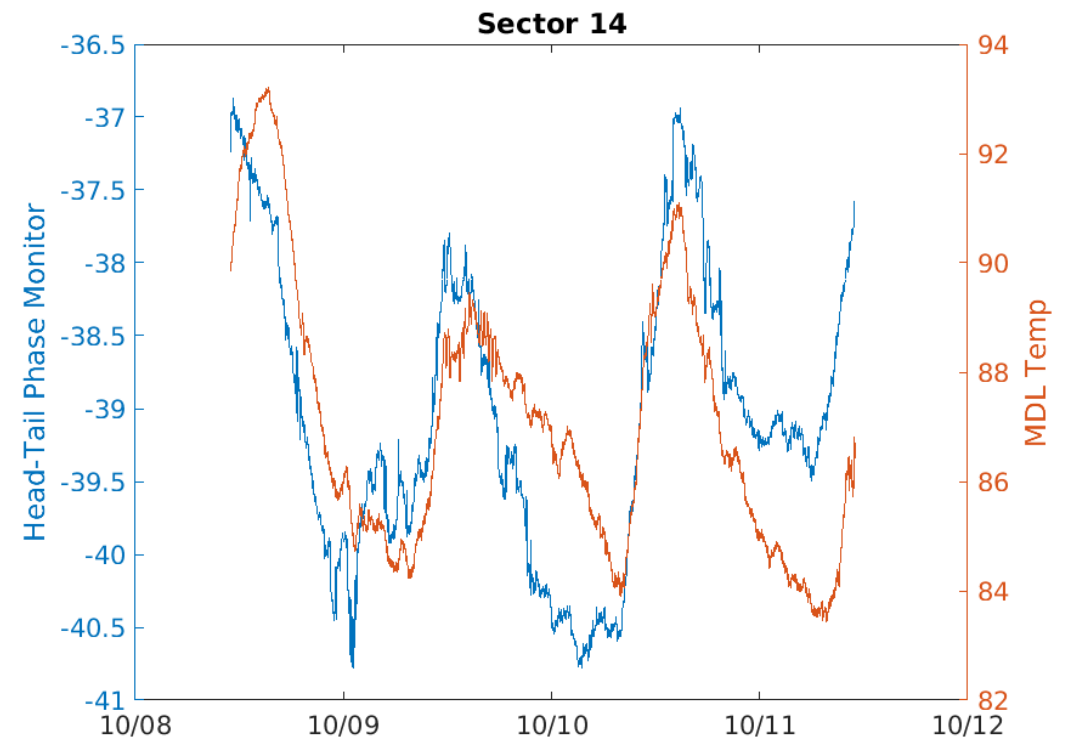
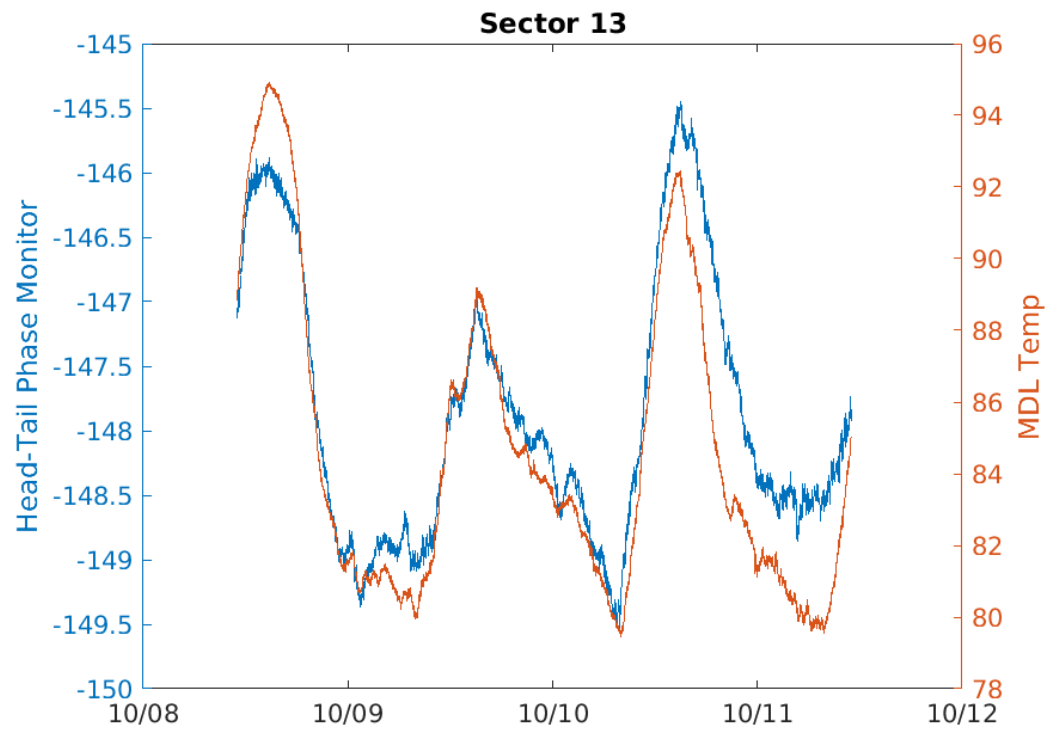
## PMDL: Feed Forward Off

- We can assume the Feed Forward was turned off during a specified time range if the PMDL values stay constant
- Time range: 10/8/23 11:00:00 to 10/11/23 11:00:00



# MDL Feed Forward

Plots at each sector (FF OFF)

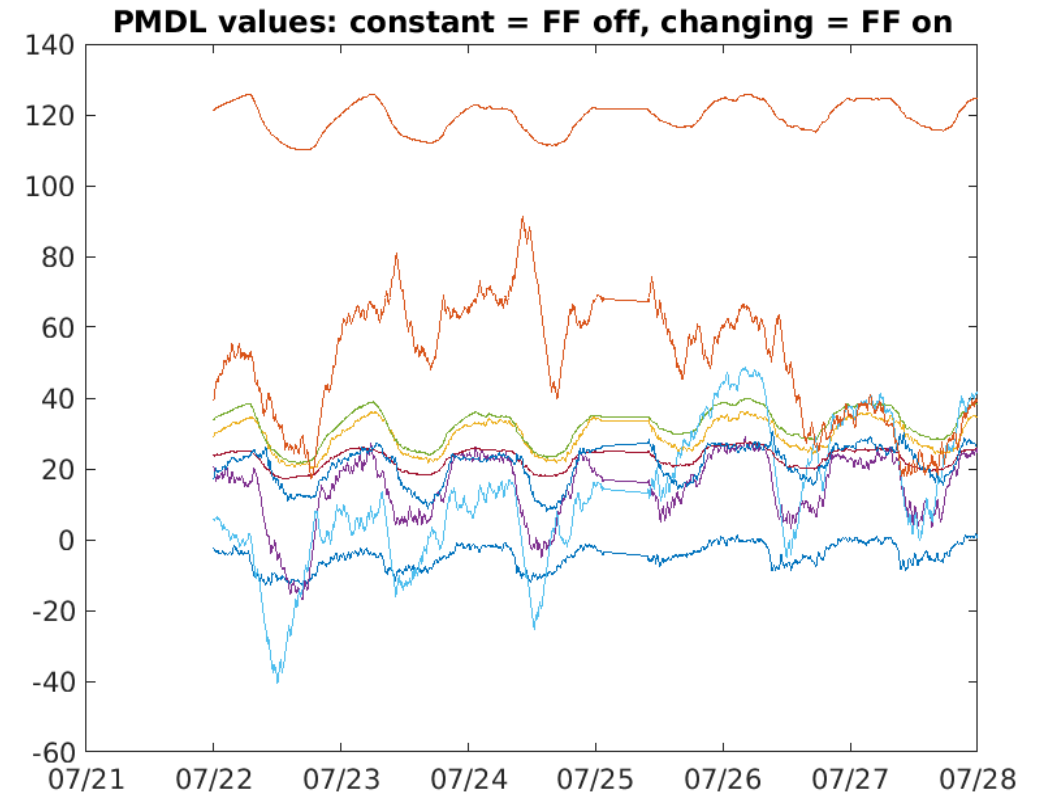




# MDL Feed Forward

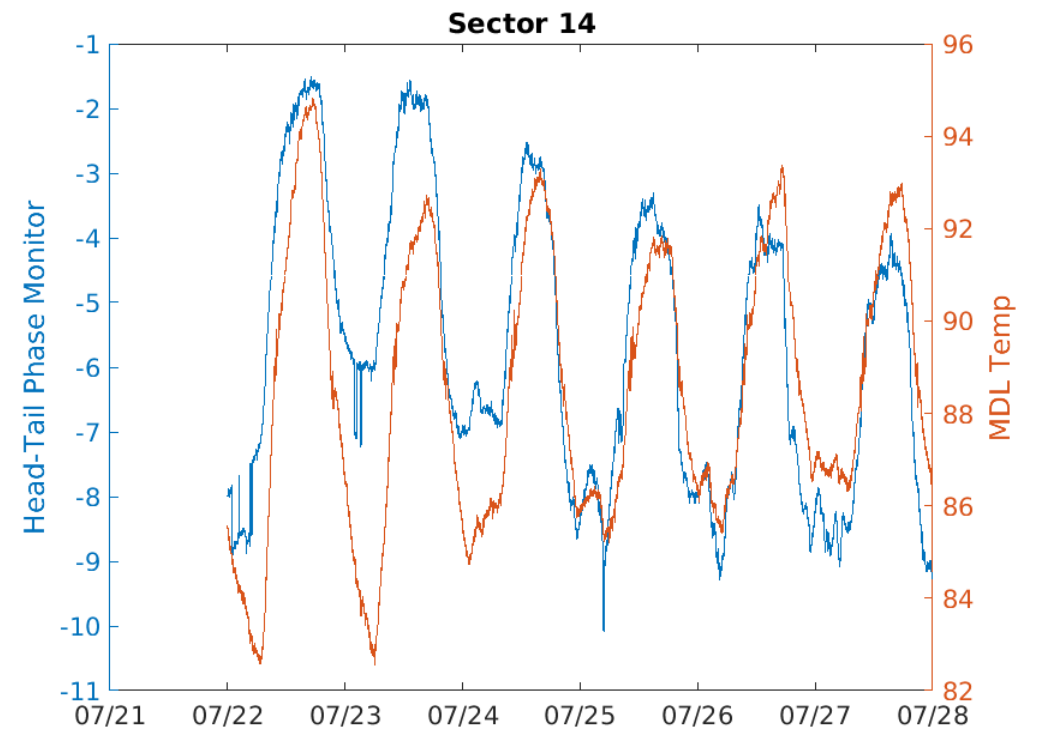
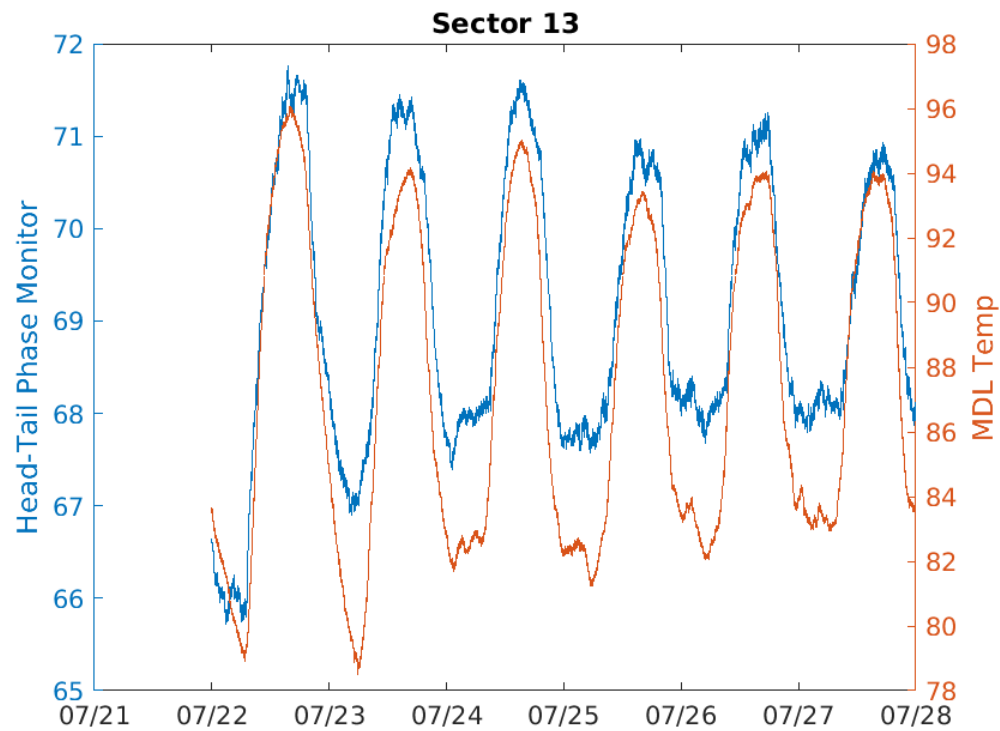
## Head-Tail Phase Monitors: Feed Forward On

- As expected, the Head-tail monitors track changes in MDL temperature when the Feed Forward is off
- We think that when the FF is **on**, the constantly updating PMDL offset will keep the difference between adjacent phase reference lines **fixed**
- We can assume the FF was turned **on** during a specified time range if the PMDL values are changing
- Time range: 7/22/22 00:00:00 to 7/28/22 00:00:00



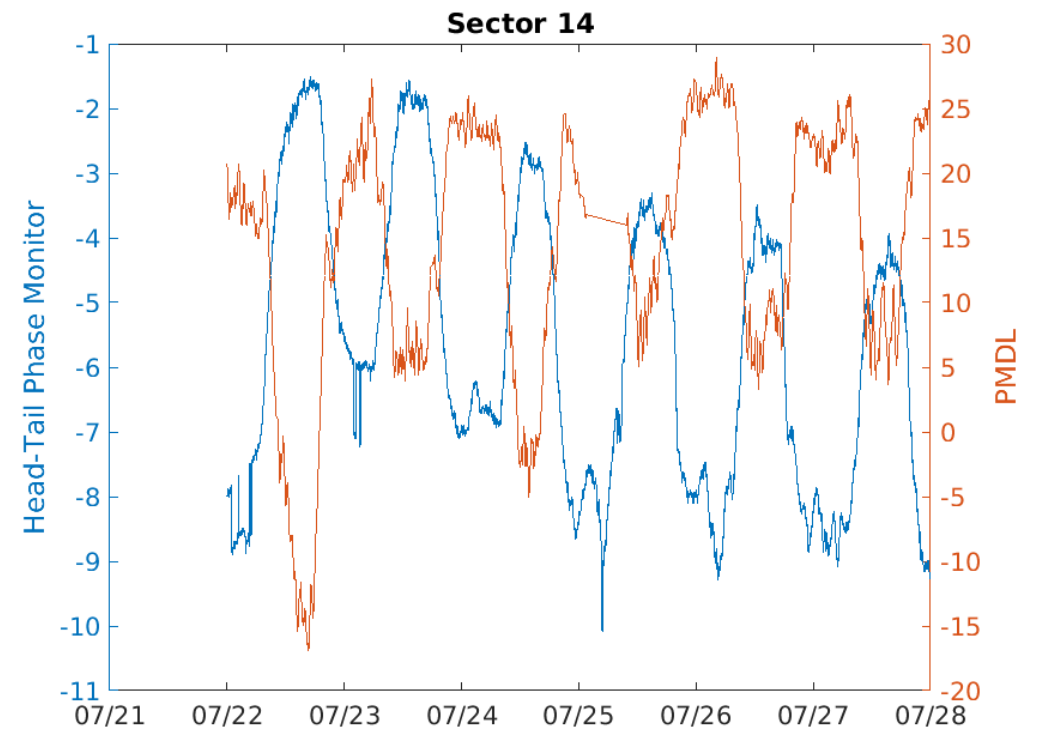
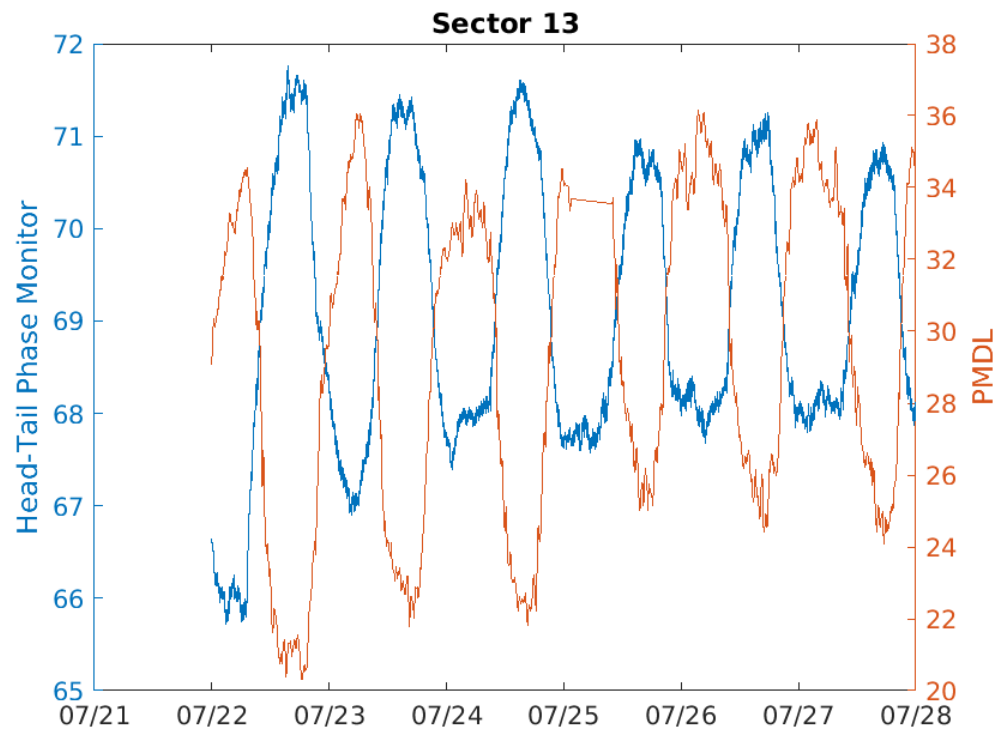
# MDL Feed Forward

Plots at each sector: H-T and MDL temp (FF ON)



# MDL Feed Forward

Plots at each sector: H-T and PMDL (FF ON)



# MDL Feed Forward

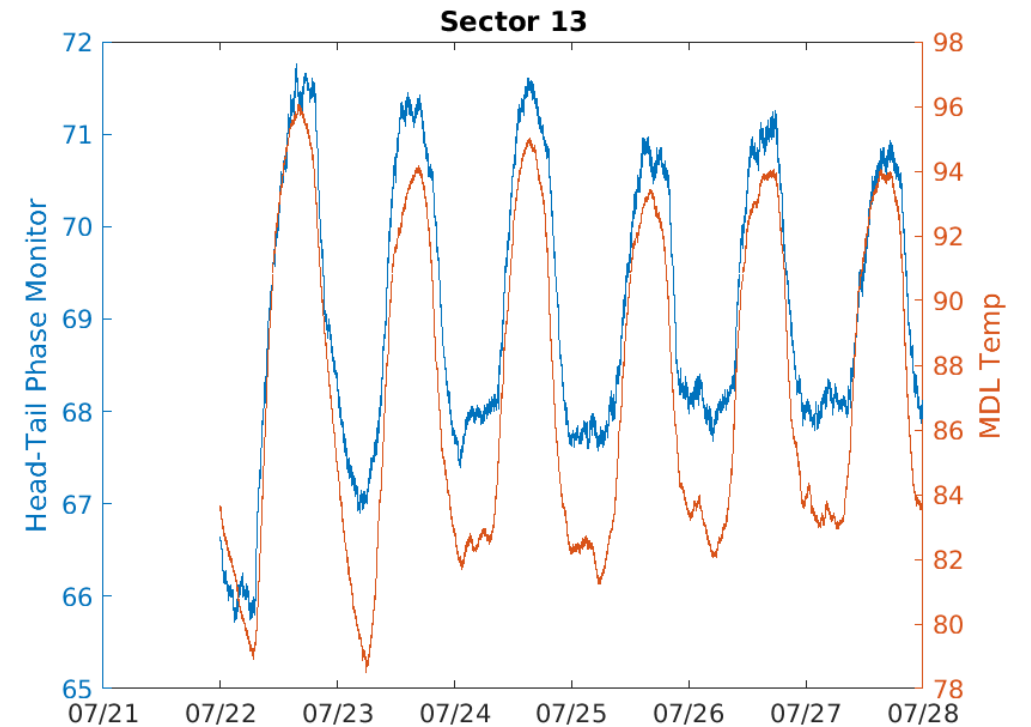
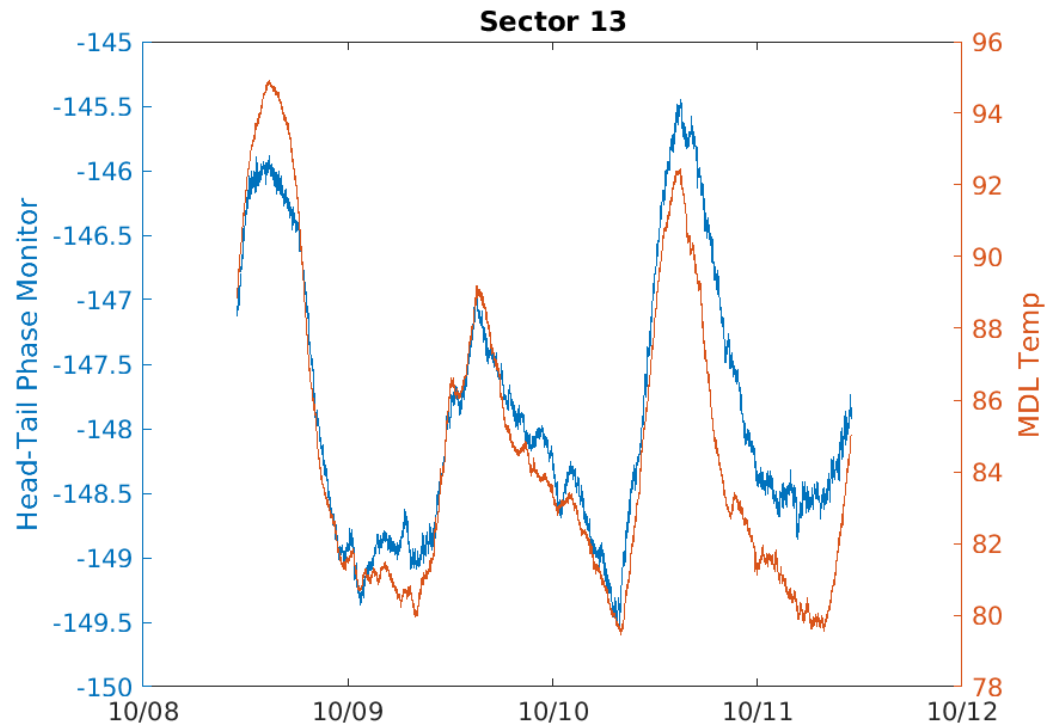
---

## Head-Tail Phase Monitors: Feed Forward On

- The Head-tail monitor reading does **not** appear to remain fixed when the FF is on
- The Head-tail monitors seem to track changes in the PMDL
- It's possible that the changes in the Head-tail monitor are **caused by** the PMDL values
- More information is needed to understand how the Head-tail monitors work

# MDL Feed Forward

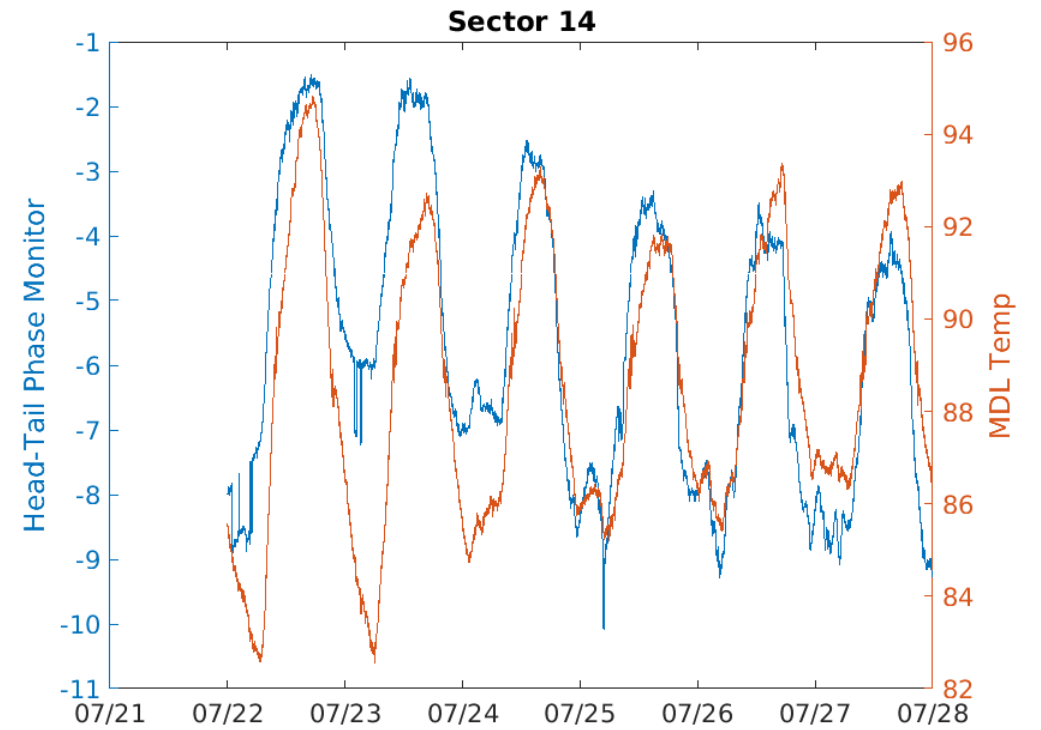
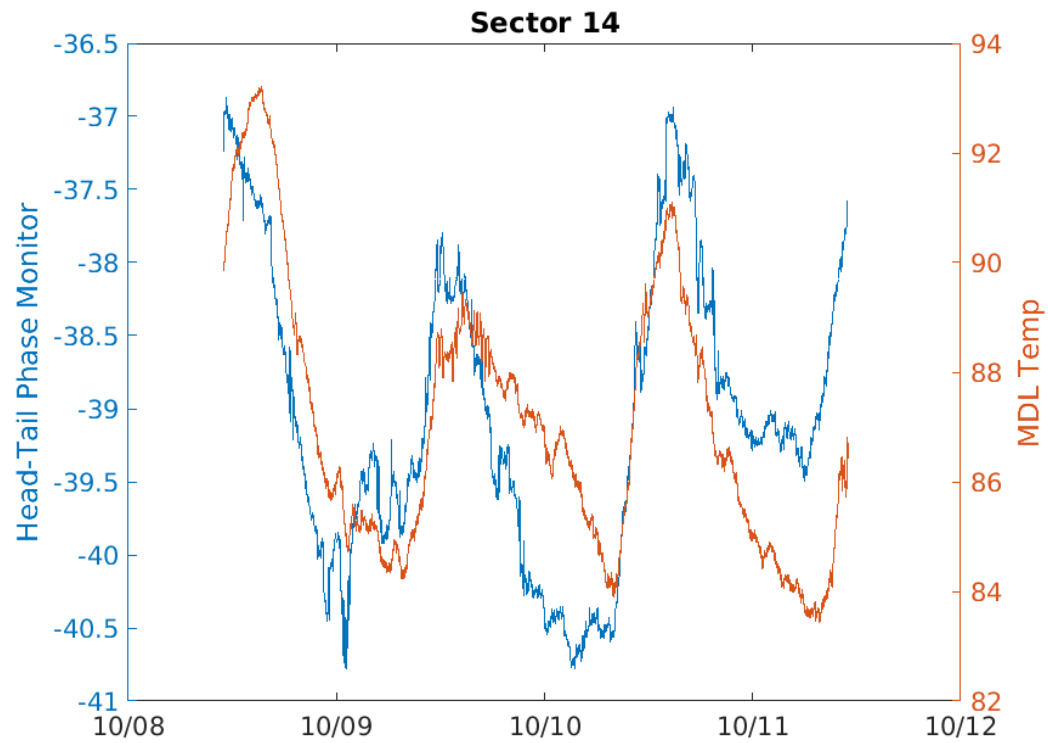
## FF OFF vs FF ON



Regardless of whether the FF is off or on, the Head-Tail monitors seem to track the MDL temp

# MDL Feed Forward

## FF OFF vs FF ON

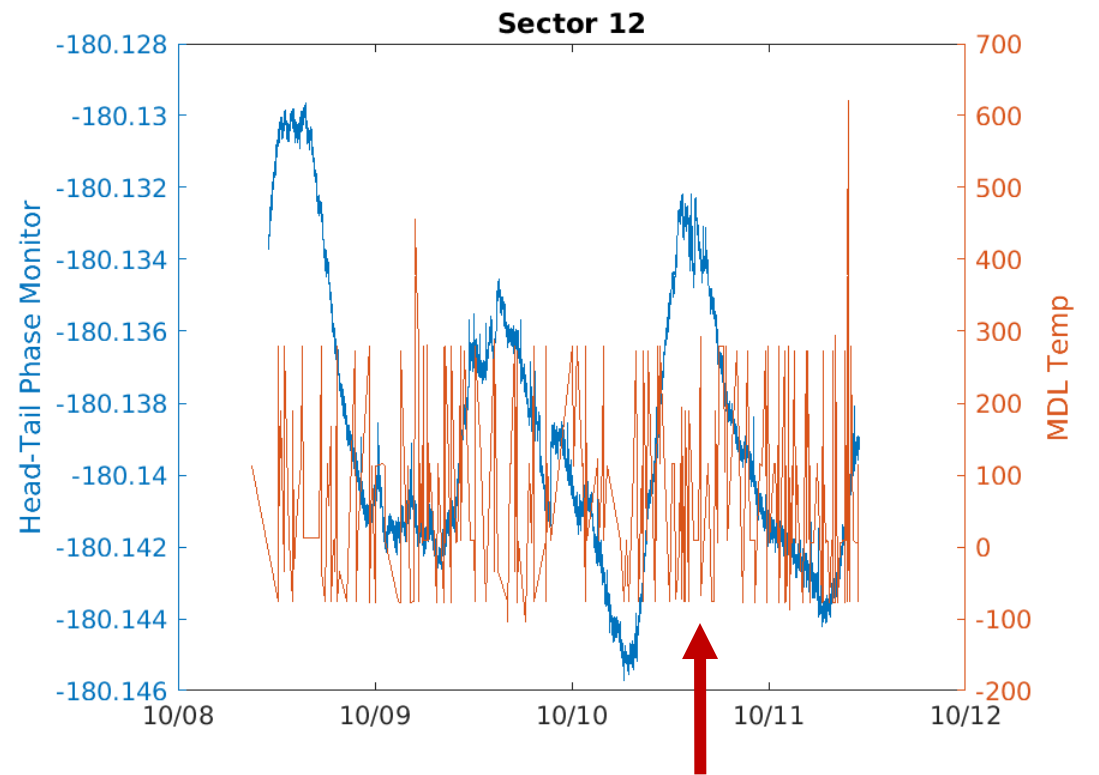
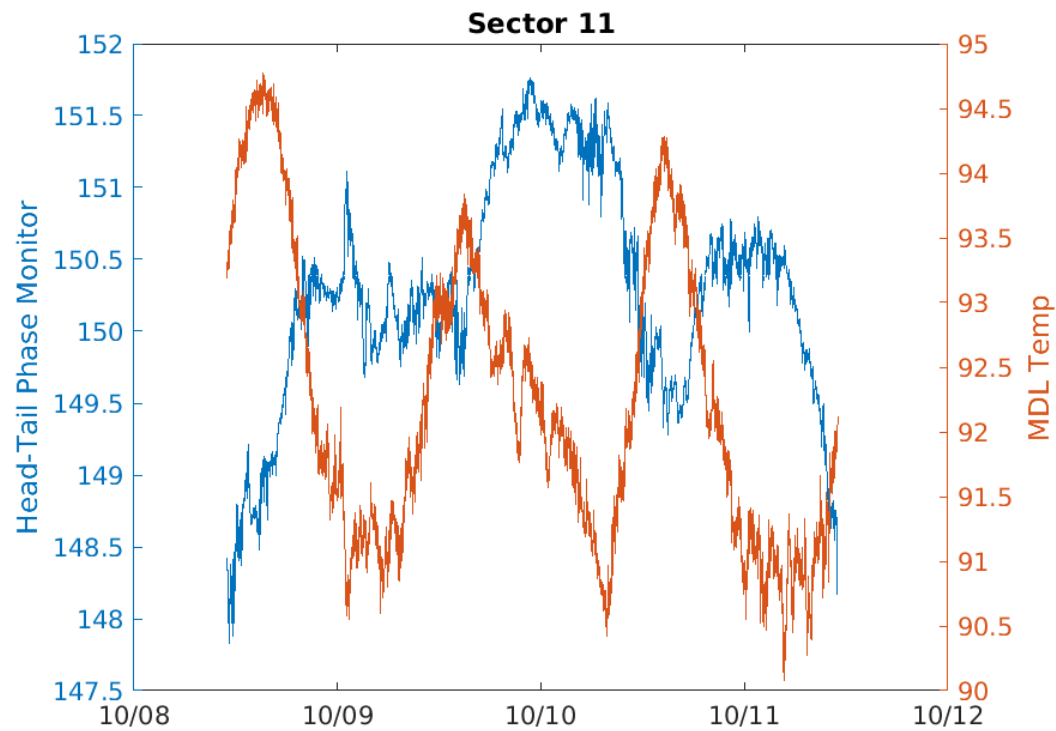


---

# All Head-Tail Monitor Plots

# MDL Feed Forward

Plots at each sector (FF OFF)

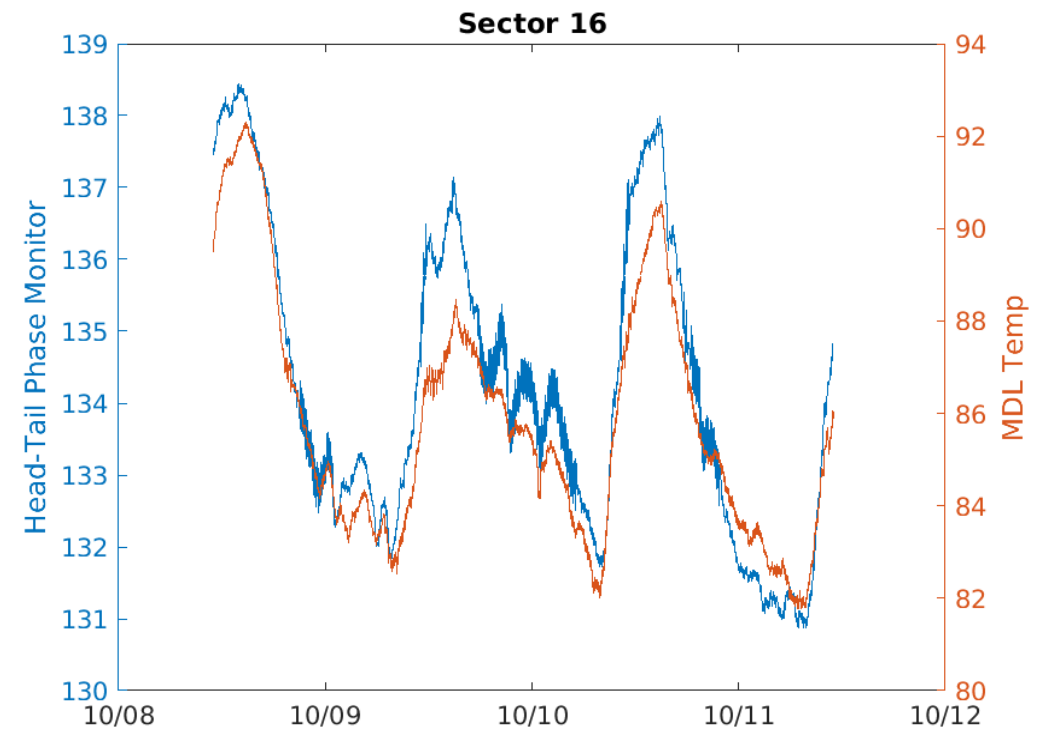
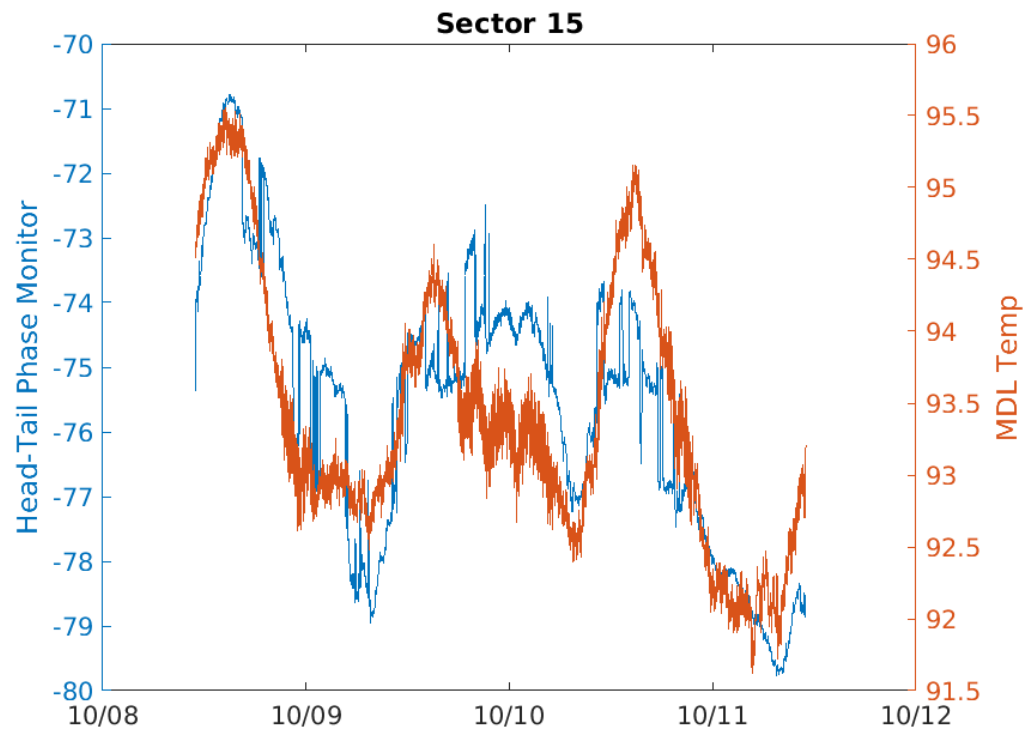


Device may need to be fixed/replaced



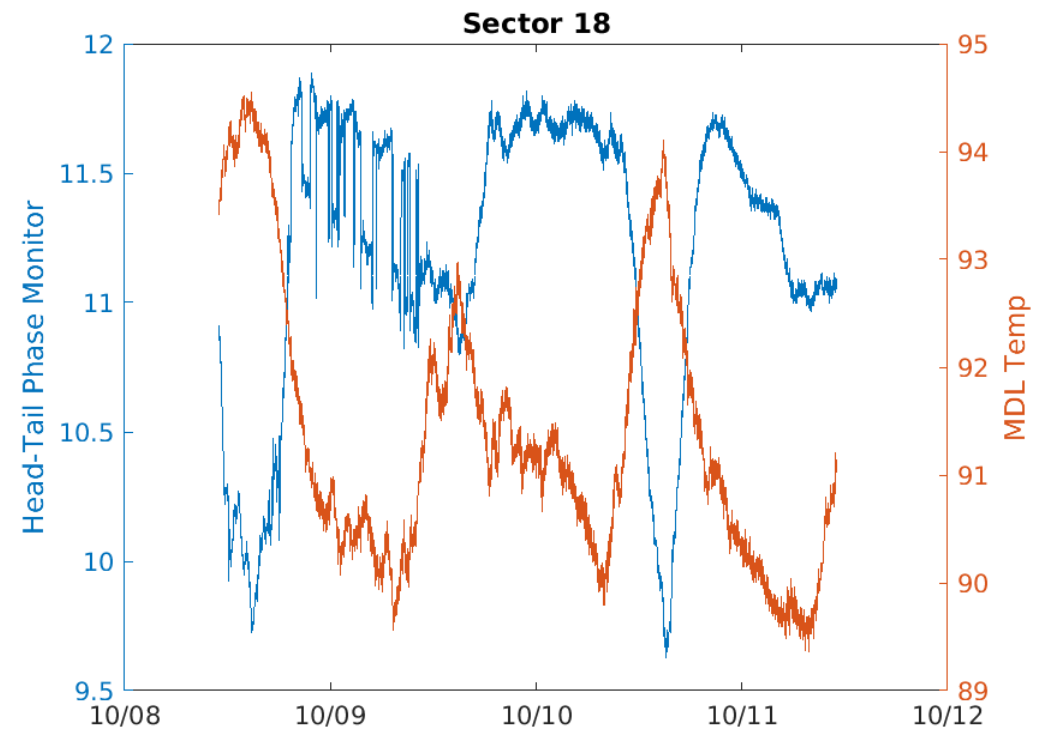
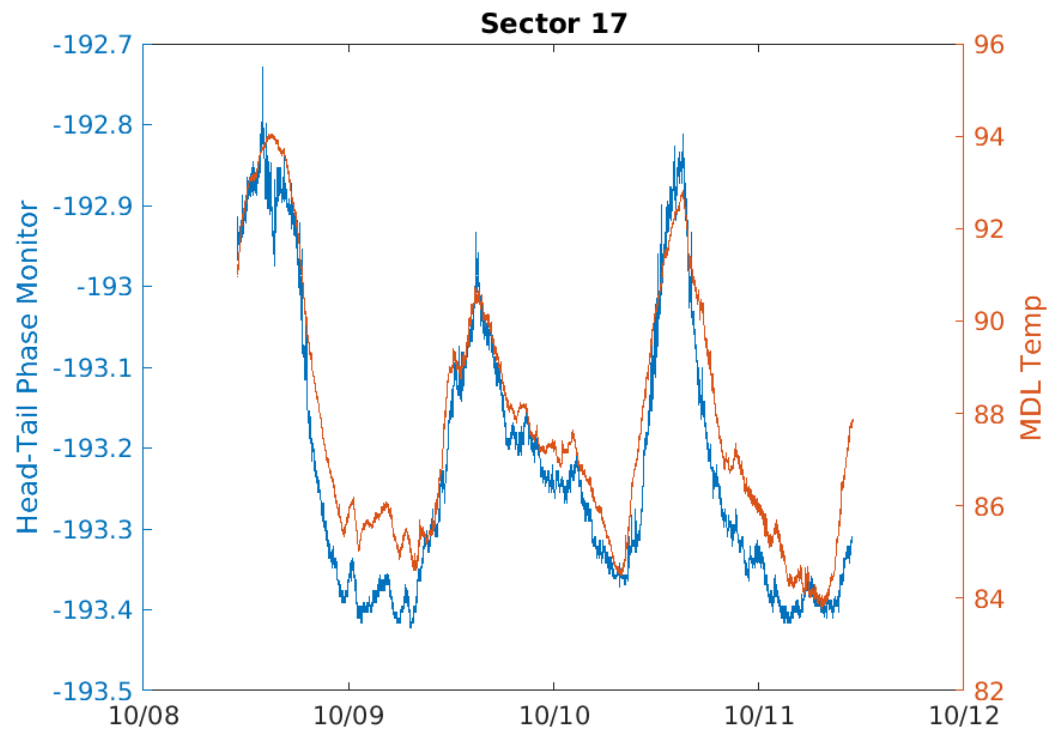
# MDL Feed Forward

Plots at each sector (FF OFF)



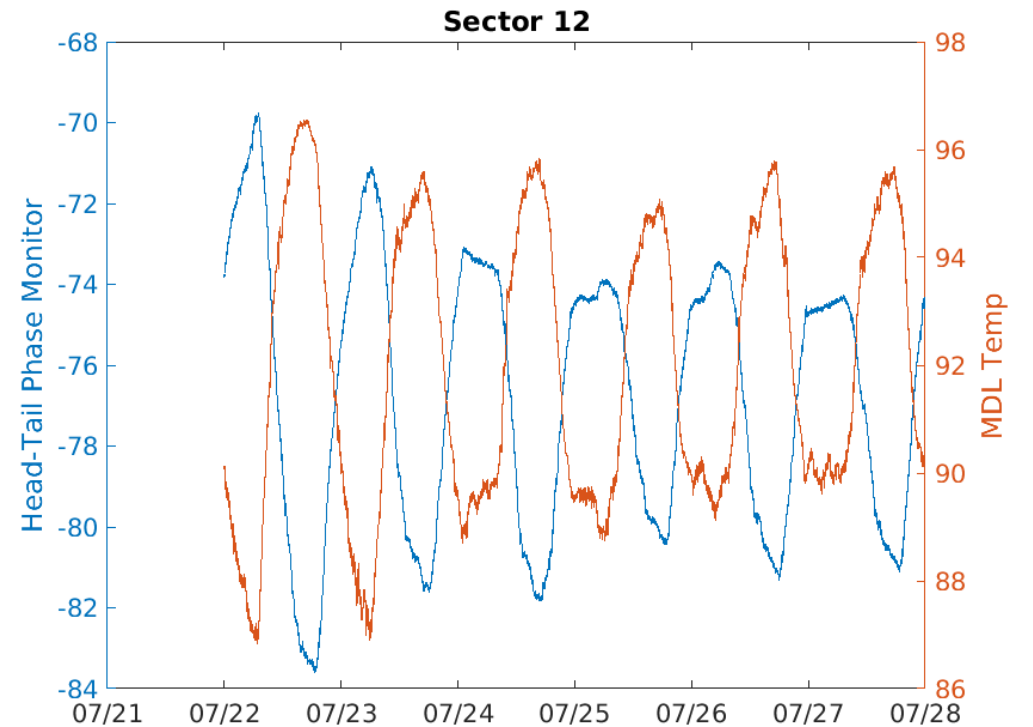
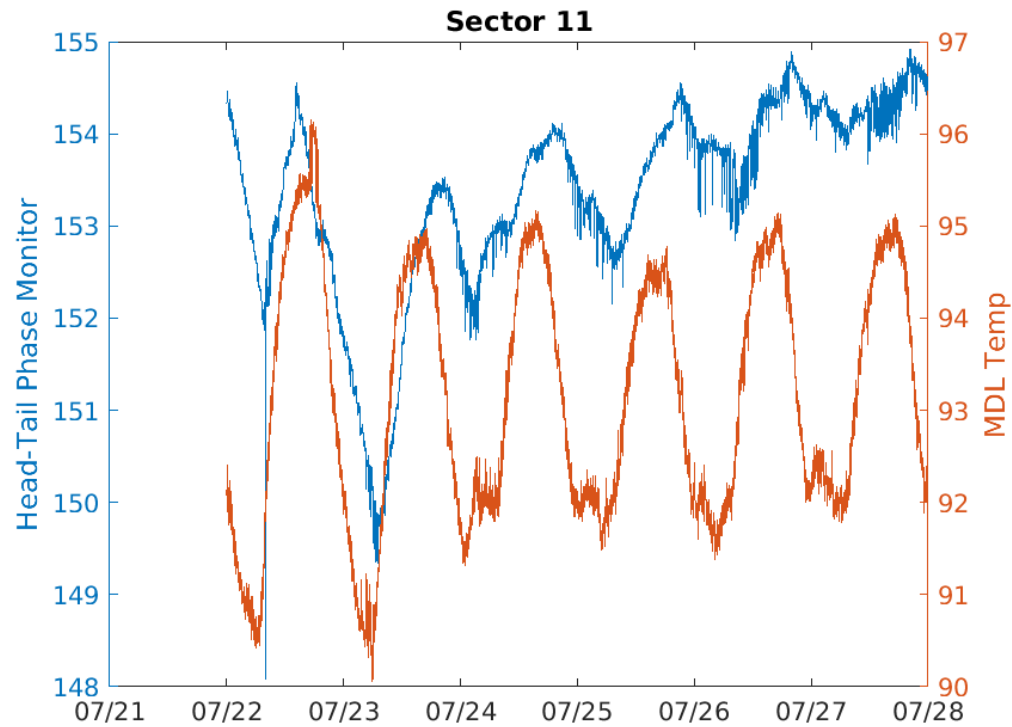
# MDL Feed Forward

Plots at each sector (FF OFF)



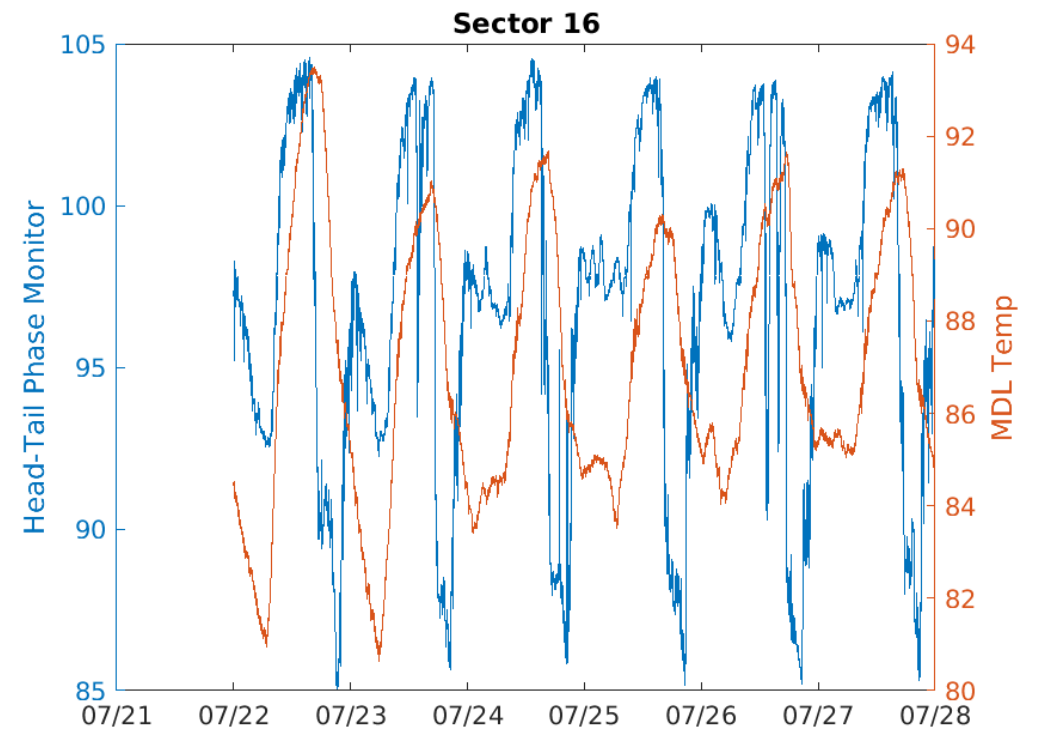
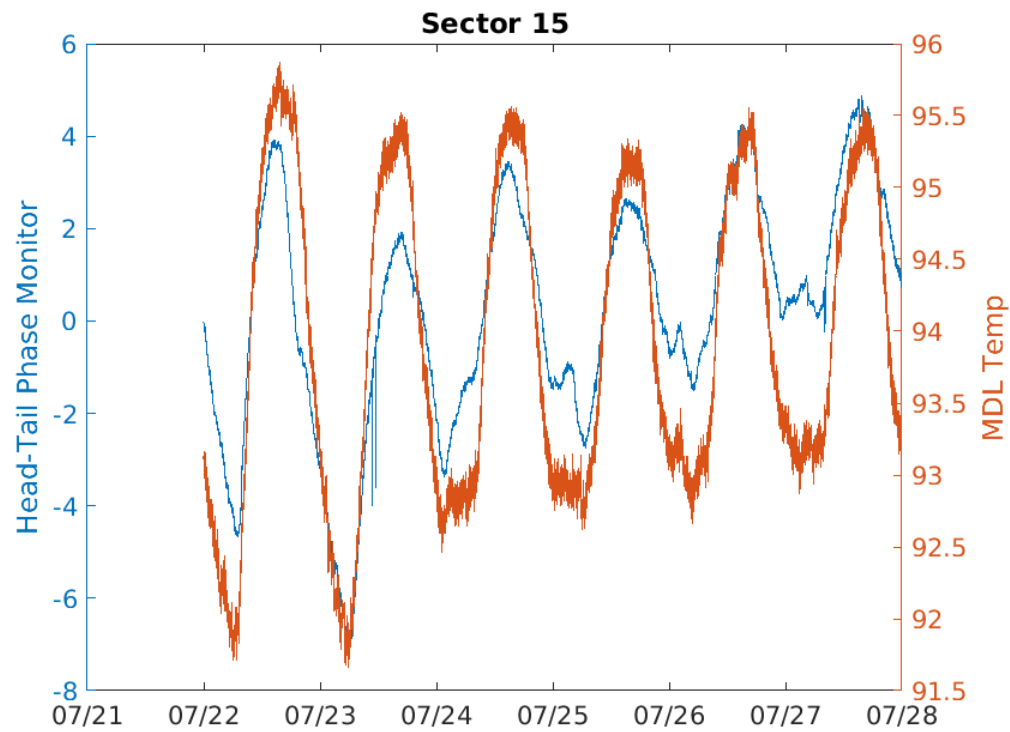
# MDL Feed Forward

Plots at each sector: H-T and MDL temp (FF ON)



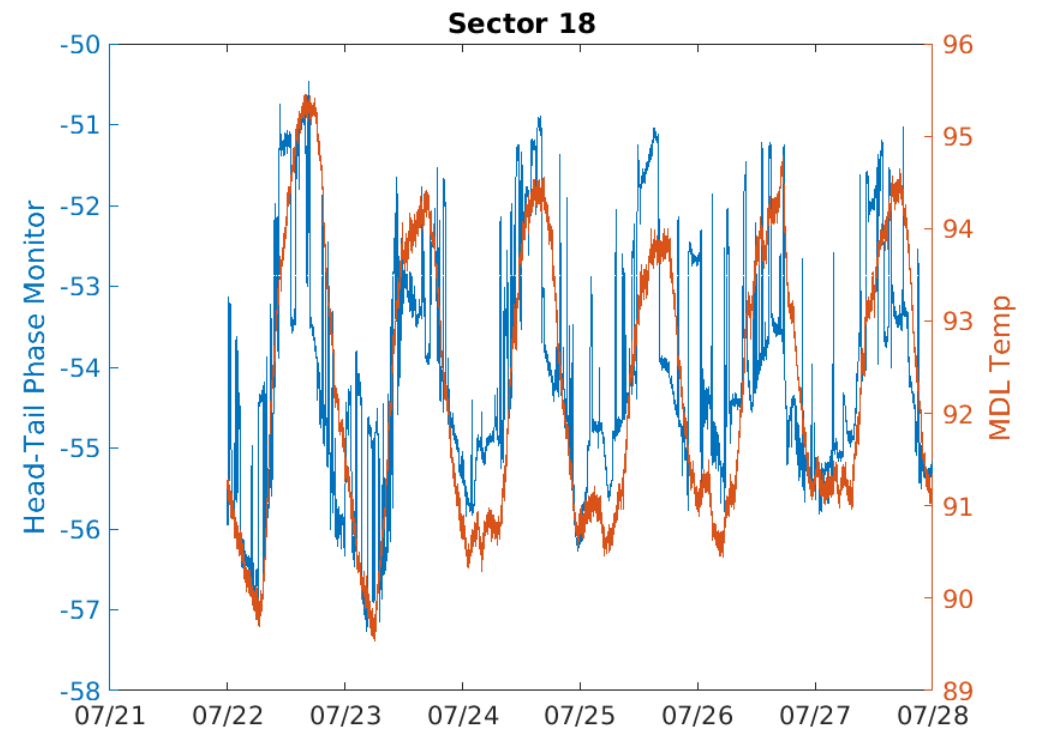
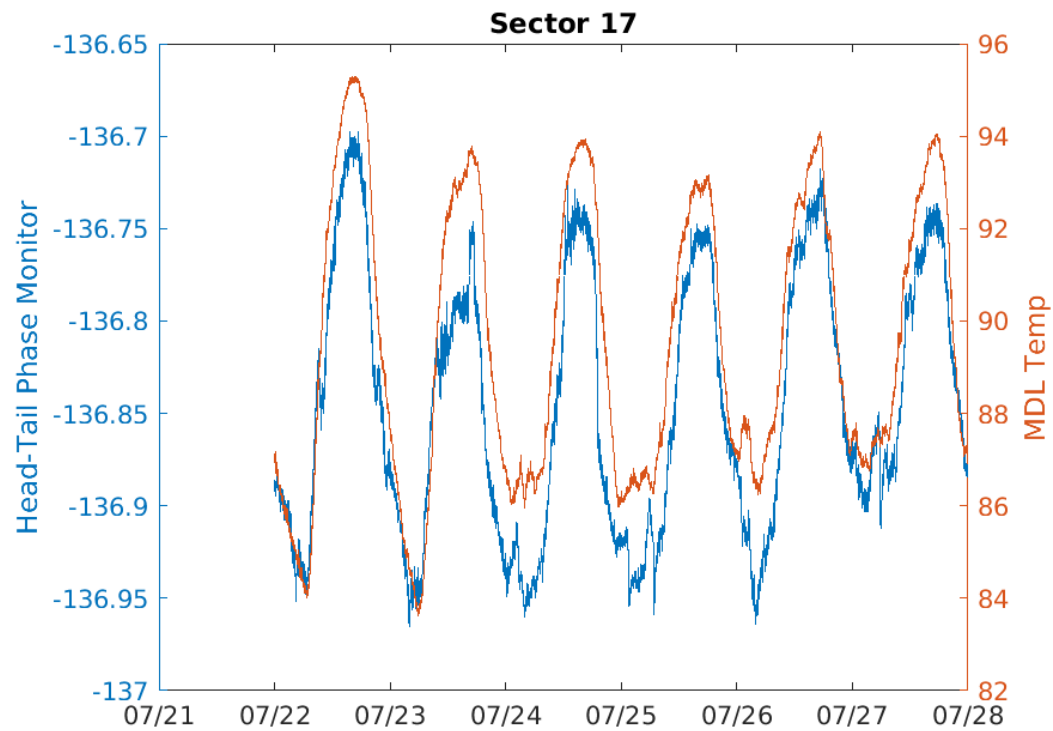
# MDL Feed Forward

Plots at each sector: H-T and MDL temp (FF ON)



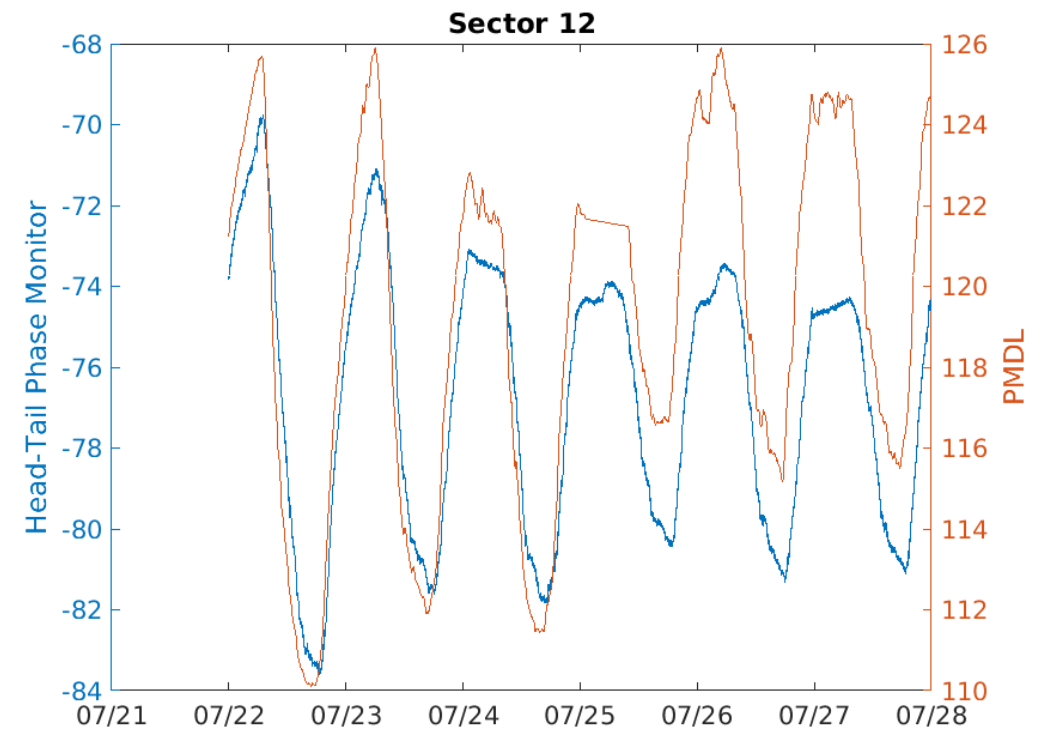
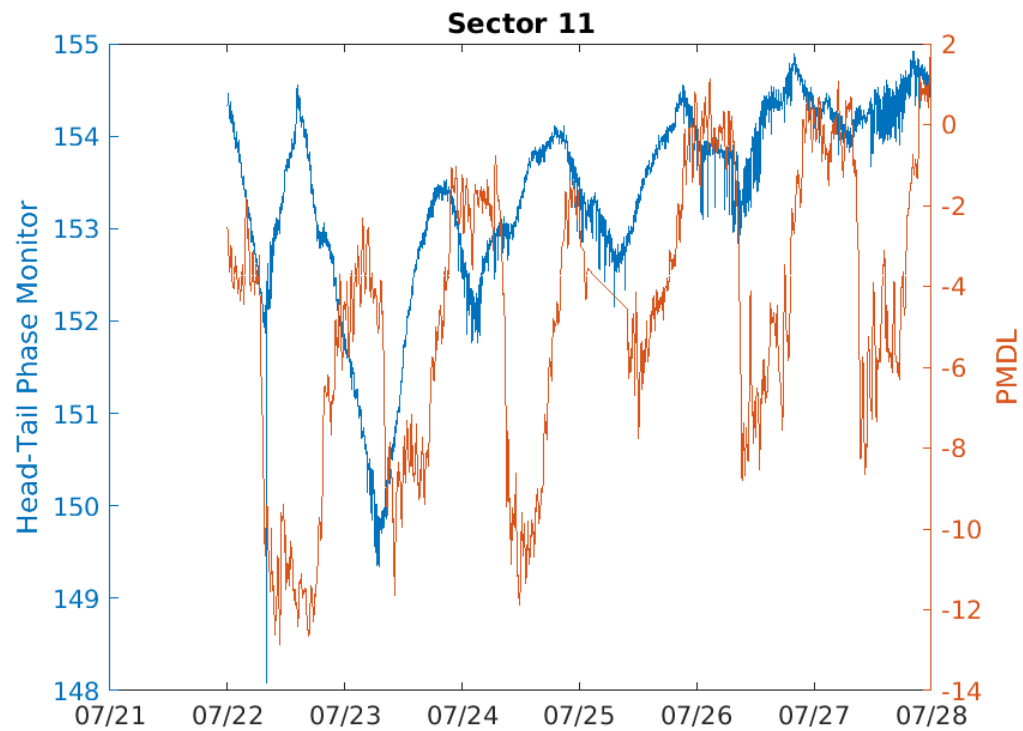
# MDL Feed Forward

Plots at each sector: H-T and MDL temp (FF ON)



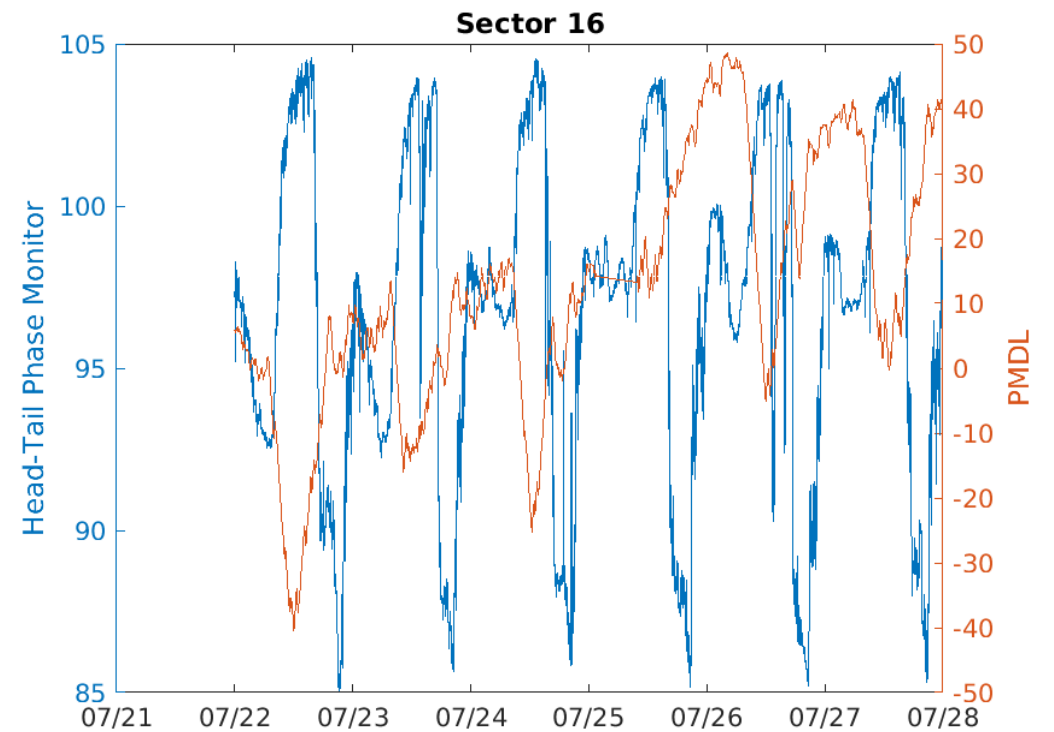
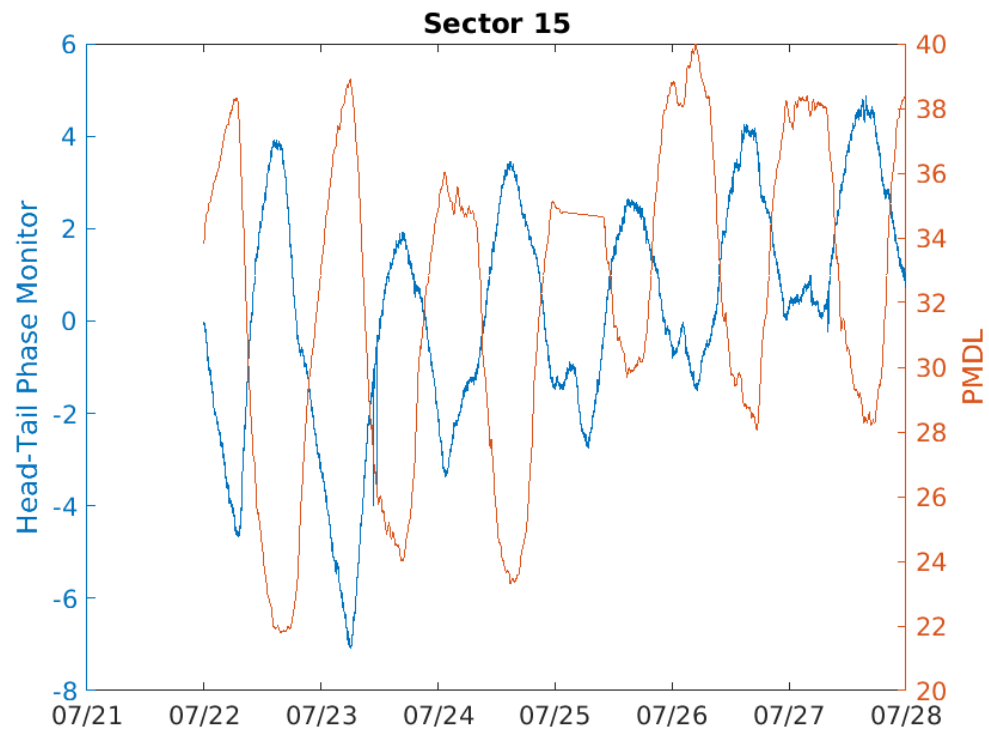
# MDL Feed Forward

Plots at each sector: H-T and PMDL (FF ON)



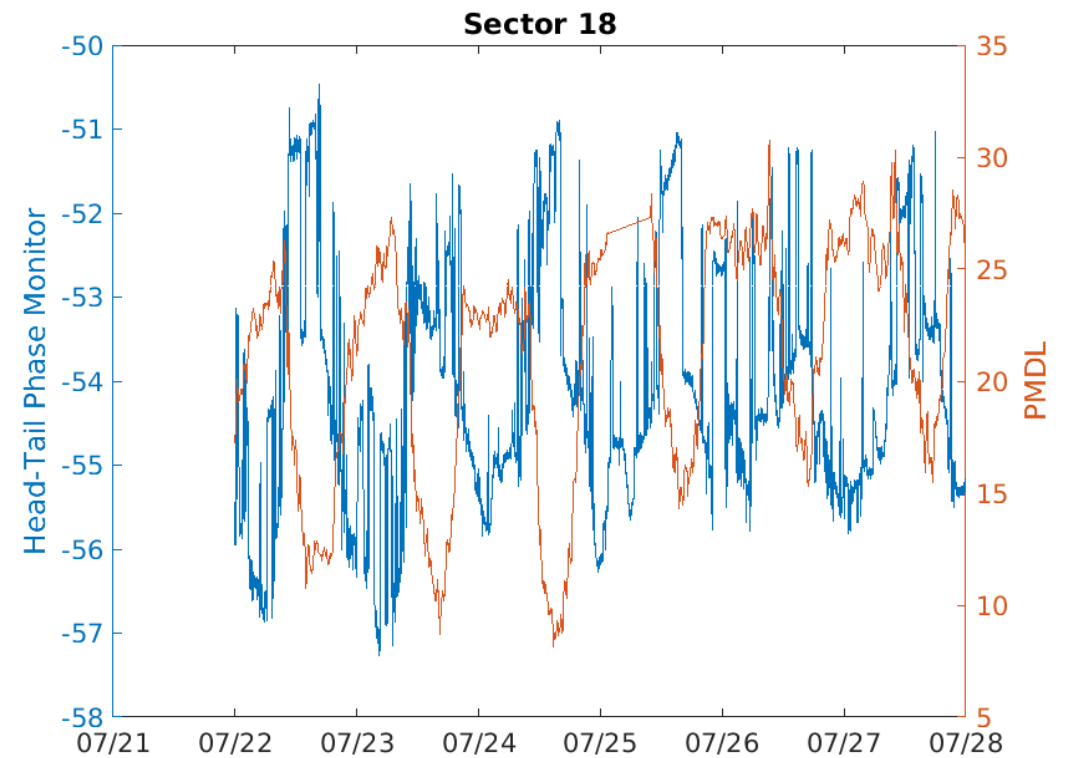
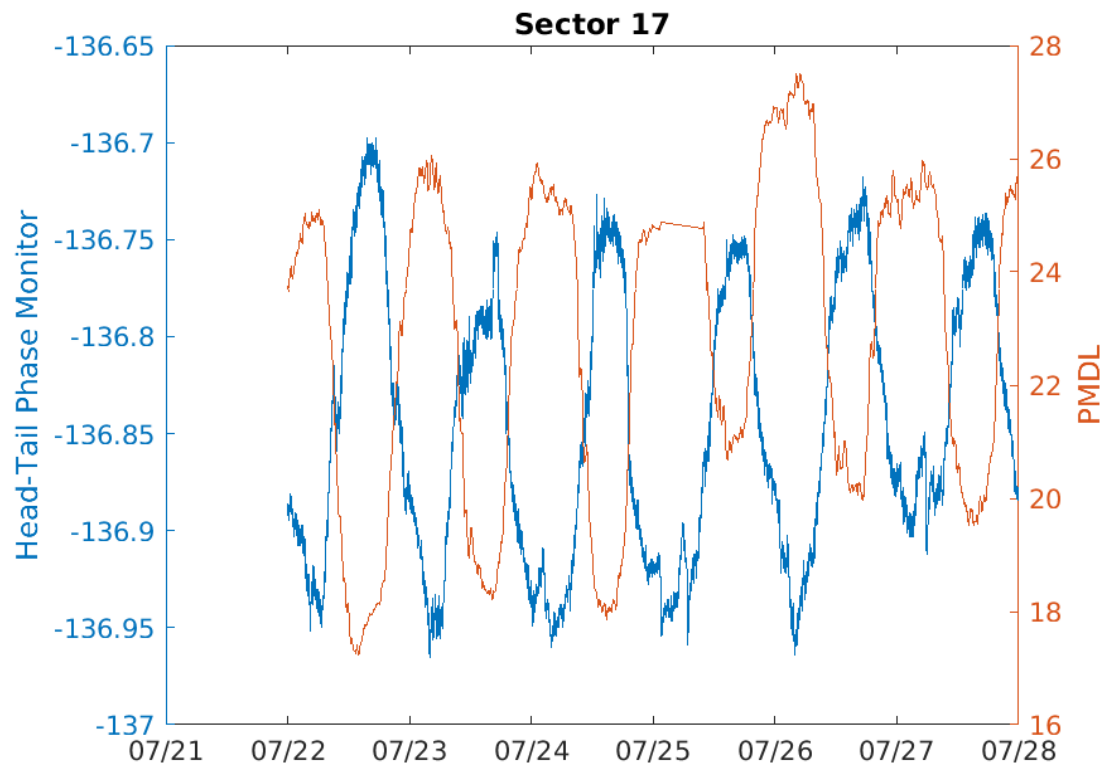
# MDL Feed Forward

Plots at each sector: H-T and PMDL (FF ON)



# MDL Feed Forward

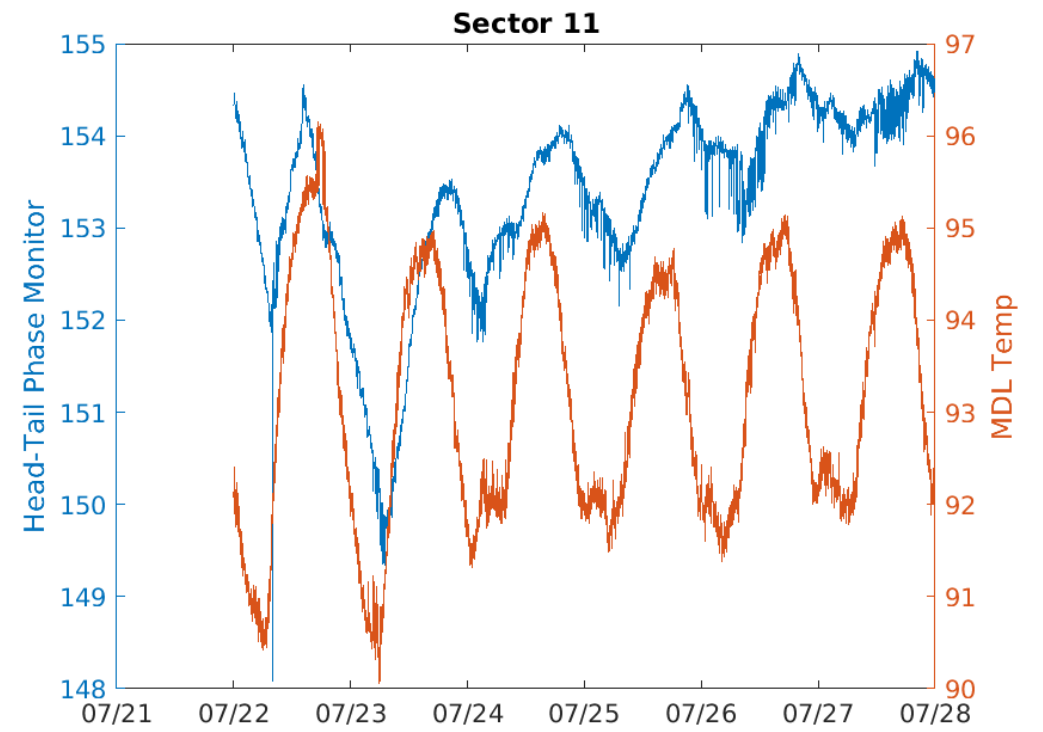
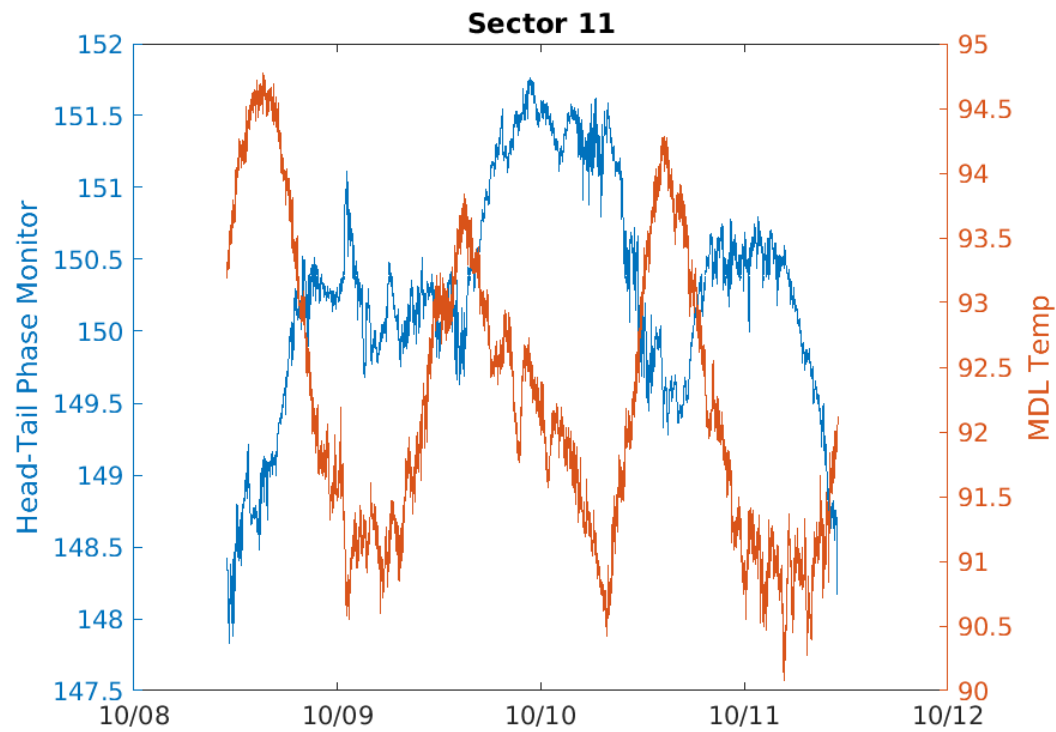
Plots at each sector: H-T and PMDL (FF ON)





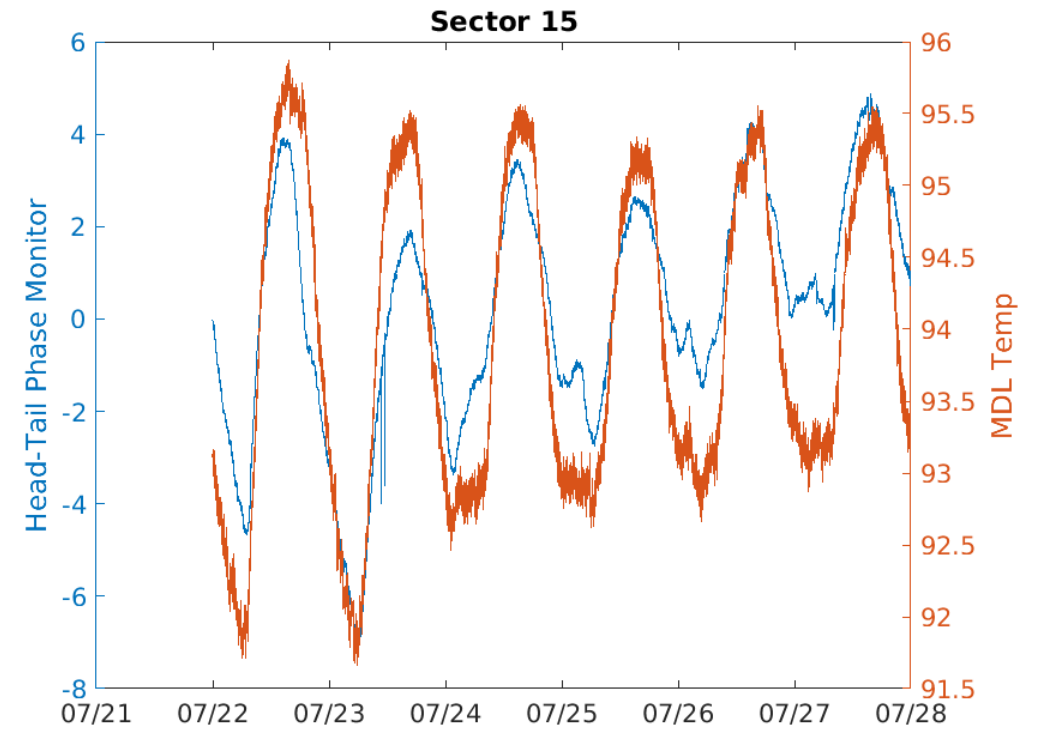
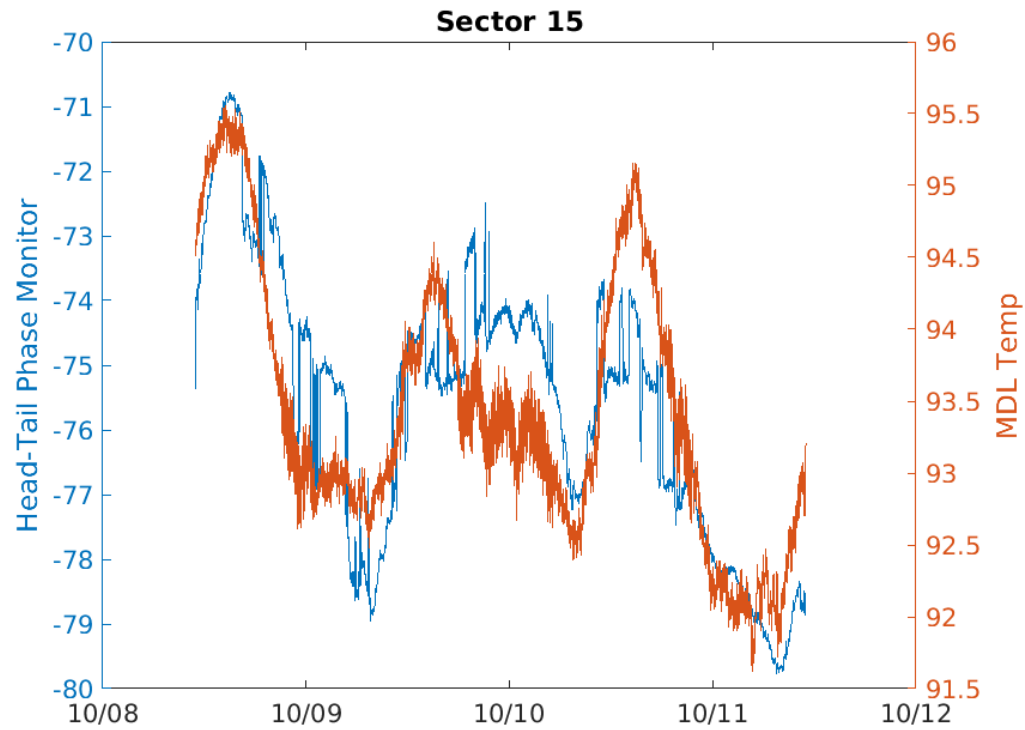
# MDL Feed Forward

## FF OFF vs FF ON



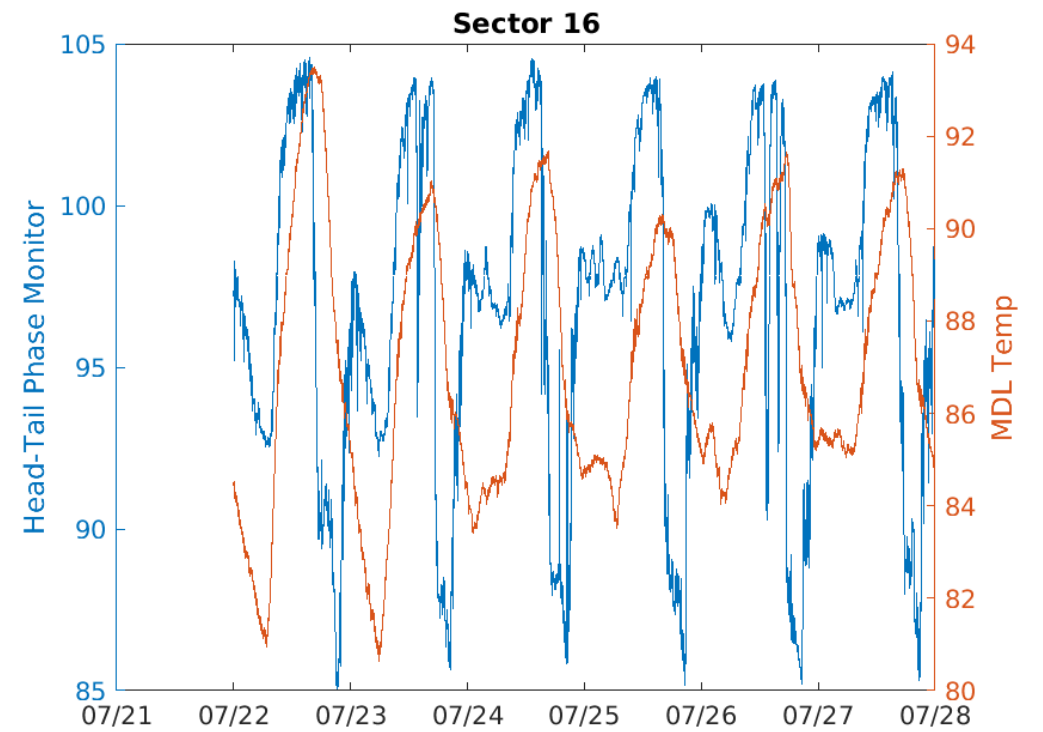
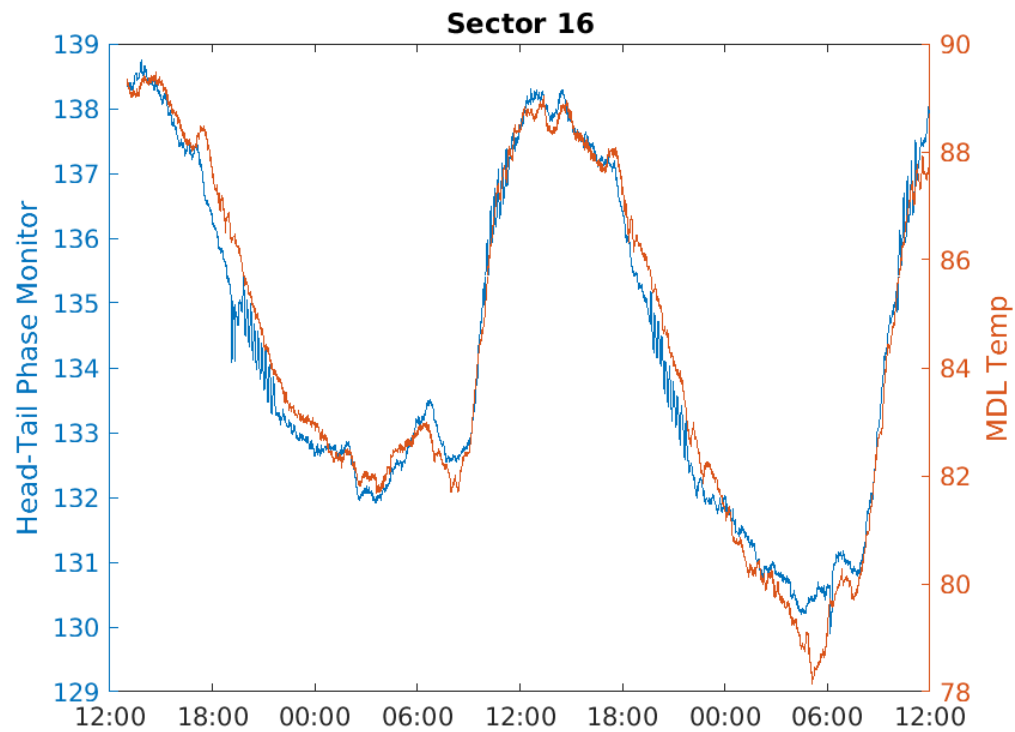
# MDL Feed Forward

## FF OFF vs FF ON



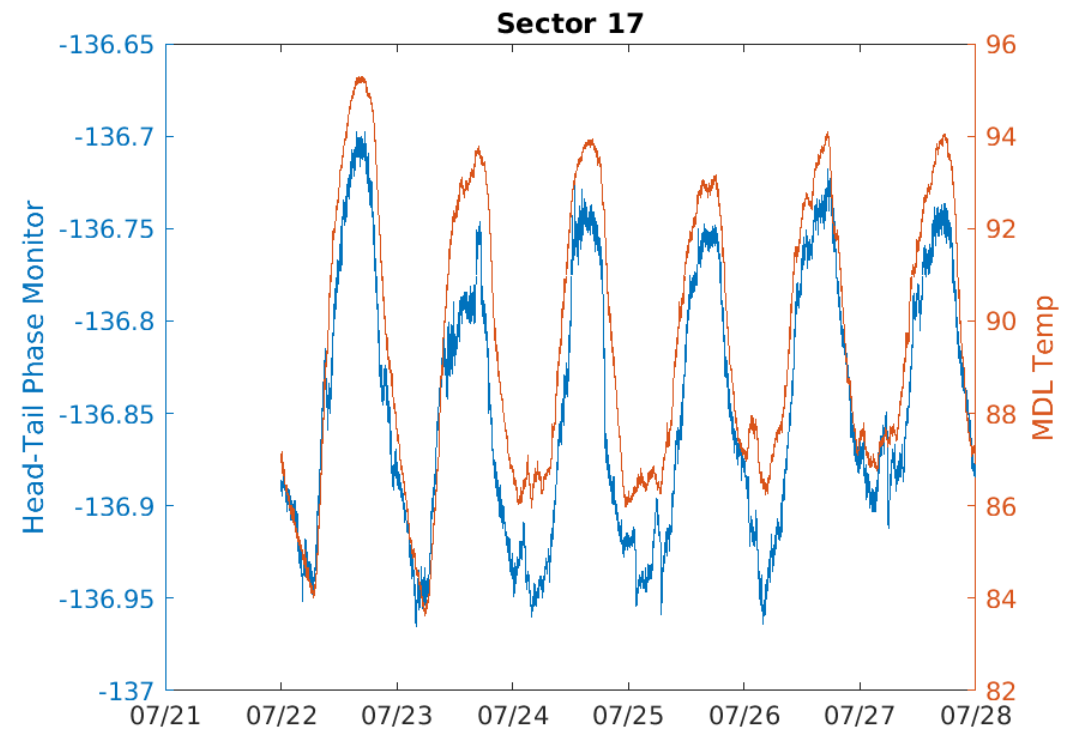
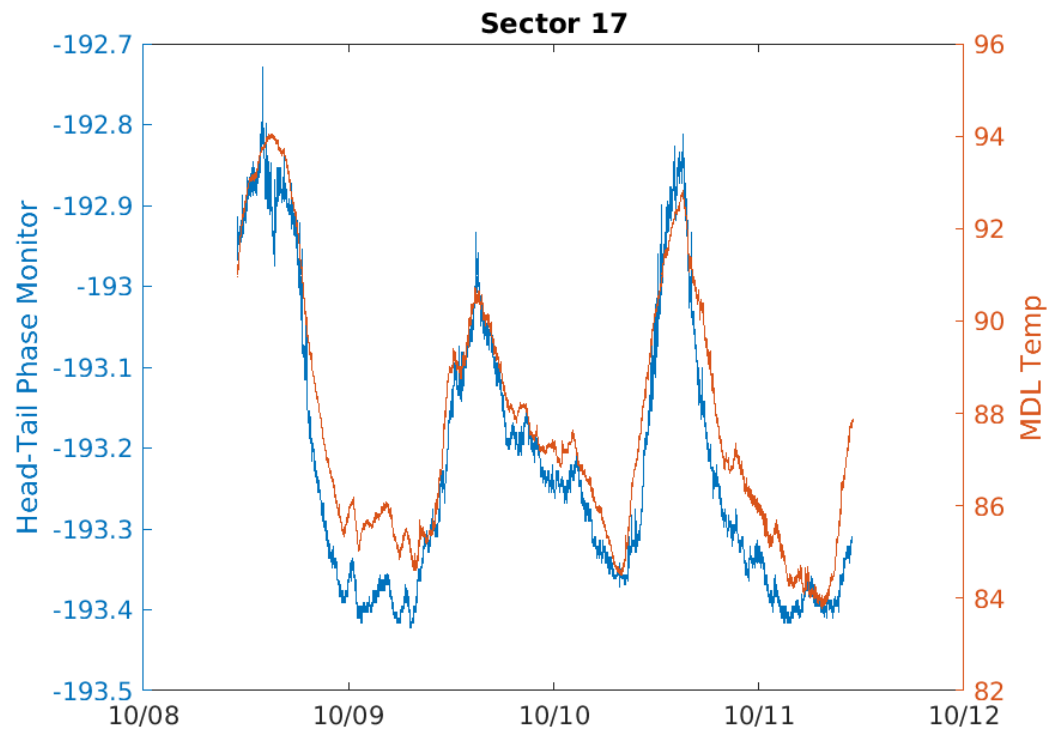
# MDL Feed Forward

## FF OFF vs FF ON



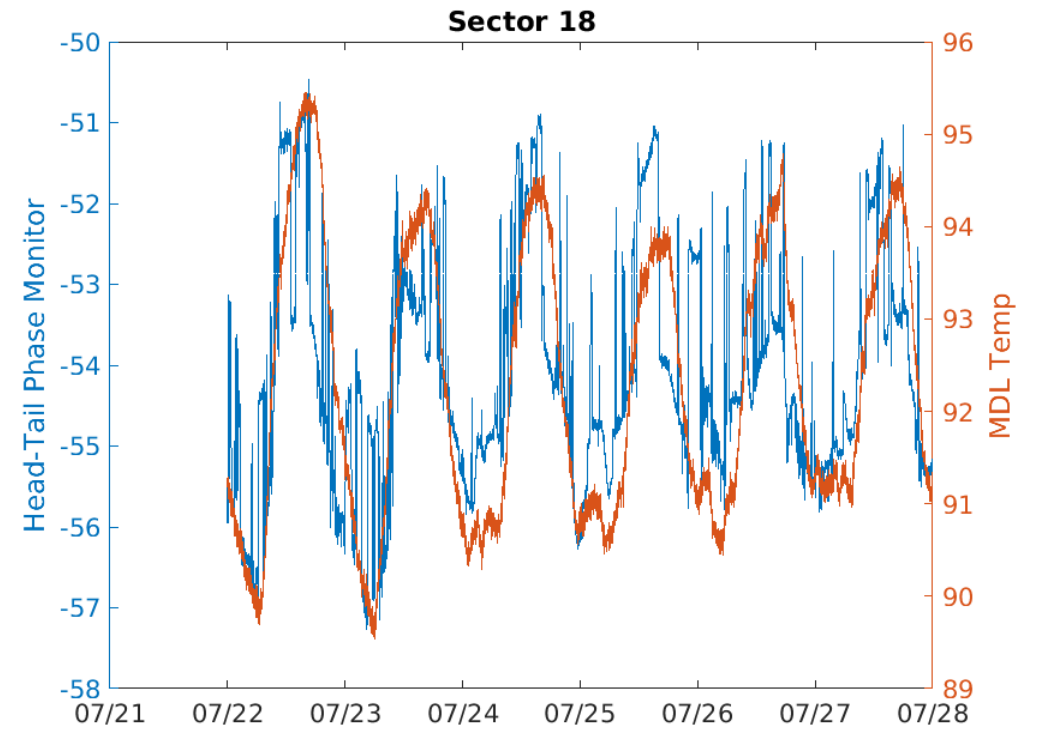
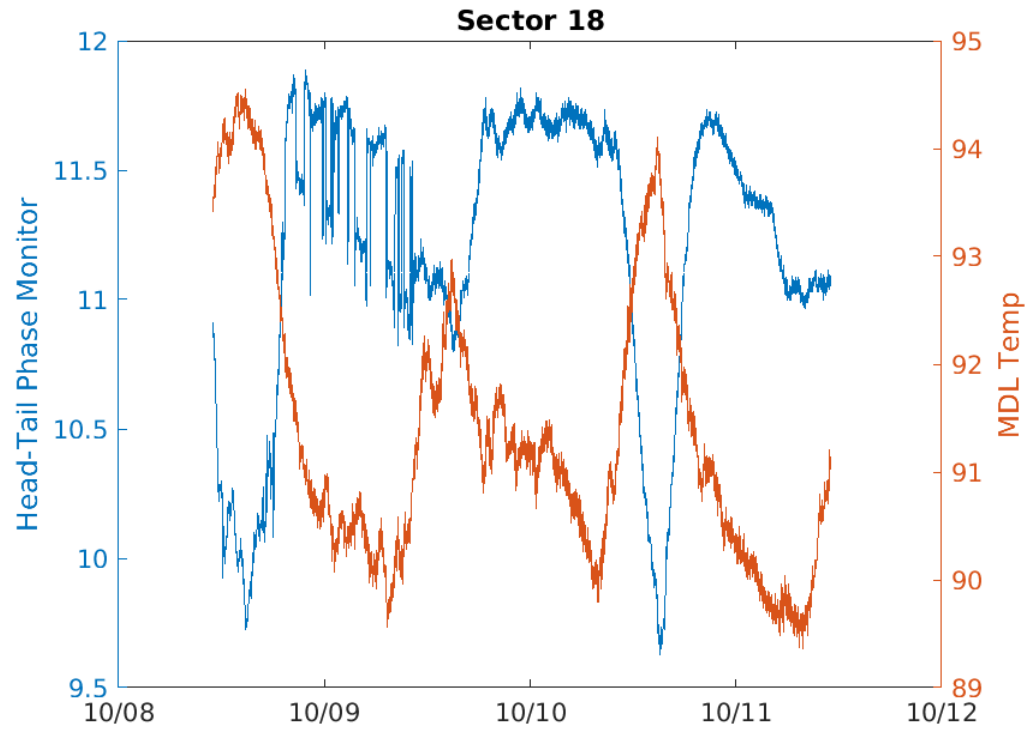
# MDL Feed Forward

## FF OFF vs FF ON



# MDL Feed Forward

## FF OFF vs FF ON



---

# Current MDLFF Algorithm

# MDL Feed Forward

---

## Glen's current algorithm

- Gets temperature, pressure, and GOLD data from archive over time range
- Fits data to linear regression model
  - Using "fitlm" MATLAB function
- Uses model to predict new PMDL values based on current temperature and pressure
  - Using "predict" MATLAB function
- Writes new PMDL values every few minutes
  
- Some issues:
  - Very few comments
  - Variable names are unclear
    - "obj.data.proc", "tt", "dt" variables are all used to store data at some point in the code
  - Multiple functions exist that do similar things
    - This script uses PV class, but "archive\_dataGet," "get\_archive," or "history" might be simpler

# MDL Feed Forward

## Glen's code

```
function GetArchiveData(obj,dateinfo)
%GETARCHIVEDATA Fetch all data from archiver
%GetArchiveData(ndays)
% Fetch data going back ndays from now
%
%GetArchiveData([date1;date2])
% Fetch data from date1 to date2 (in datevec
if length(dateinfo)==1
    ad = [datevec(datetime(clock))-days(dateinfo
else
    ad = dateinfo ;
end
obj.pvlist.pset('ArchiveDate',ad);
obj.pvlist.pset('UseArchive',2);
caget(obj.pvlist);
ttA=obj.pvlist.ArchiveSync('minutely');
obj.data.raw=ttA;
obj.ModelDate=ad;
end
```

PV:

```
if obj.UseArchive>0 % Get data from EPICS archiver
    st=datetime(obj.ArchiveDate(1,:));
    if obj.UseArchive>1
        et=datetime(obj.ArchiveDate(2,:));
    else
        et=st;
    end
    [v,t]=archive_dataGet(char(obj.pvname(ipv)),st,et);
```

archive\_dataGet:

```
% Read values from archive.
[v,t]=deal(cell(numel(name),1));
for j=1:numel(name)
    disp(['Reading ' name{j}]);
    try
        [v{j},t{j}]=get_archive(name{j},st,et,0,[],1);
```

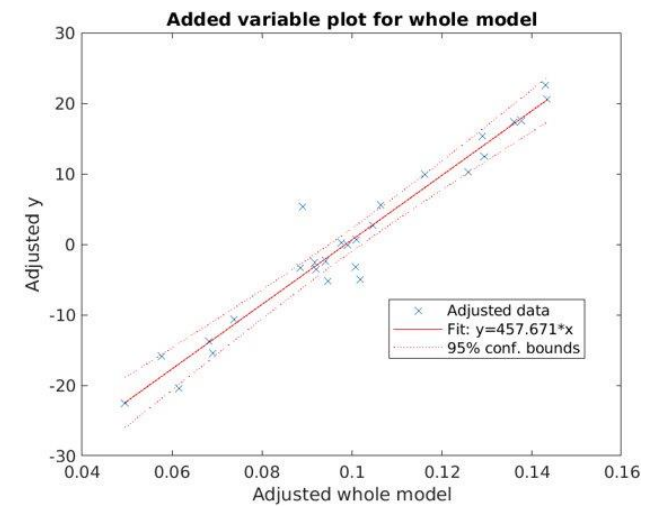
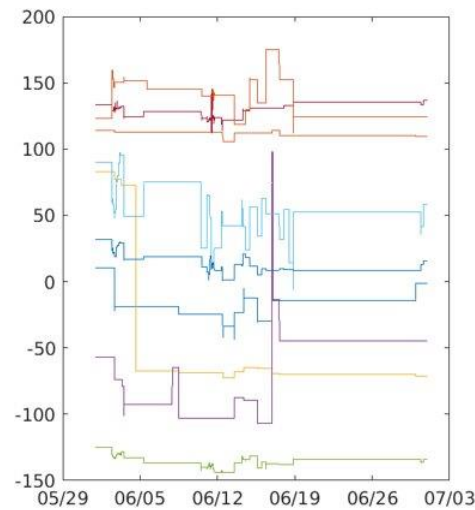
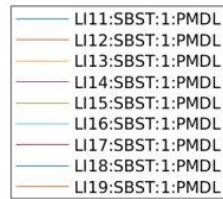
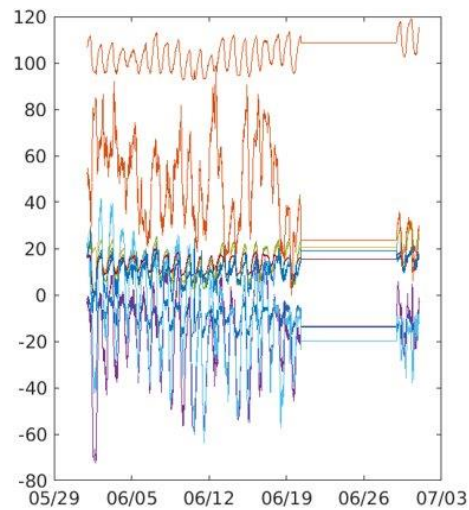
get\_archive:

```
opts={};if ~density, opts={'Operator','firstSample'};end
[times1,values1]=history(name,[datetime(starttime) datetime(end
times1=datestr(times1);
```



# MDL Feed Forward

Trying to recreate the algorithm



# MDL Feed Forward

---

## Next Steps

Keep trying to recreate algorithm

- Make sure that we can get the same results as Glen's code

Evaluate current performance

- Phase scans of subboosters with FF on
  - As GOLD values update, we can see if the FF is accurately tracking and writing new PMDL values

Consider other potential solutions

- Shift on Friday

---

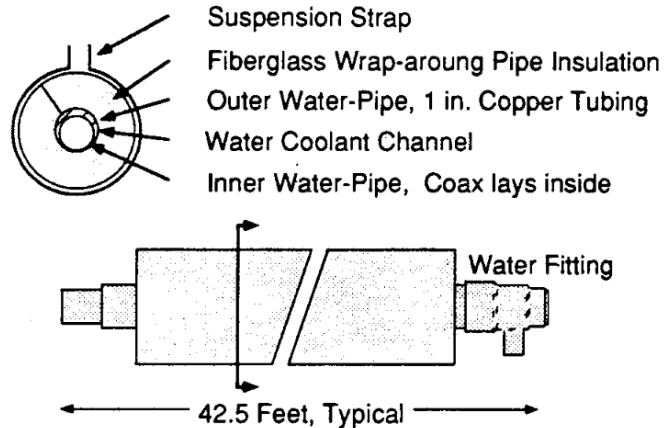
# Head-Tail Monitors and Phase Reference Lines

# Temperature at Phase Reference Lines

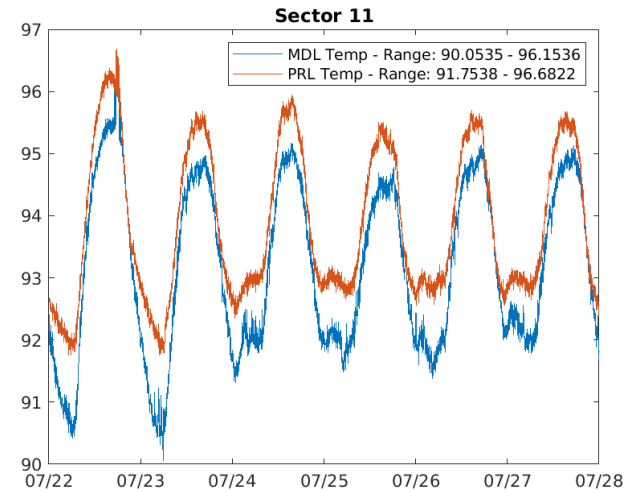
## PRL is temperature stabilized

This seems to be true

- Temperatures vary by only a few degrees
- MDL temperature generally has a much larger range

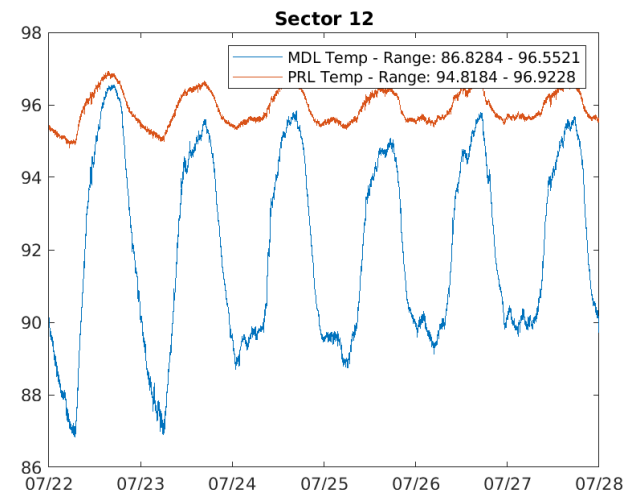


**Fig. 4:** Detail of the PRL insulation package. Each line segment consists of a length of temperature-stable 1/2-inch semirigid foam Heliax, surrounded by a water jacket and conventional water line insulation. Lines are suspended on cables to decouple changes in building length due to ambient temperature changes from phase length of reference line.



MDL has a small temperature range (~6 deg) at Sector 11

PRL range is ~5 deg

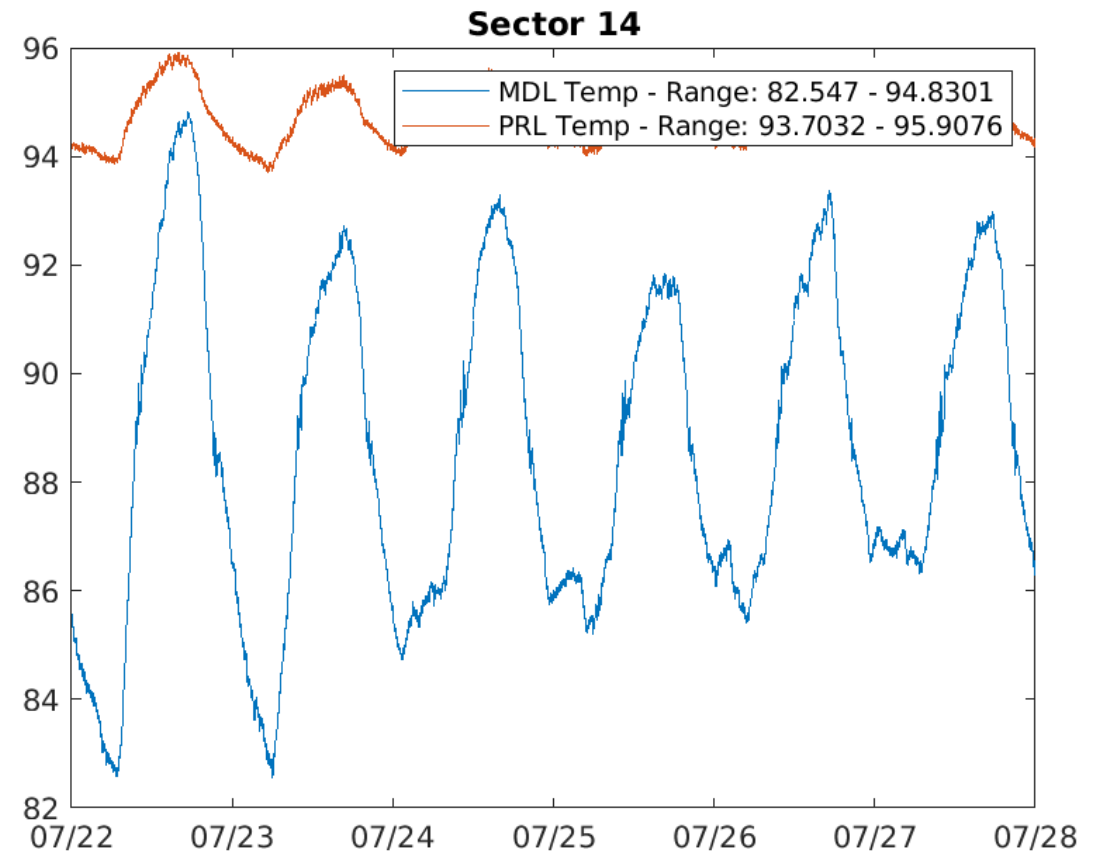
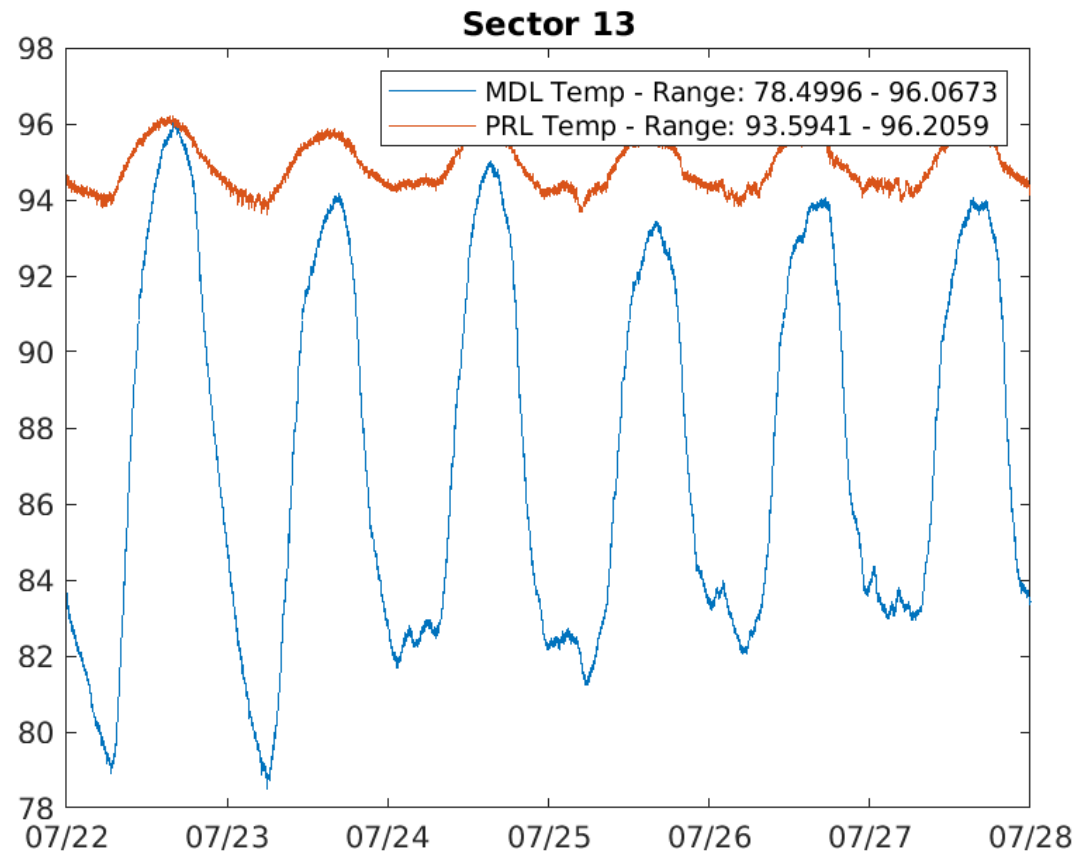


MDL has a larger range (~10 deg) at Sector 12

PRL still temperature regulated (varies by only ~2 deg)

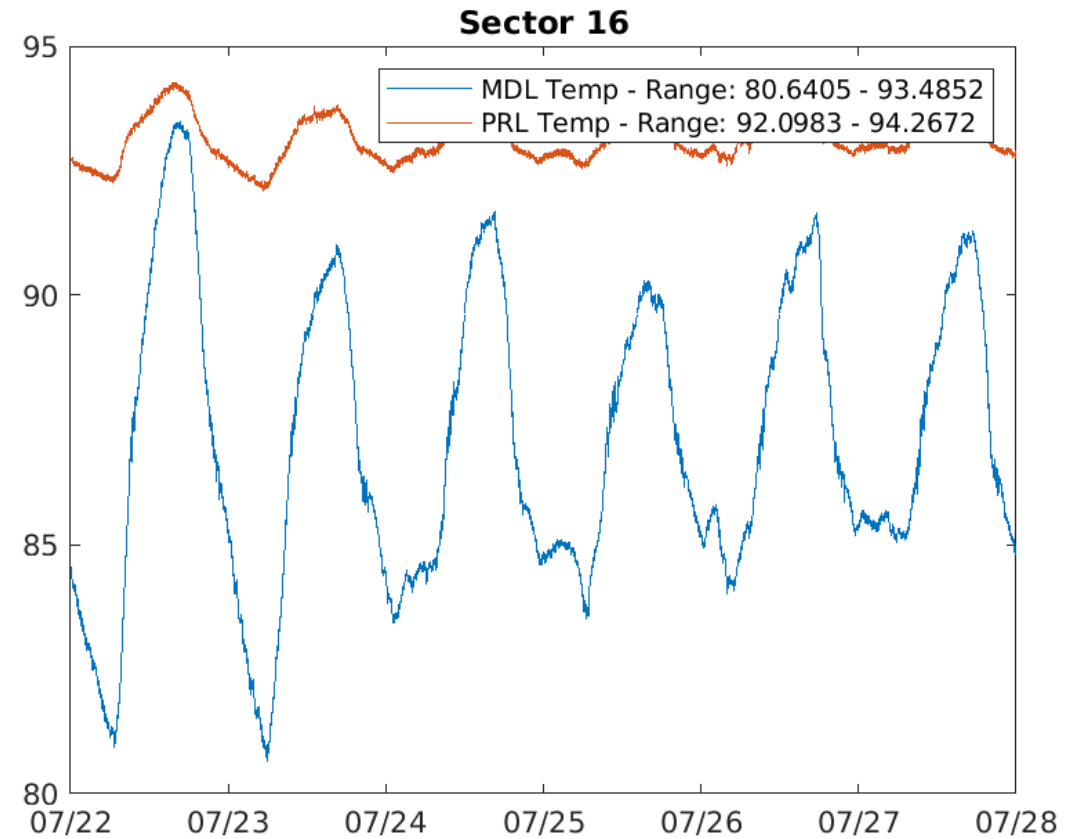
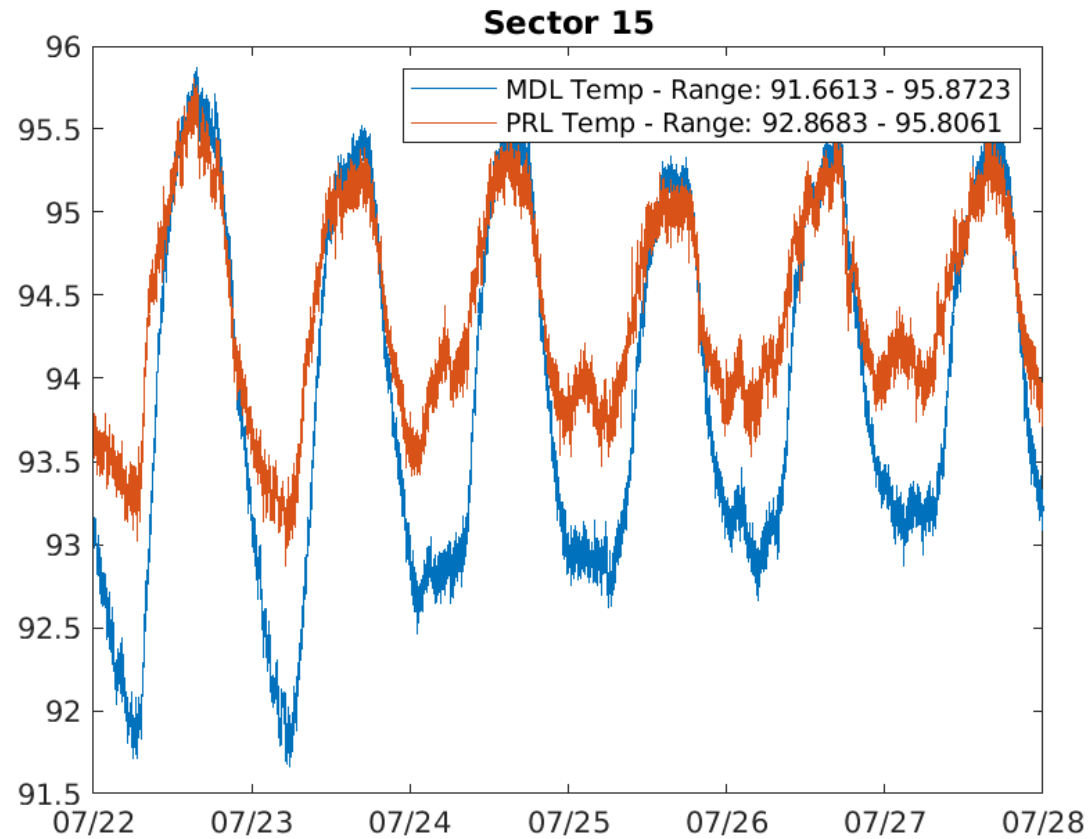
# Temperature at Phase Reference Lines

PRL is temperature stabilized



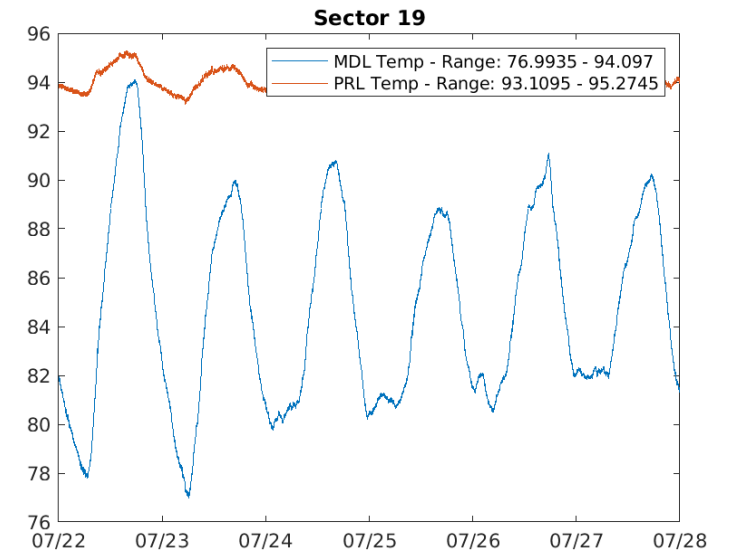
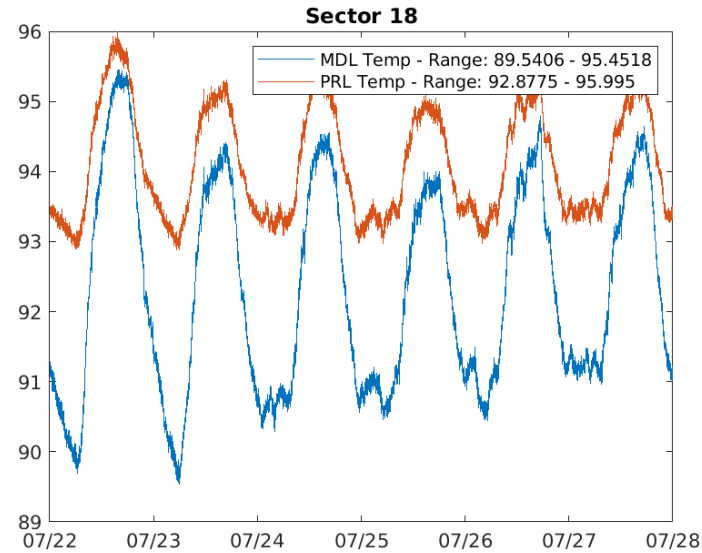
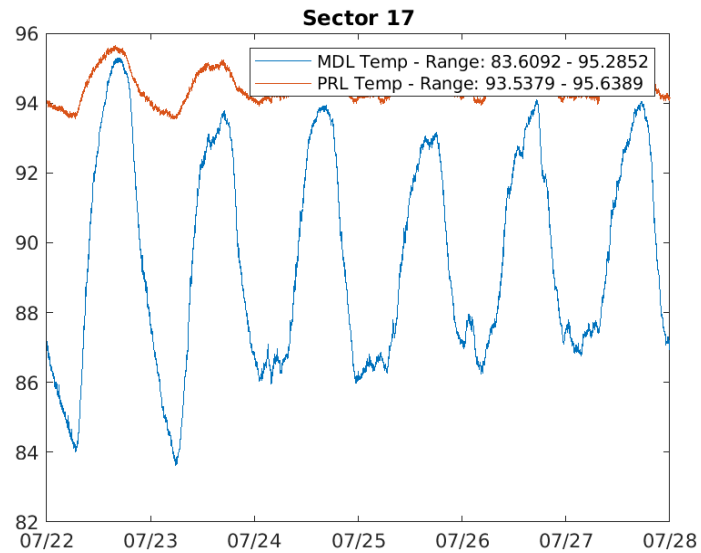
# Temperature at Phase Reference Lines

PRL is temperature stabilized



# Temperature at Phase Reference Lines

PRL is temperature stabilized

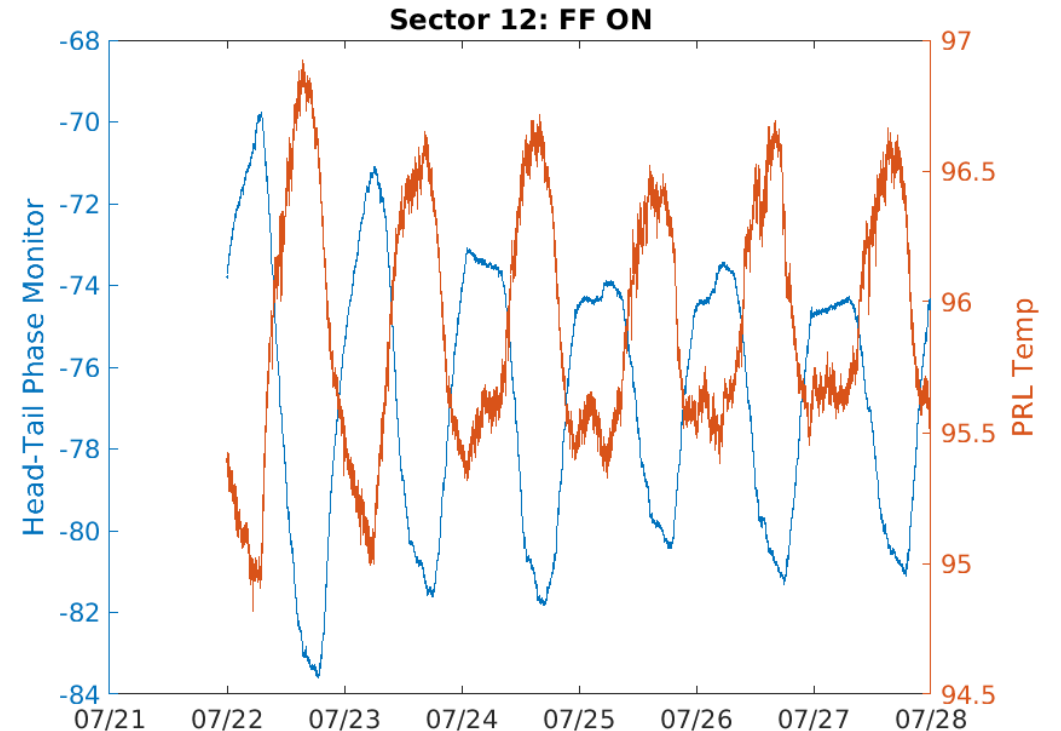
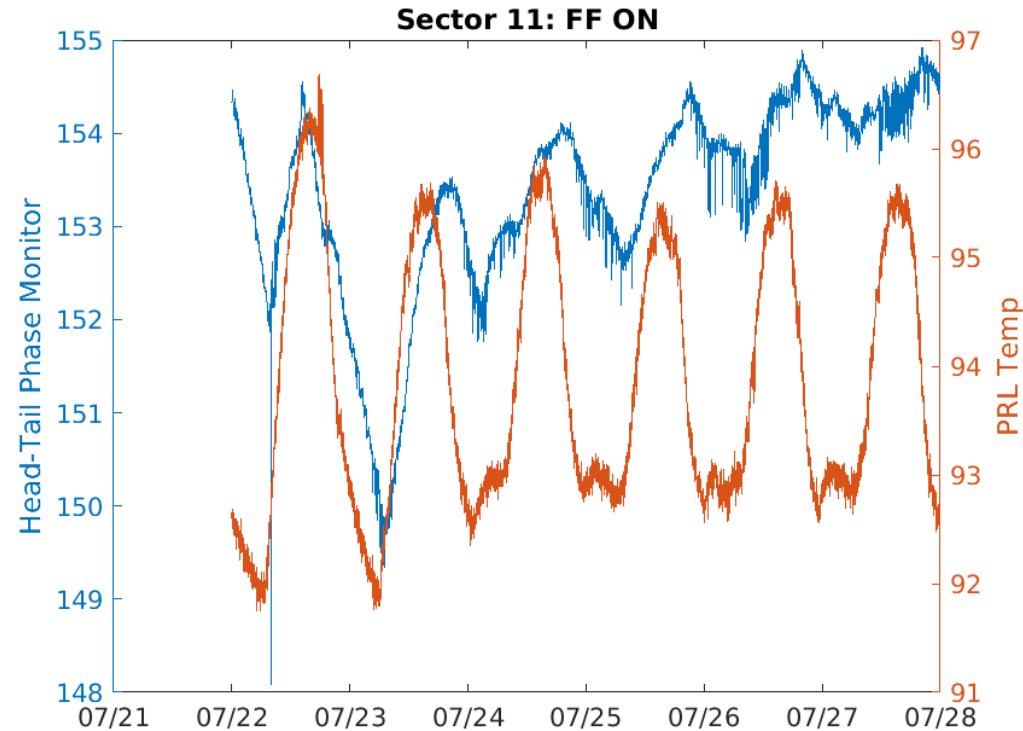


# Temperature at Phase Reference Lines

PRL is temperature stabilized

Nonetheless, PRL temperature still fluctuates diurnally

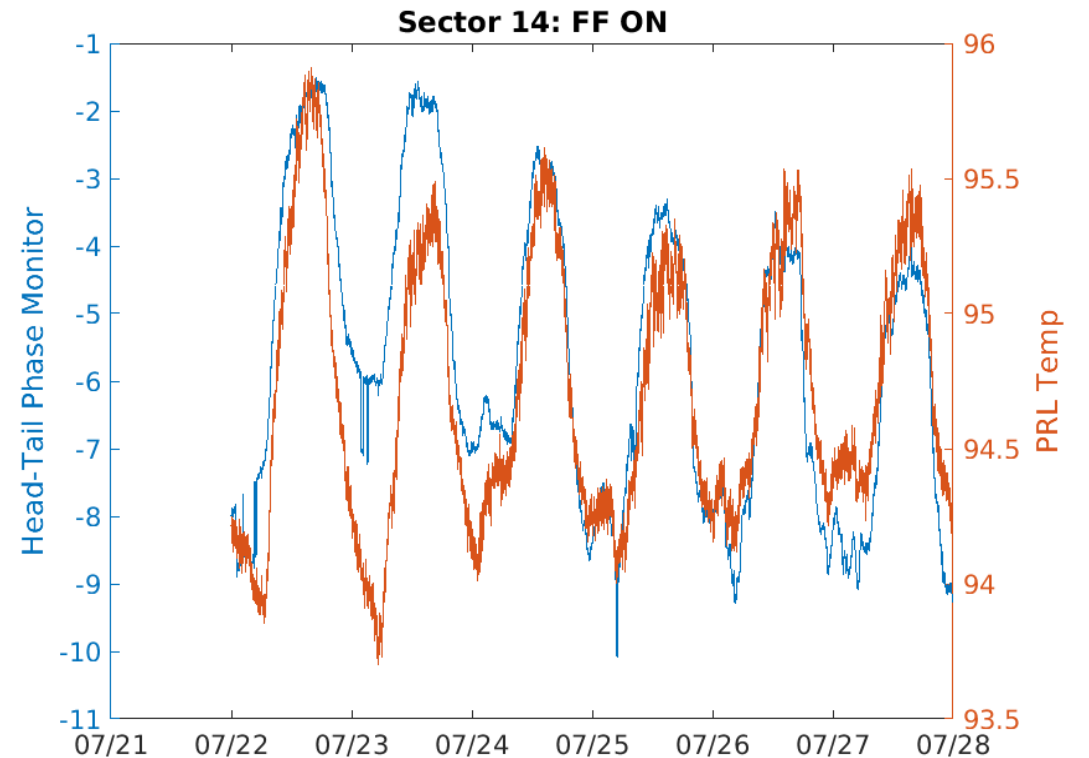
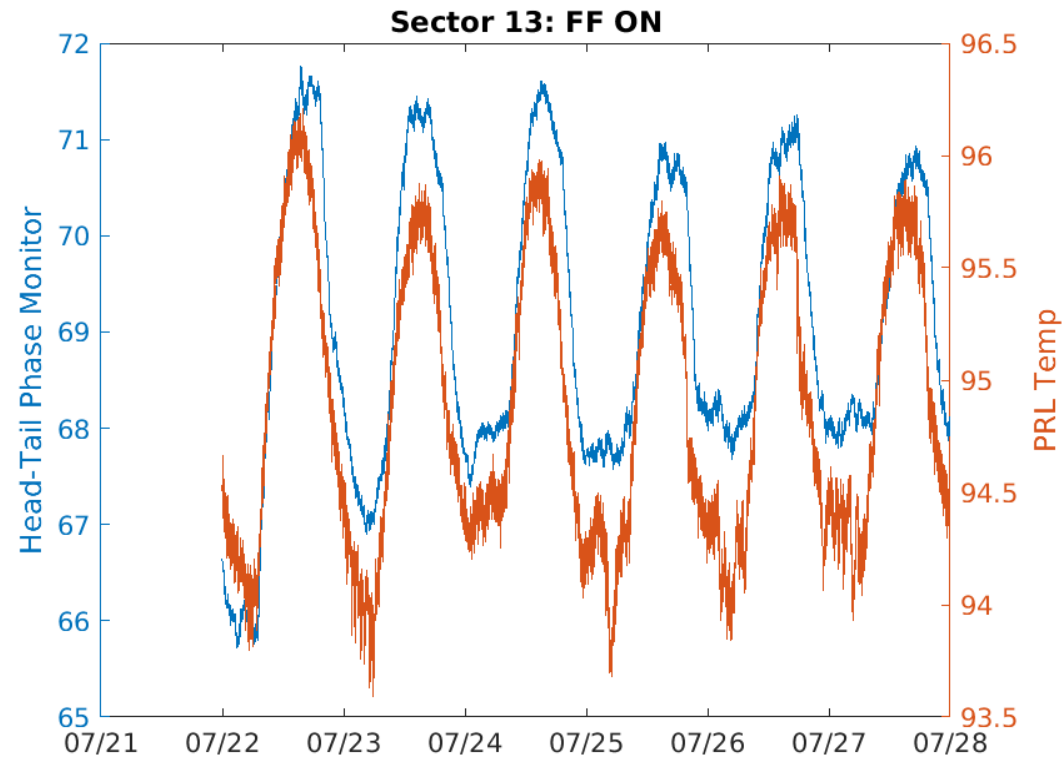
- Head-Tail Monitors track changes in PRL temp, even when FF is on





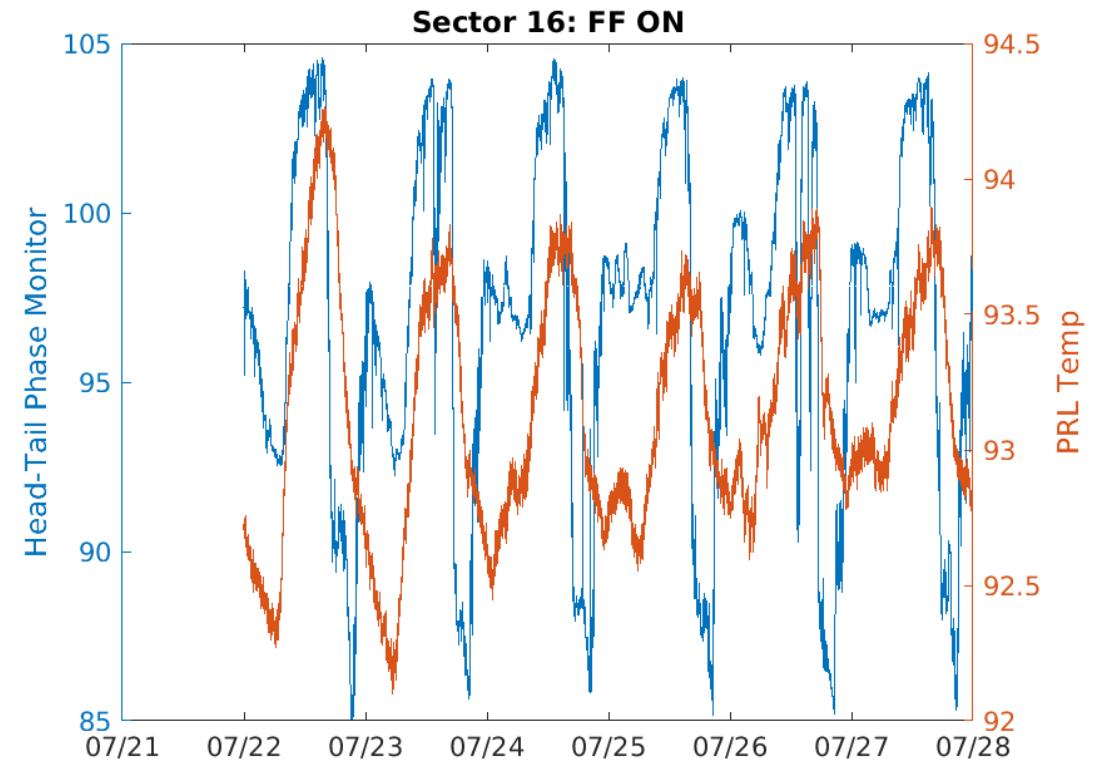
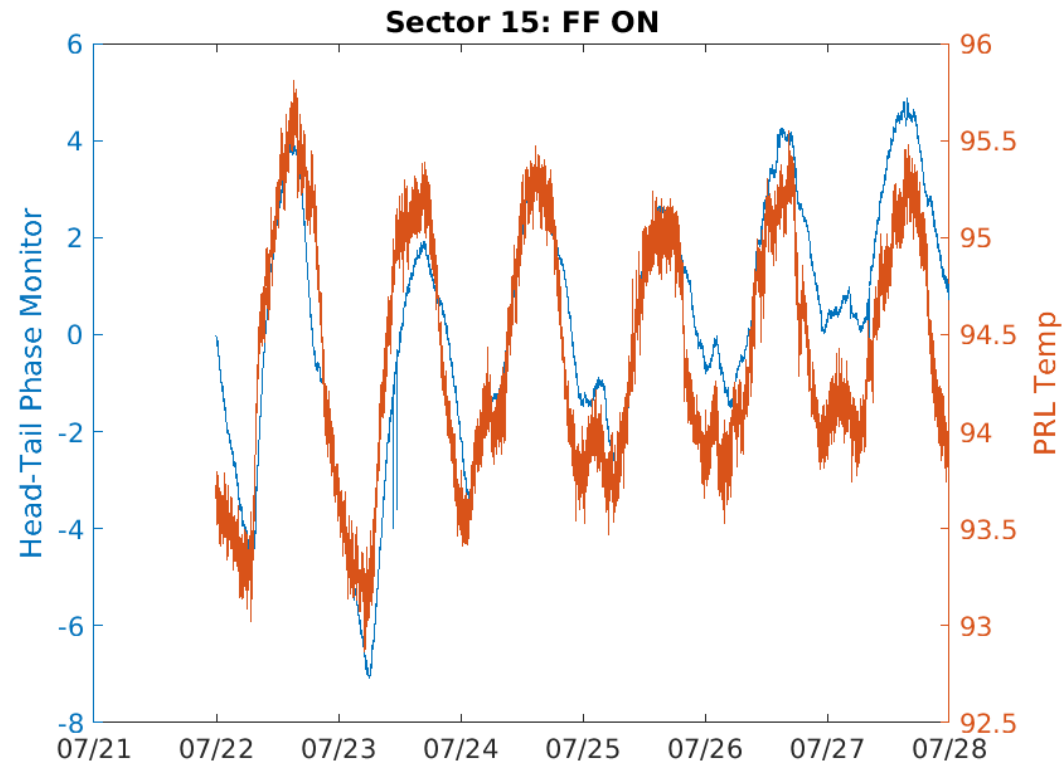
# Temperature at Phase Reference Lines

Head-Tail Monitor and PRL Temp at each sector



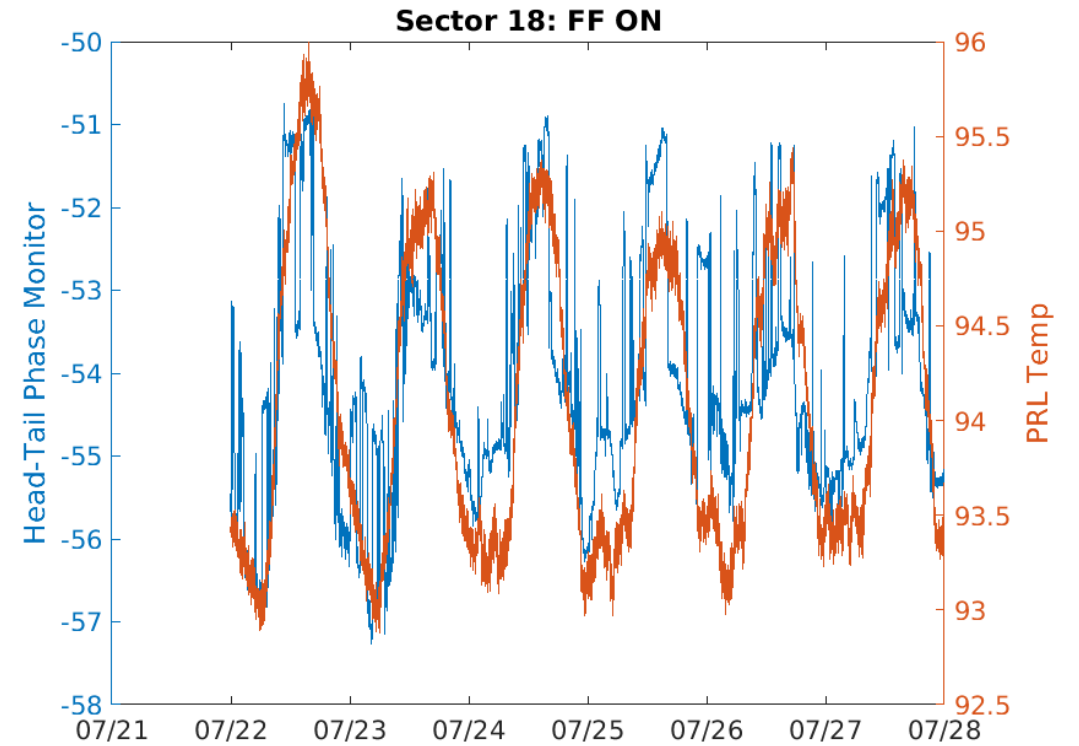
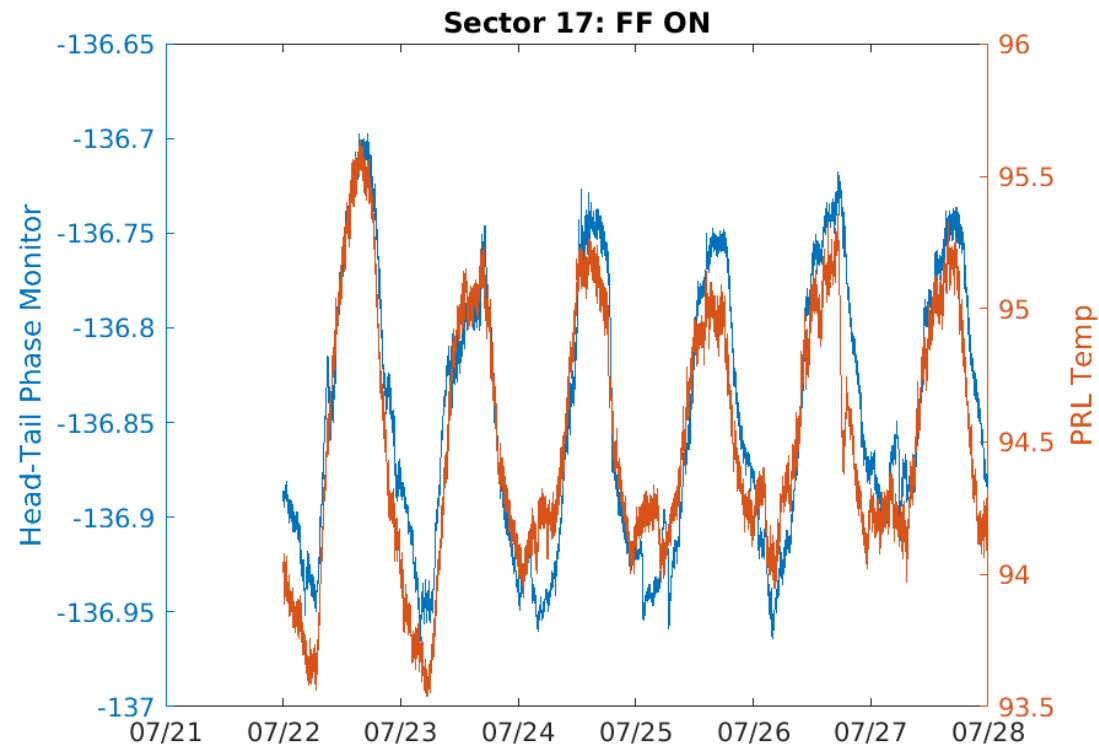
# Temperature at Phase Reference Lines

Head-Tail Monitor and PRL Temp at each sector



# Temperature at Phase Reference Lines

Head-Tail Monitor and PRL Temp at each sector

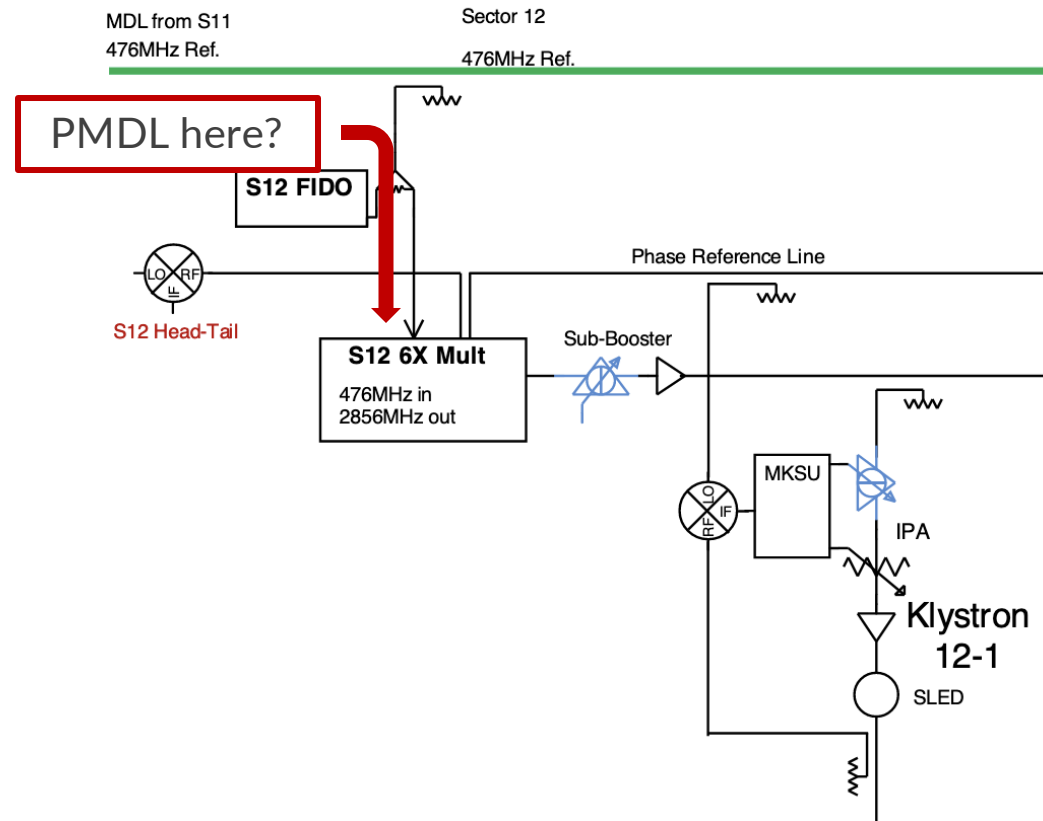


# Temperature at Phase Reference Lines

## Analysis/Further Questions

It's possible that the Head-Tails are tracking changes in temperature (even if they are small) at the PRLs

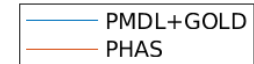
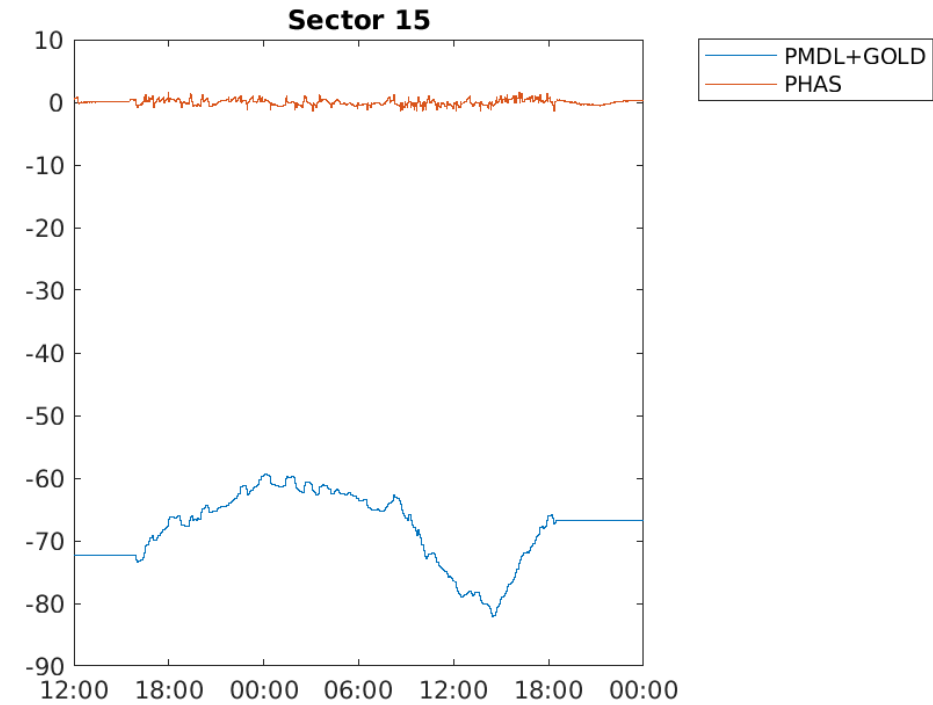
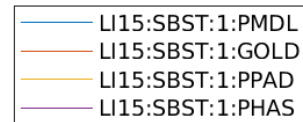
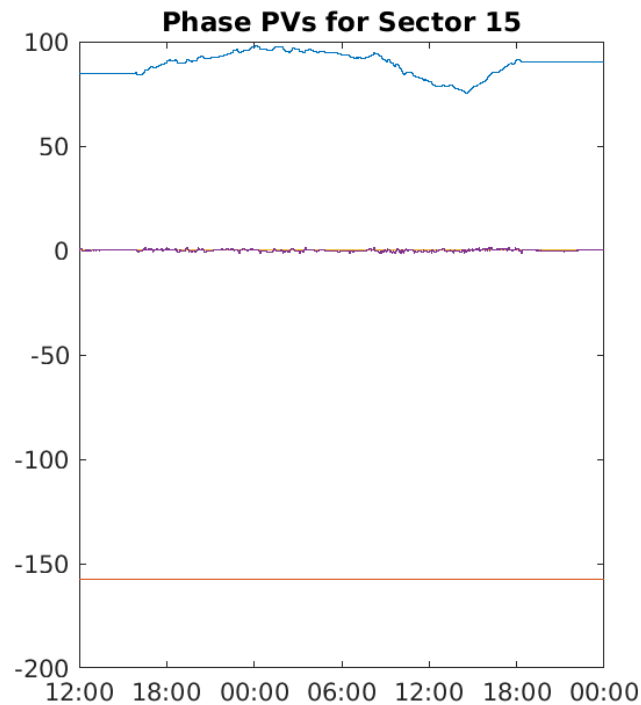
Depending on how the PMDL is applied (which I am still trying to understand), the PRLs may not see the impact of the PMDL



# Phase Calculations

## How do we get PHAS?

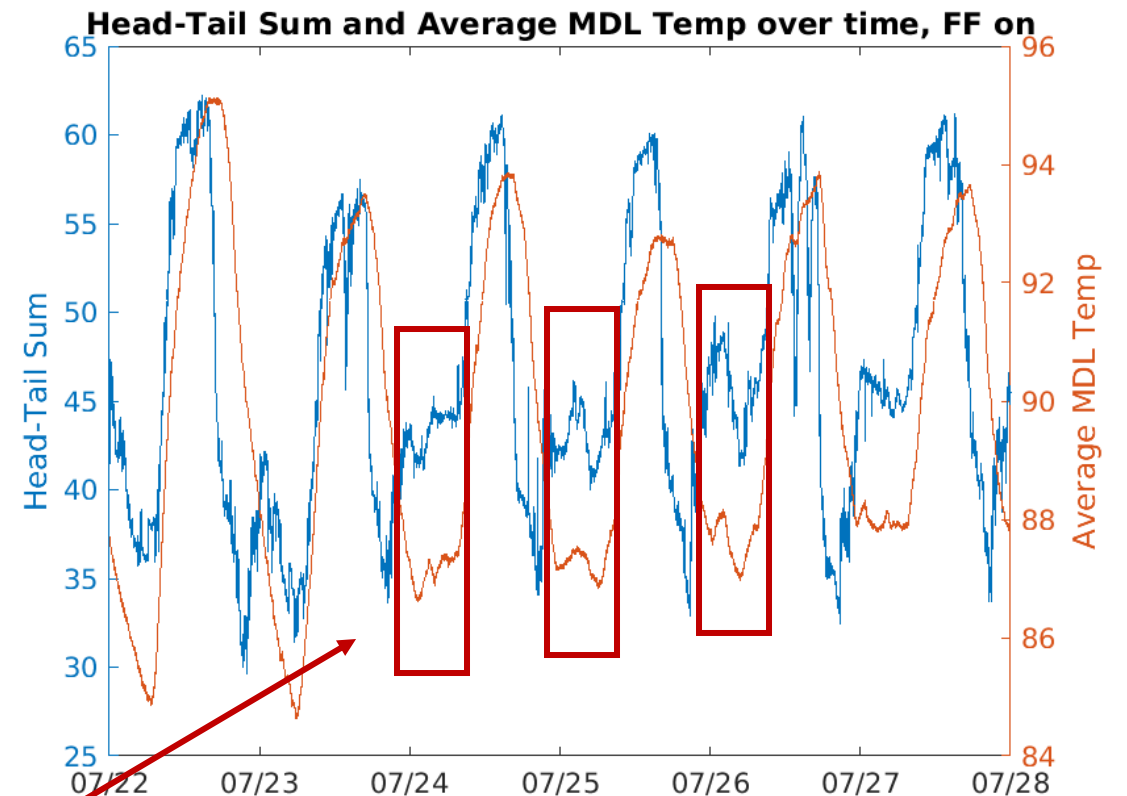
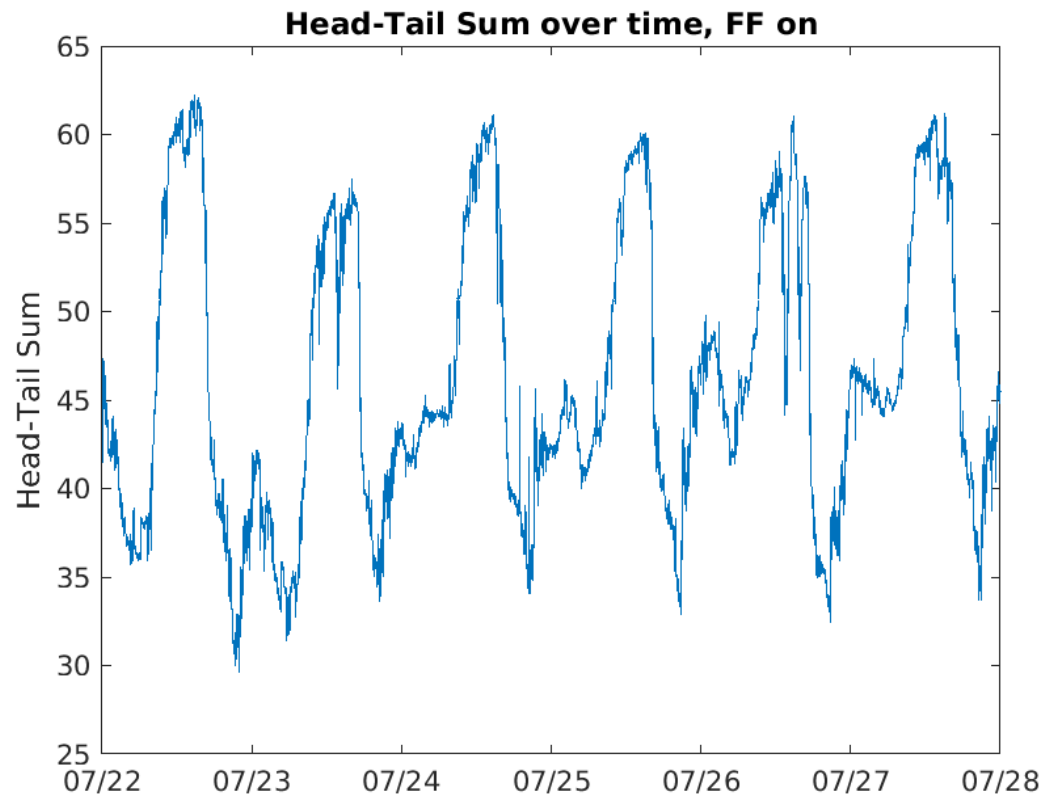
Trying to understand the relationship between PMDL, GOLD, and PHAS to understand what H-T is really tracking



# Sum of Head-Tail Monitors

## "Total Error"

Will the *sum* of all the Head-Tail Monitors stay constant when the FF is on, or will it also fluctuate diurnally?



Similar spikes?

Unclear if there is a correlation

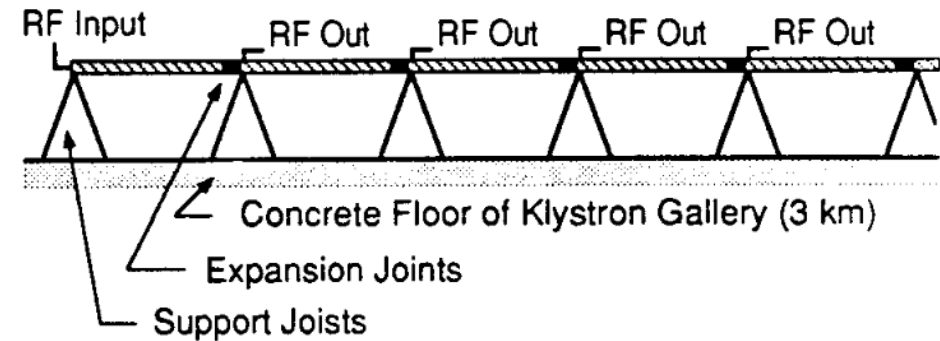
# More on the MDL

## MDL Structure (assuming information is up to date)

The MDL is fixed to the floor of the klystron gallery at each sector

At the end of each sector there are expansion joints on the MDL that are supposed to allow the MDL to contract/expand, while still keeping the overall length of the MDL fixed

At the time, this seemed to be a sufficient solution for the MDL expansion problem



**Fig. 1: The MDL runs the accelerator length in the klystron gallery. RF is distributed to the local RF distribution system in each sector, where timing information is extracted, and frequency is increased by a factor of 6. Attachment to gallery floor helps decrease temperature dependence by constraining the physical line length.**