# Mechanical Motion Measurement System Design, Initial Results and Experiments with Orbit Feedback

Workshop on Ambient Ground Motion and Vibration Suppression for Low Emittance Storage Rings
12/11/2017

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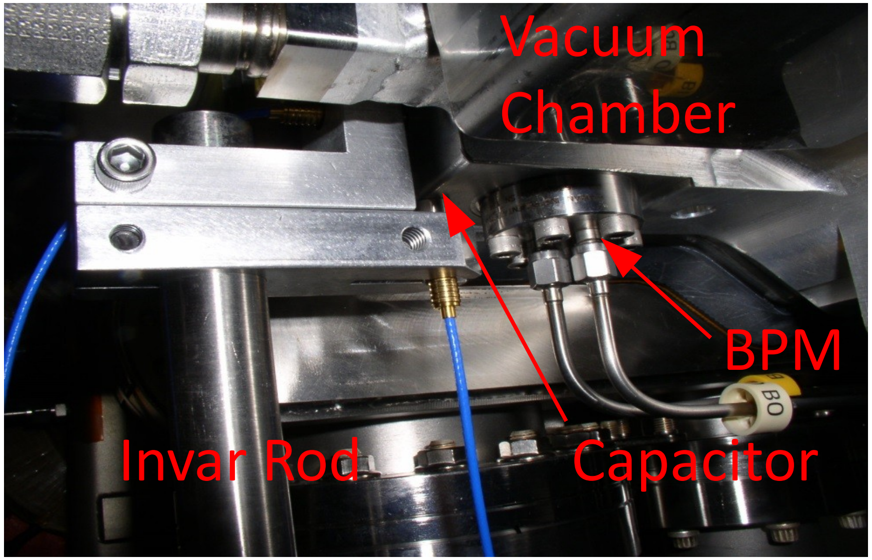
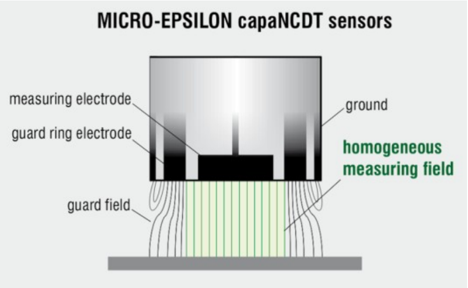
# Outline

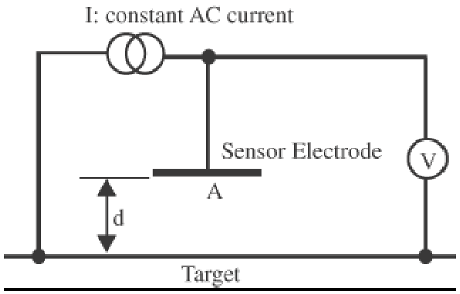
- *Goal is to use a measurement of the bpm mechanical position relative to a fixed reference to correct the bpm beam position reading*
- Driven by demanding long-term (7 days) drift specification of 1 μm rms (~4 μm peak to peak) for the APS-Upgrade multi-bend acromat (MBA) ring
- Only long-term mechanical drift and beam motion considered in these experiments (tens of seconds, minutes, hours, days)
- Mechanical Measurement System (MMS) Engineering Design
  - **Capacitive System (horizontal and vertical planes)**
  - **Hydrostatic System (vertical plane only)**
- APS Upgrade diagnostics R&D systems layout in sector 27 of the APS storage ring
- Initial results using the MMS
- Using the MMS to correct BPM beam position-experiments:
  - While locking the electron beam using APS orbit feedback system
  - From a least-squares fit to bpm position data corrected for capacitive and hydrostatic sensors
- Conclusion

# MMS: Capacitive Detector

- Principle: RF BPM vacuum chamber structure and an electrode form a capacitor
- Capacitive reactance at a given frequency is therefore proportional to the separation d of the electrode from the chamber
- Capacitive electrodes are mounted on a super invar rod with a coefficient of expansion less than 270 nm / °C over the full 1 m length
- Manufacturer: Micro Epsilon
- System: capaNCDT 6220/DL6220 multi-channel system with resolution of 20 nm



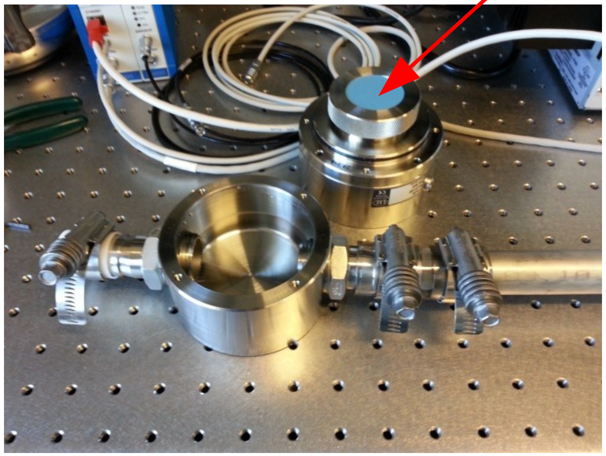



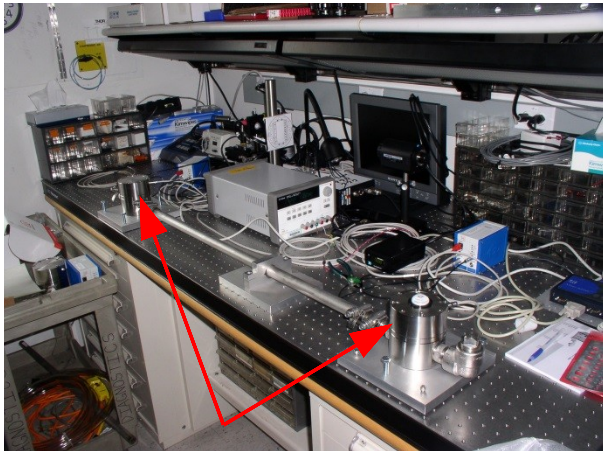




# MMS: Hydrostatic Detector

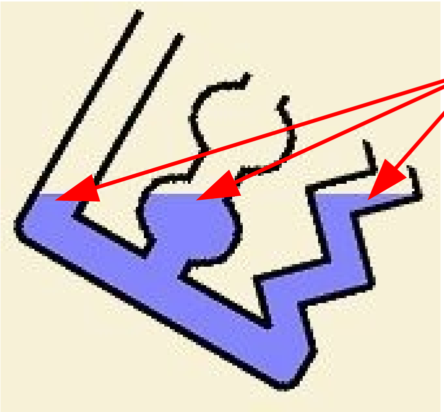
- Principle: An electrode and the water surface in a container form a capacitor and "communicating vessels principle"
- Capacitive electrode uses a heater to eliminate condensation on the electrode
- Operation uses same principle as capacitive detector and similar Micro Episilon electronics (similar resolution)
- Probable systematic errors for a large hydrostatic system due to volume changes from temperature etc.

Electrode and Heater



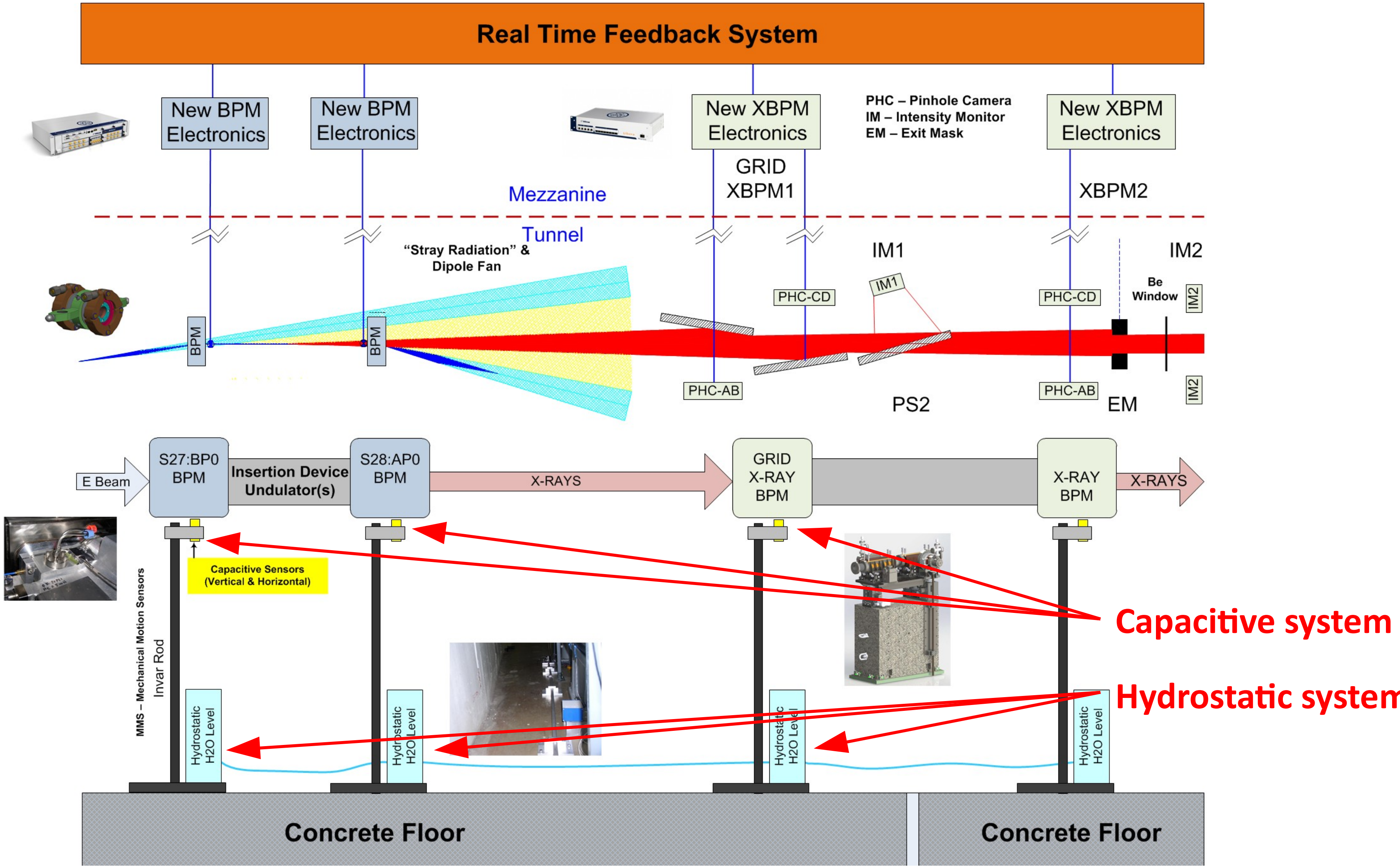


H$_2$0 Reservoirs and Sensors

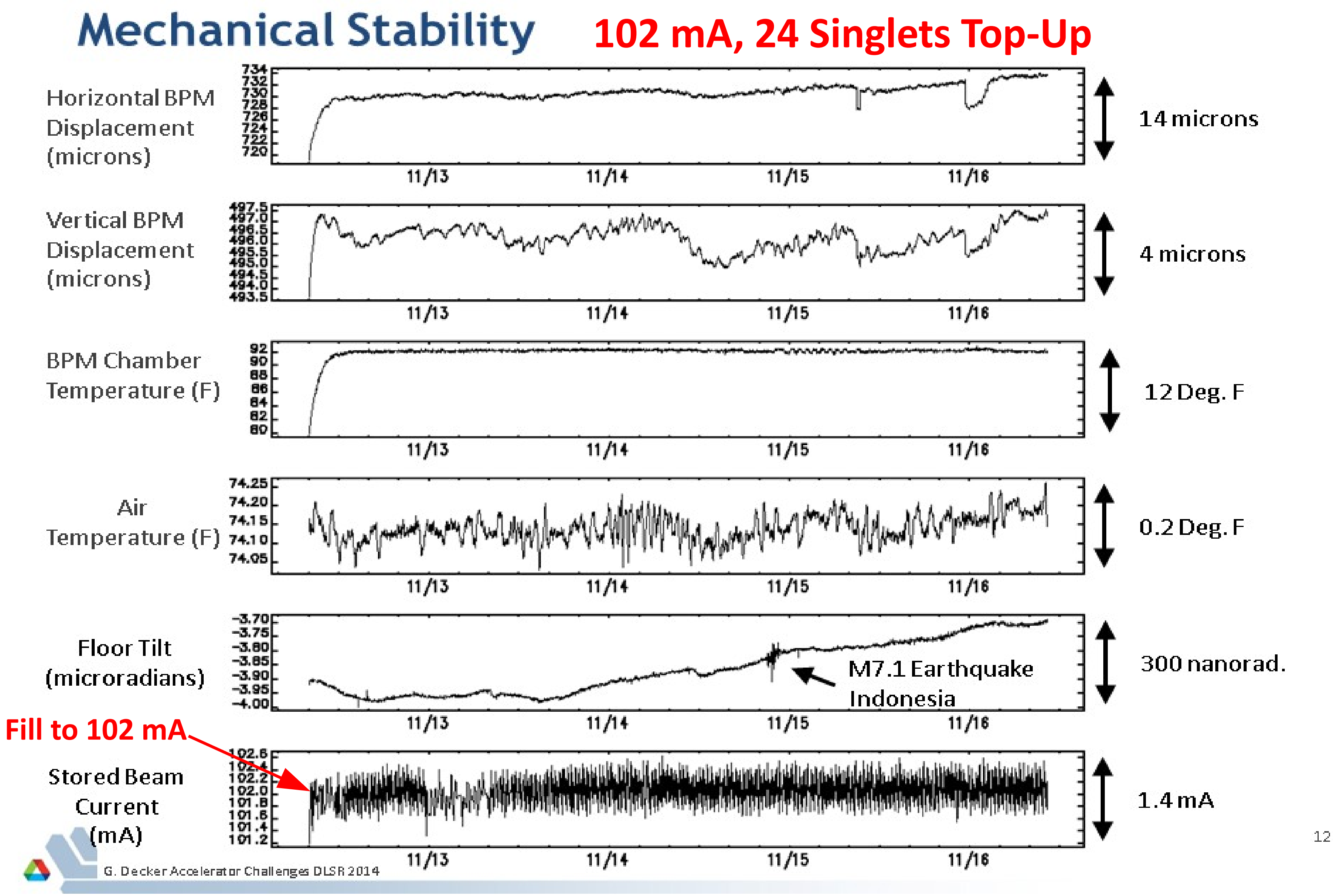


Communicating Vessels:
H$_2$0 level is the same relative to ground no no matter the orientation or shape of the vessels
*Provides an absolute vertical Reference*

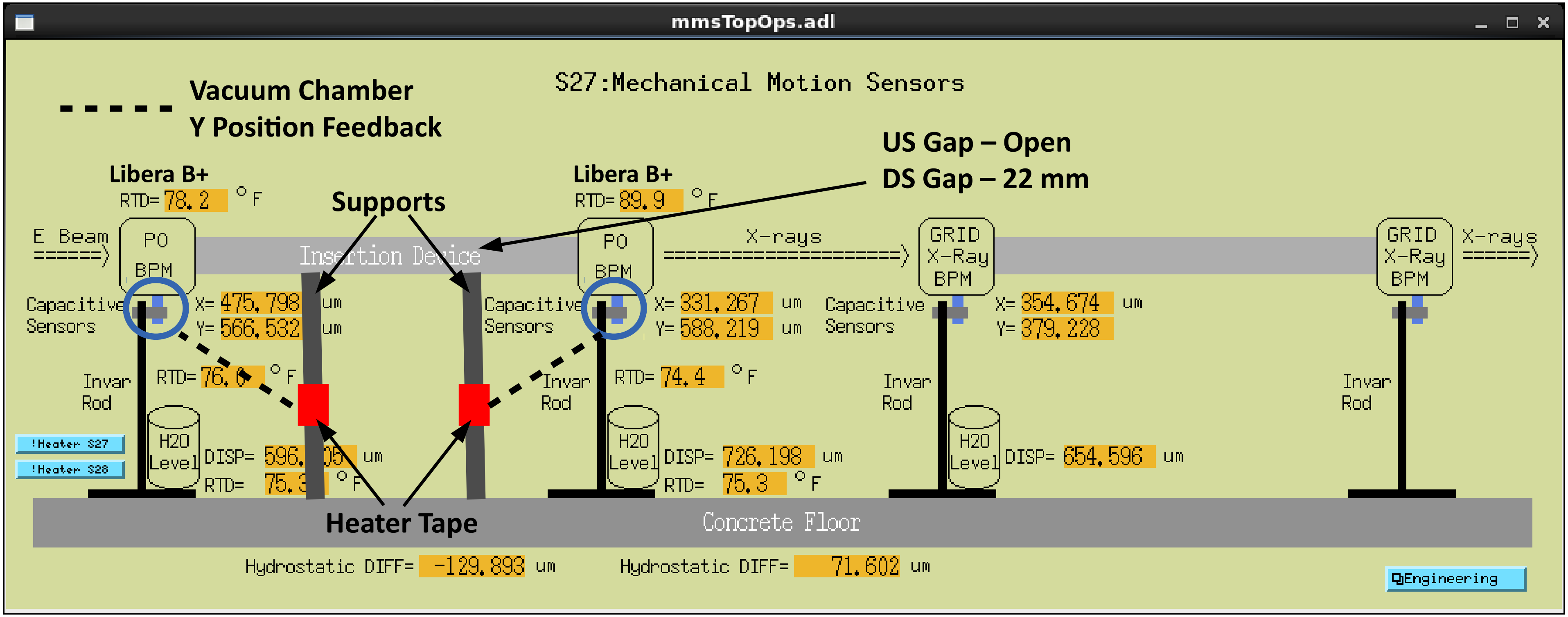
# APS Upgrade Diagnostics Systems R&D in Sector 27



# Initial Results from the Capacitive and Hydrostatic Systems

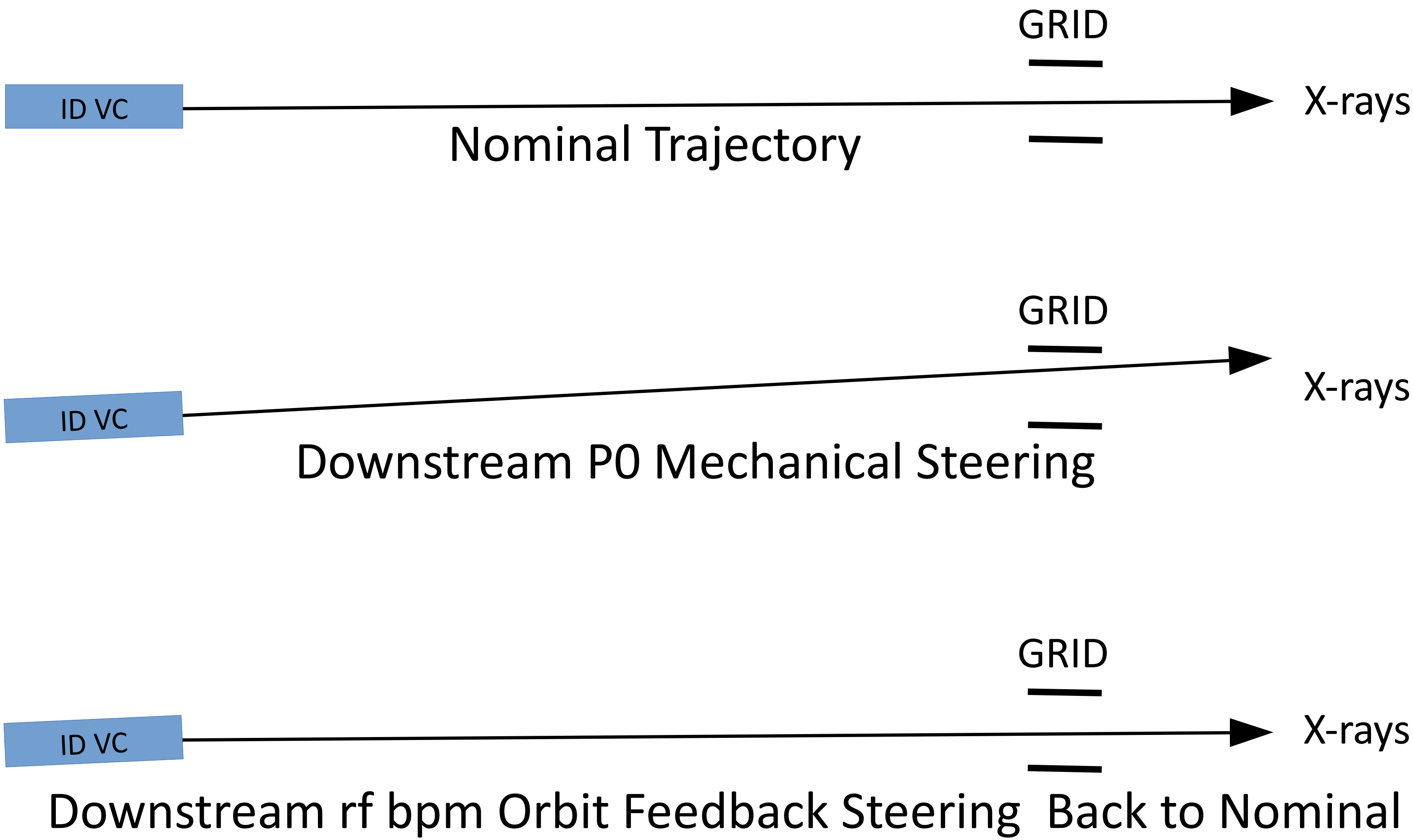


# Initial Results: Capacitive Sensors In Mechanical Feedback



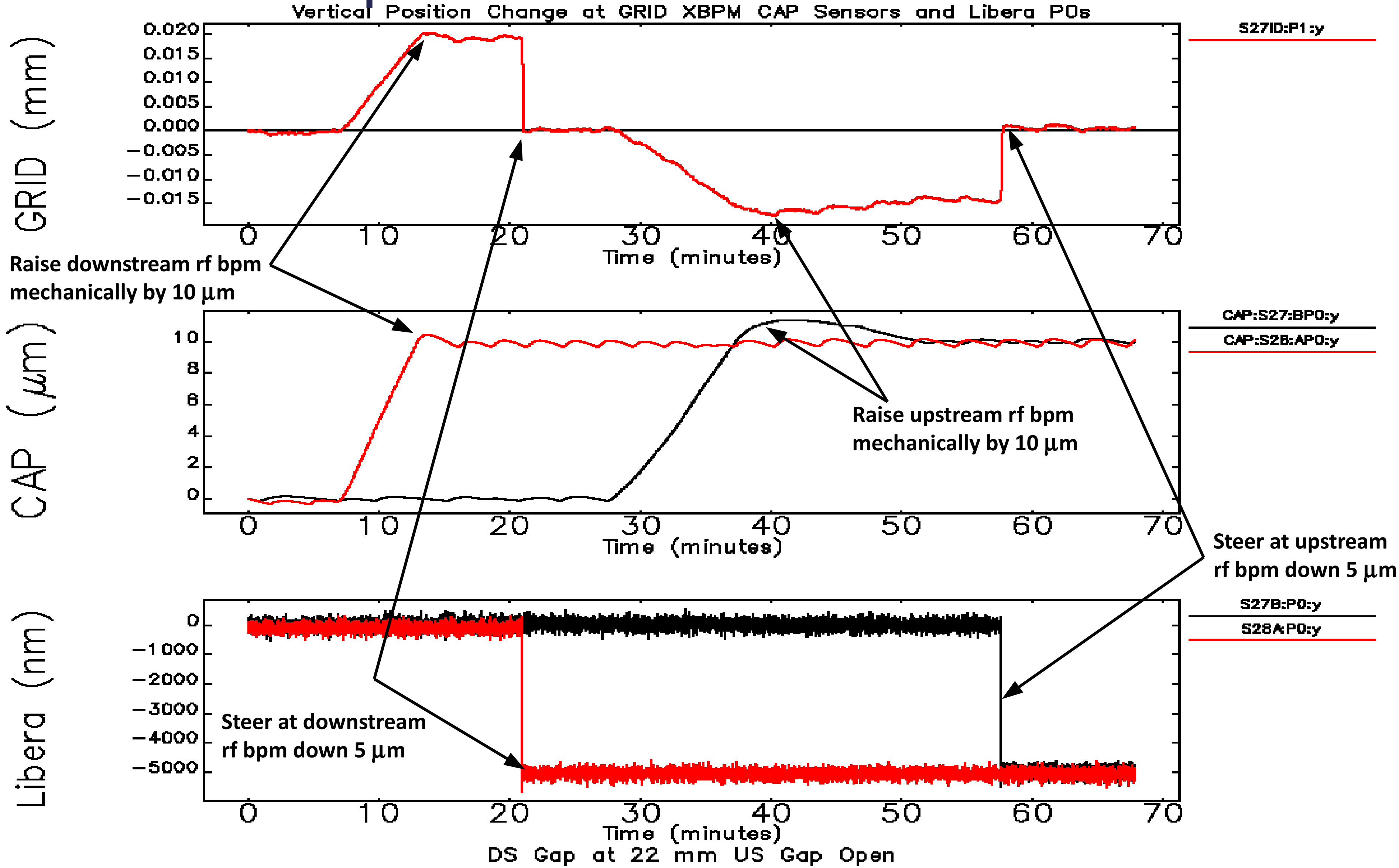

- Using heater tape on the ID vacuum chamber supports, move the upstream and downstream ID rf bpms using the capacitive sensors in a simple feedback loop
- Experiment:
  - Using orbit feedback, lock the electron beam at upstream and downstream rf bpms using a local square matrix
  - With undulator gaps at 15 mm, move the upstream and downstream ID vacuum chamber rf bpms
  - Observe and predict X-ray beam motion at downstream “GRID” X-ray bpm

# Initial Results:  Capacitive Sensors In Mechanical Feedback cont.



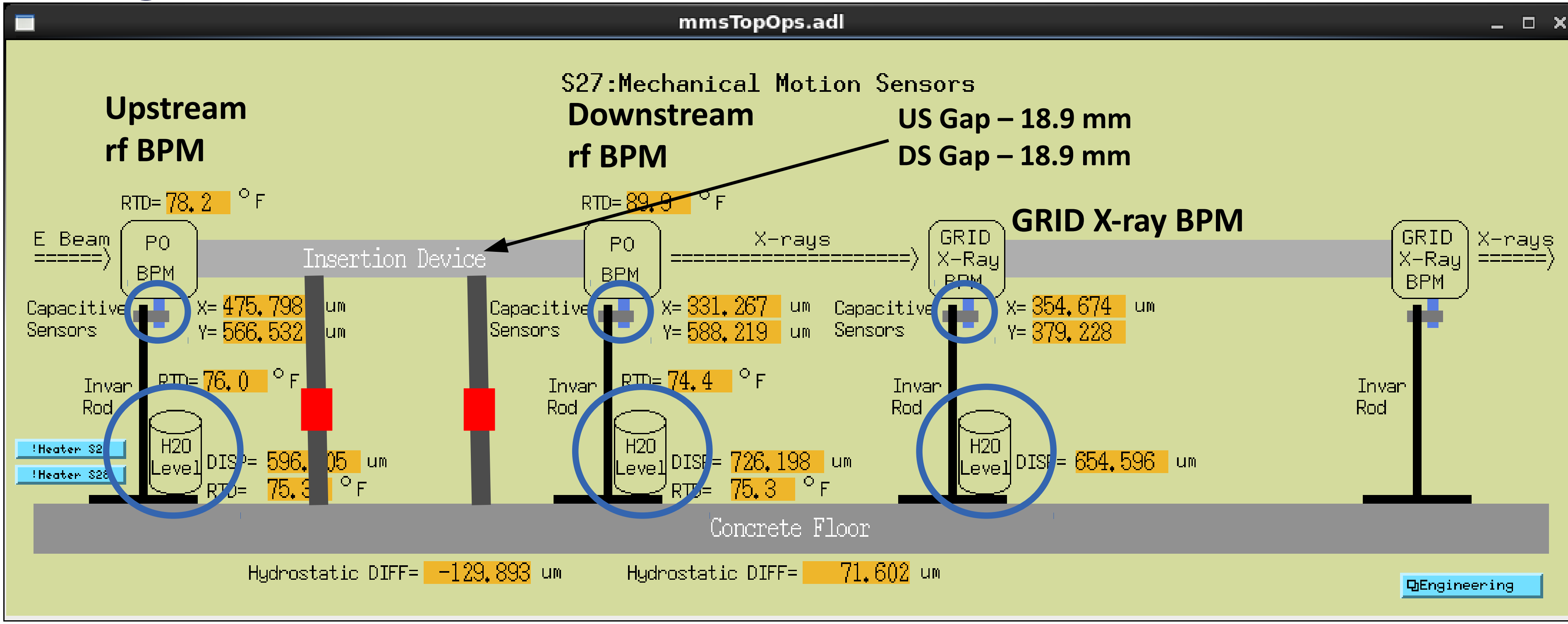

- End result is ID VC has a mechanical angle equal to 2 μrad up
- Do the same experiment with the upstream part of the ID VC ending with a net offset of the vacuum chamber vertically and the beam centered in the GRID X-ray bpm

# Initial Results: Capacitive Sensors In Mechanical Feedback cont.




- Results experiment with DS gap at 22 mm and US gap open
- Found factor of 2 calibration error in the capacitive sensors

# Using the MMS to Correct BPM Position




- Use orbit feedback to demonstrate how to use the MMS (both capacitive and hydrostatic systems) to correct BPM position for mechanical motion of the bpms
- Created “local square matrix” in the vertical plane in sector 27 to lock the beam at upstream and downstream rf bpms and predict the position at the GRID X-ray bpm (ID gaps at 18.9 mm)
- Run local square matrix for a week and record all MMS, rf and X-ray bpm parameters
- With the electron beam orbit locked at the rf BPMs, any extra motion seen by the GRID X-ray bpm is due to mechanical motion
- *Goal is to show how one corrects bpm position reading using capacitive and hydrostatic position readings*

# Using the MMS to Correct BPM Position cont.

- Used 24 singlets, 102 mA top-up
- Predict change in X-ray beam position at the GRID assuming straight line optics
- Take into account HS and Capacitive sensor data at all three bpms
- Equations for the X-ray beam prediction at the GRID assuming the origin (source point) is in the middle of the two undulators:

$$(1)\,\Delta y_{GRID} = (\Delta y_{A:P0} - \Delta y_{B:P0})\frac{Lg}{Lu} + \Delta y_{A:P0}$$

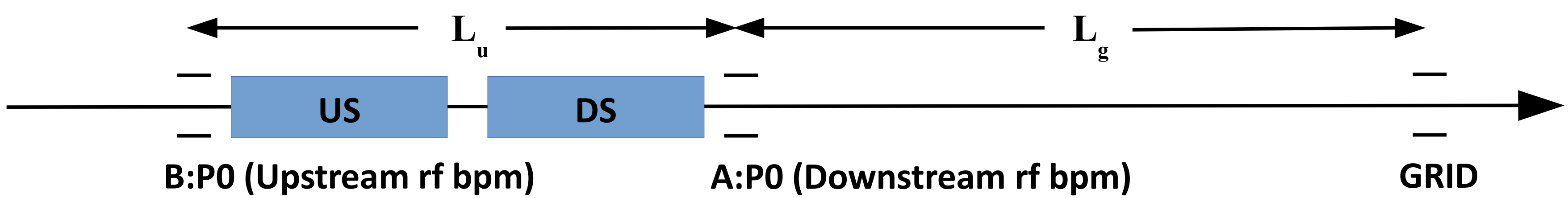
$$Lu = 5.0\,m$$

$$Lg = 16.1\,m$$

$$(2)\,\Delta y_{A:P0} \rightarrow \Delta y_{A:P0} + \Delta y_{A:P0_{CAP}} + \Delta y_{A:P0_{HS}}$$

$$(3)\,\Delta y_{B:P0} \rightarrow \Delta y_{B:P0} + \Delta y_{B:P0_{CAP}} + \Delta y_{B:P0_{HS}}$$

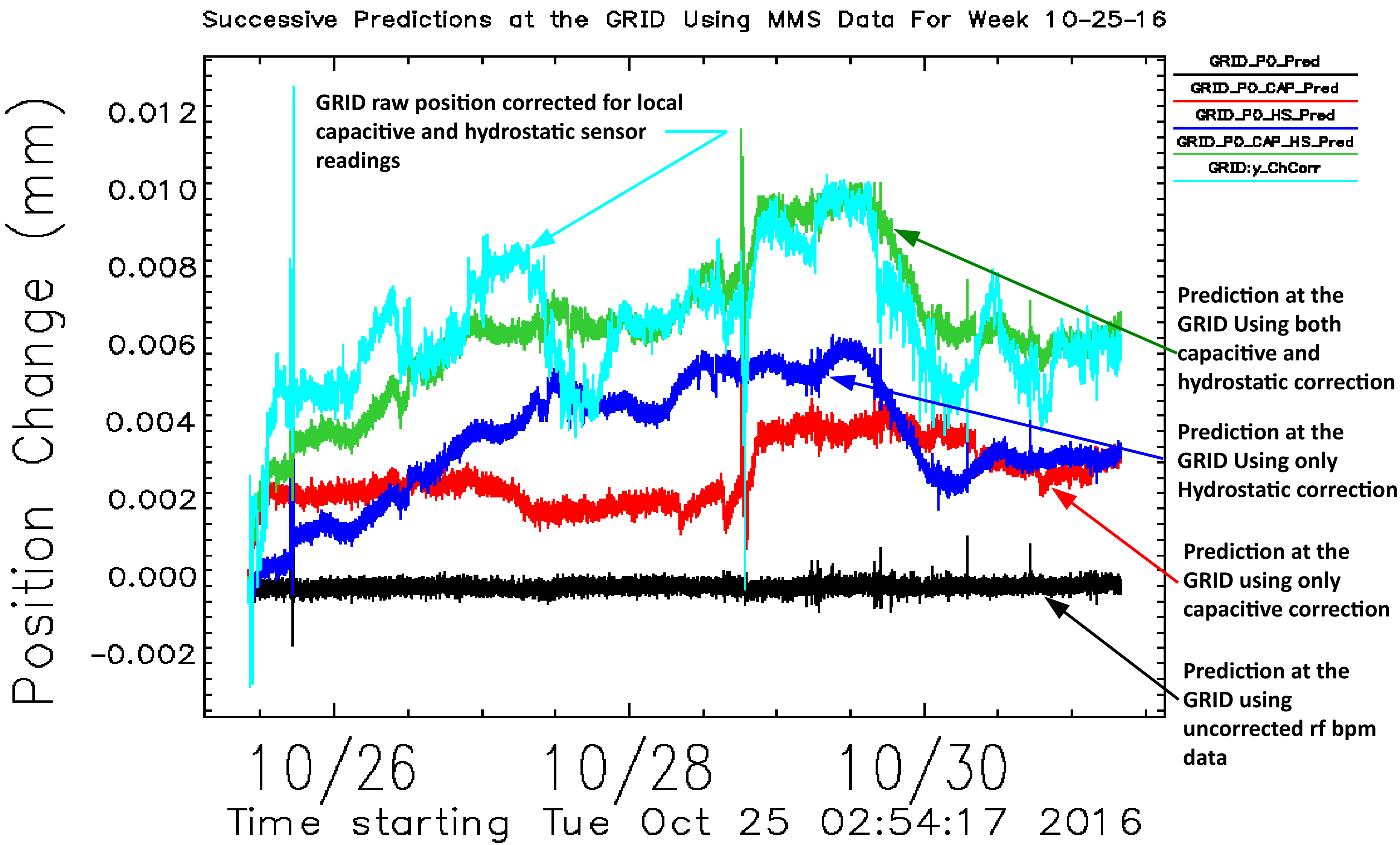
- Sector 27 geometry:



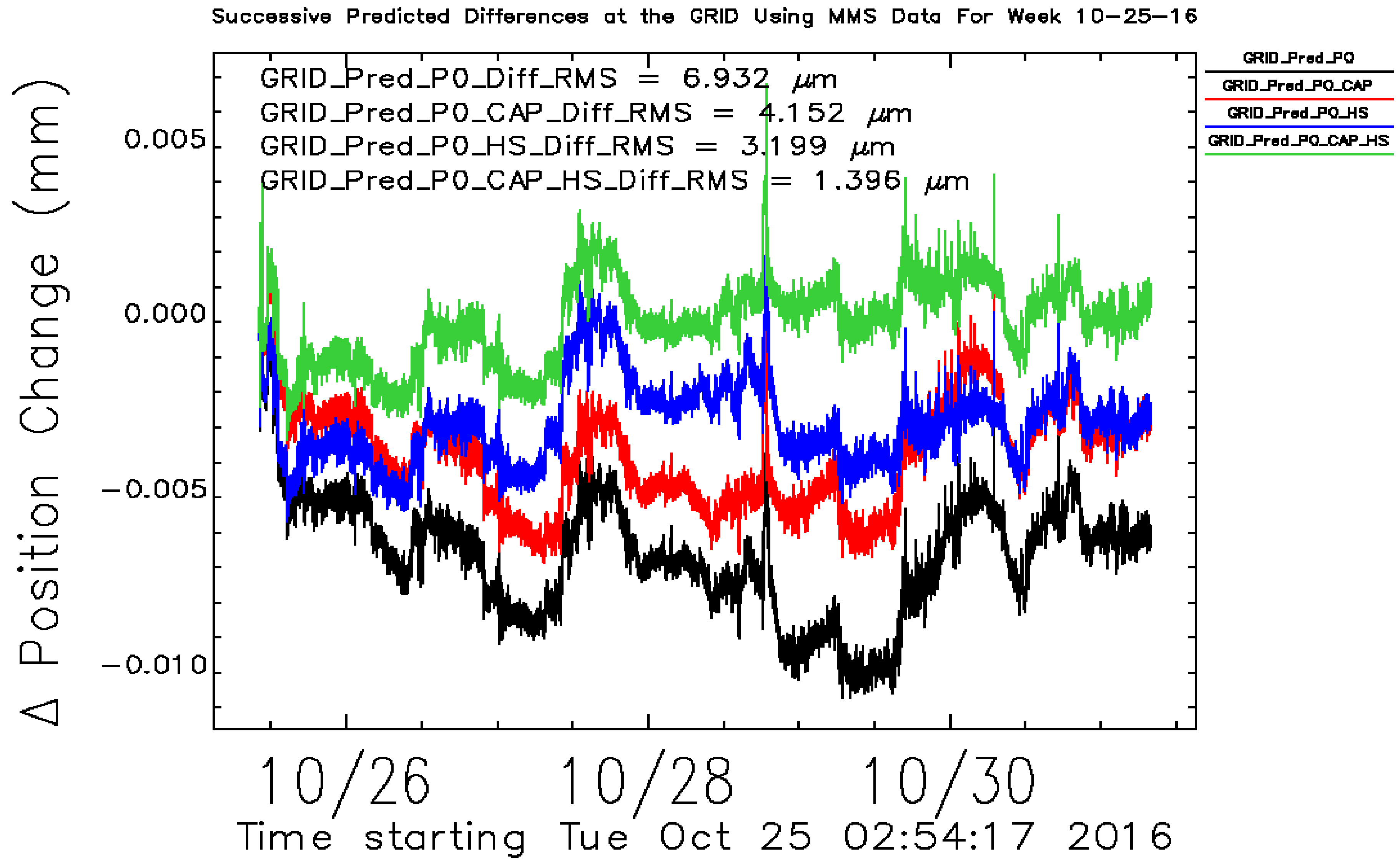

- Compare the position measurement change at the GRID (corrected for local capacitive and hydrostatic measurements) to the prediction given by equations (1) – (3).

$$(4)\,\Delta y_{GRID-Measured} \rightarrow \Delta y_{GRID-Measured} + \Delta y_{GRID_{CAP}} + \Delta y_{GRID_{HS}}$$

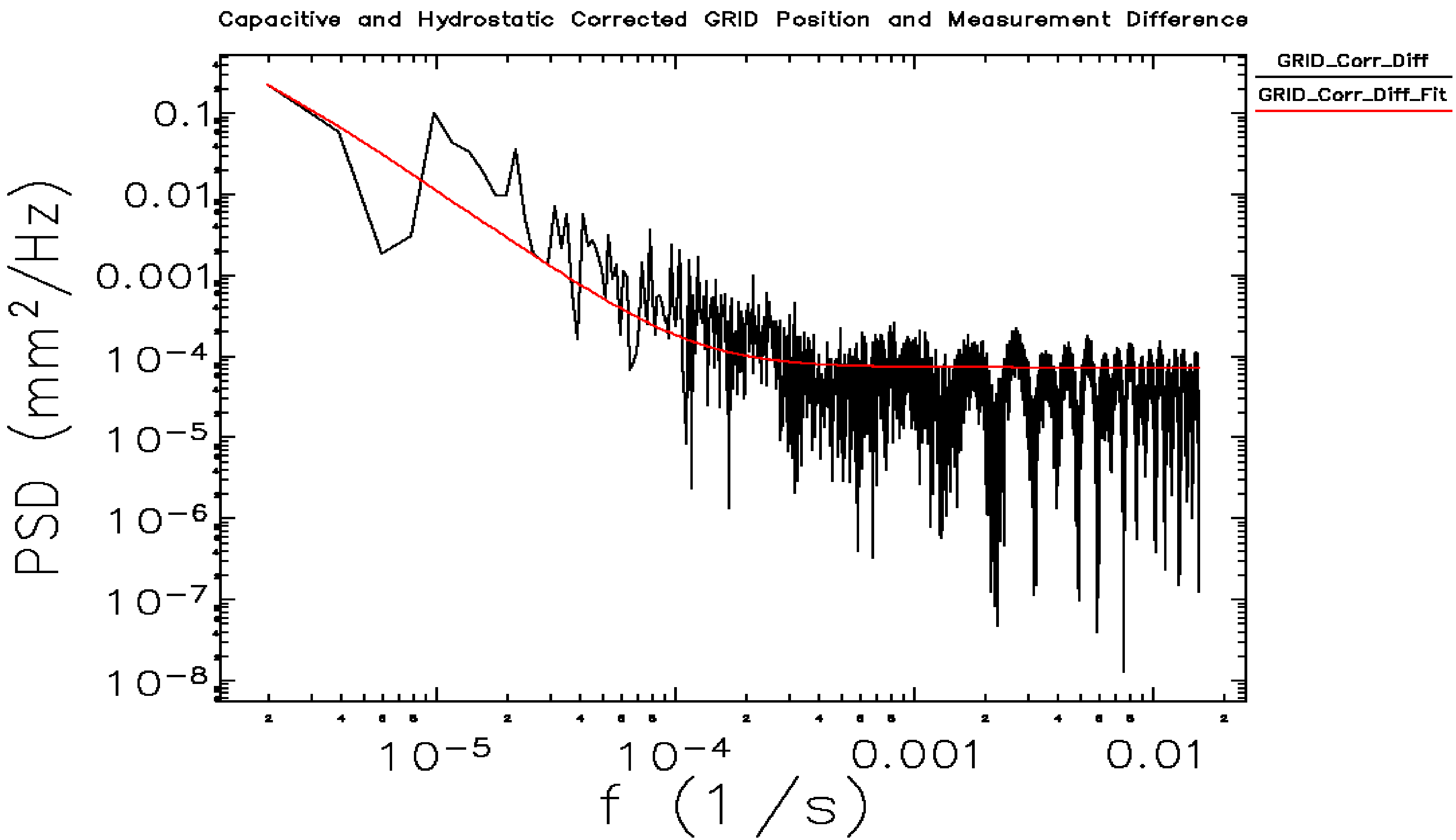
# Experiment Locking the Electron Beam at the P0s: Processed Data – P0 (successive corrections for HS and CAP motion) data prediction at the GRID: GRID Corrected for CAP, HS motion



# Experiment Locking the Electron Beam at the P0s: Processed Data – P0 (successive corrections for HS and CAP motion) data prediction at the GRID: GRID Corrected for CAP, HS motion DIFFERENCES



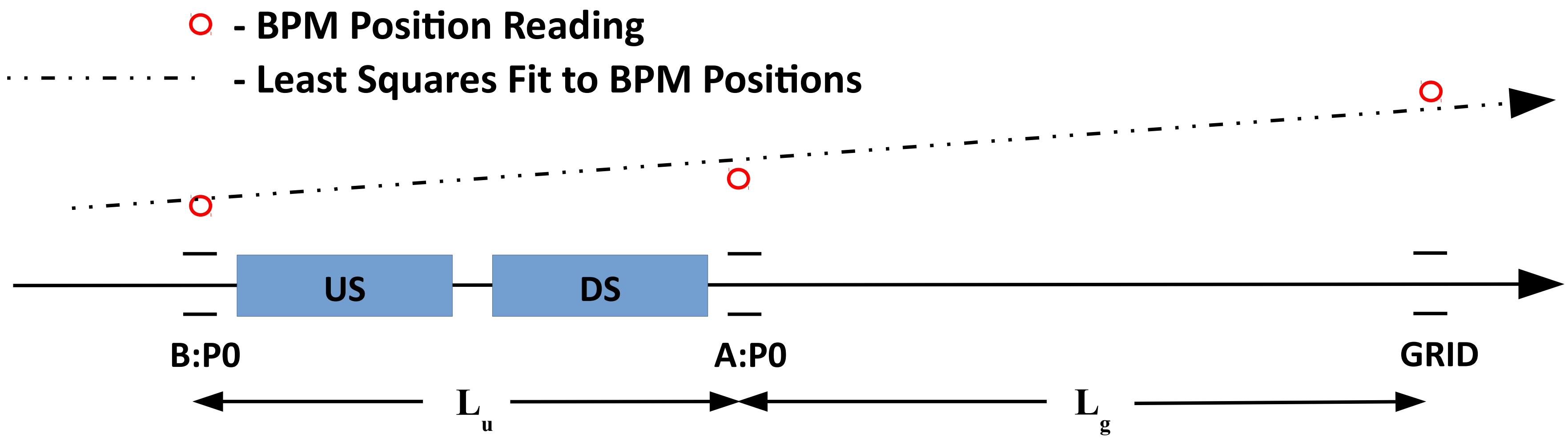
# Predicted Beam Position at the GRID and Corrected GRID Position in the Frequency Domain with 1/f Noise Fit



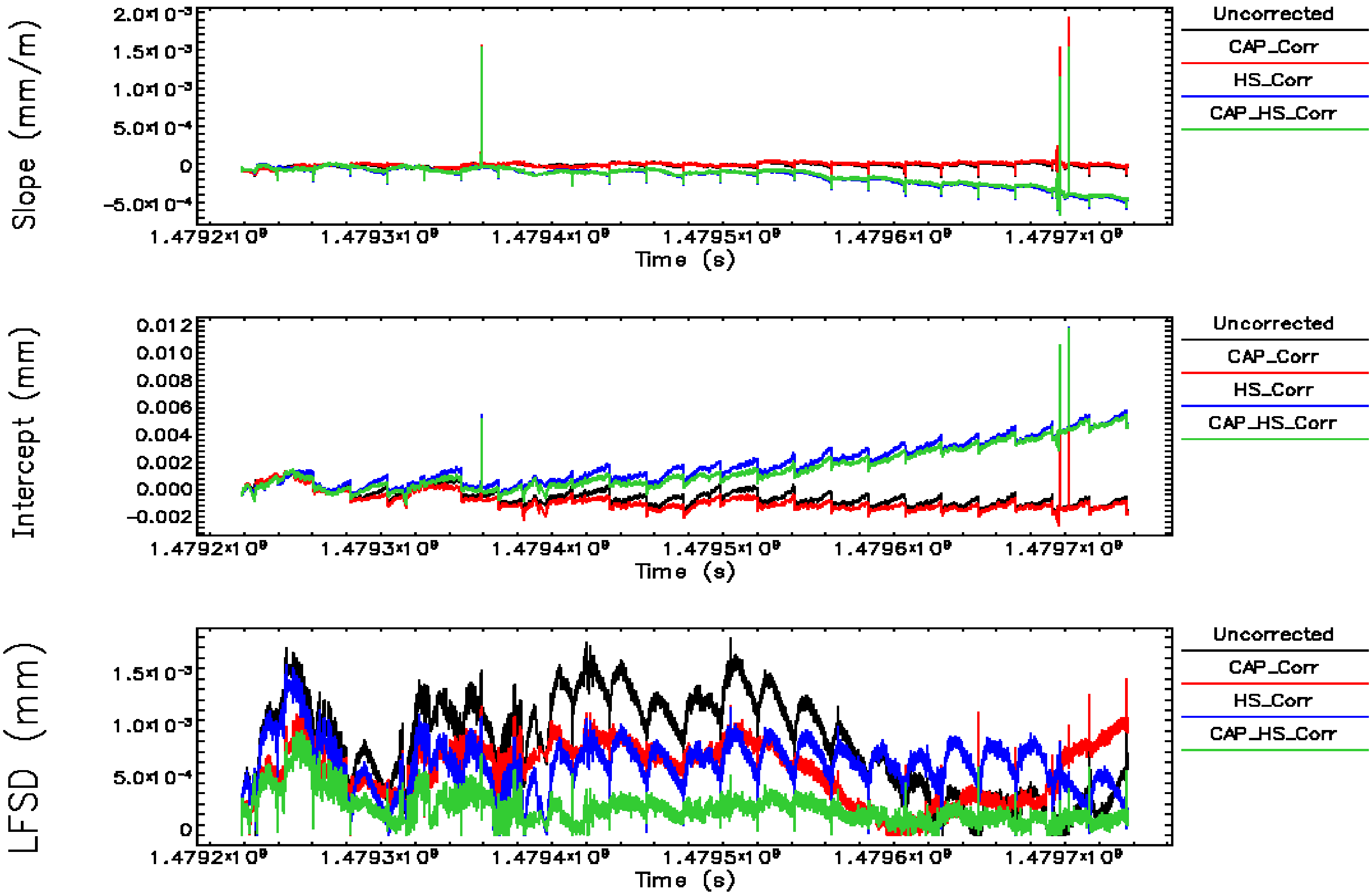

PSD Noise Assumed to Vary as $1/f^2$

# Least Squares Fit to P0, GRID Position Change Data

- A least squares fit to these three bpms should reveal a smaller rms residual as CAP and HS motion is taken into account locally at each bpm
- Residual left over should be simply the rms orbit left over after rms orbit is minimized by orbit feedback (for an overdetermined system of more bpms than correctors)
- Procedure is similar to the prediction analysis: successively correct for hydrostatic and capacitive motion and look at slope, interccept and standard deviation of the three residuals



# Least Squares Fit to P0, GRID Position Change Data Vertical Plane, 324 Singlets: Processed Data



# Conclusion

- At ANL/APS we have developed capacitive and hydrostatic mechanical position sensing systems
- Initial results showed one can use both systems to measure mechanical movement of the floor and vacuum chamber rf and Xray bpm supports
- Inital results showed one can use the capacitive system to predict changes at the GRID X-ray bpm when locking the beam at the ID upstream and downstream rf bpms and moving the vacuum chamber using simple mechanical feedback
- Logging MMS and rf bpm data over a week using a local square matrix to correct exactly at the ID upstream and downstream rf bpms showed:
  - One can predict changes at the GRID X-ray bpm with remaining errors on the level of the rms spec for APS-U MBA ring (so one can correct the raw bpm readings using MMS data)
  - In the frequency domain remaining errors can be modeled as 1/f noise
- The least squares fit analysis showed a similar reduction in rms residual error at the two rf and Xray bpms as capacitive and hydrostatic position readings are used to correct the raw bpm reading
- Obtained similar results in the horizontal plane where there is only capacitive mechanical motion measurements
- *Main conclusion is that from these experiments, correction of bpm readings for underlying mechanical motion of the bpm vacuum chamber and floor can improve the raw bpm readings for long term drift relative to an absolute position reference*

# Extra Slides

- Extra Slides outlining similar experiments

# Experiment Locking the Electron Beam at S27B:P0 and the GRID

- Used Hybrid, 102 mA top-up
- Predict change in electron beam position at S28A:P0 assuming straight line optics
- Take into account HS and Capacitive sensor data at all three bpms
- Equations for the electron beam prediction at the GRID assuming the origin is in the middle of the two undulators:

$$(1)\,\Delta y_{A:P0} = (\Delta y_{GRID} - \Delta y_{B:P0})\frac{Lu}{Lg+Lu} + \Delta y_{B:P0}$$

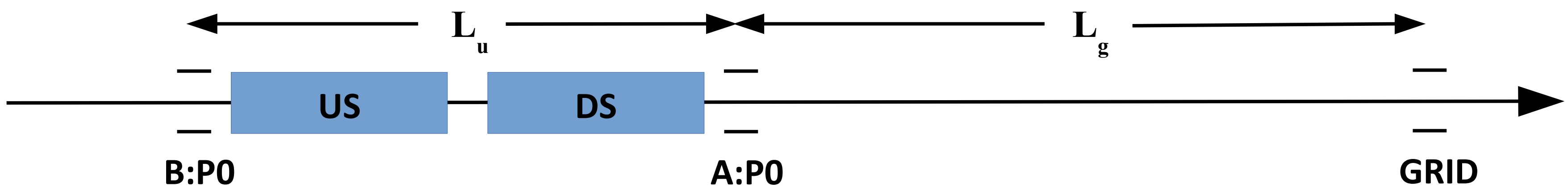
$$Lu = 5.0\,m$$

$$Lg = 16.1\,m$$

$$(2)\,\Delta y_{GRID} \rightarrow \Delta y_{GRID} + \Delta y_{GRID_{CAP}} + \Delta y_{GRID_{HS}}$$

$$(3)\,\Delta y_{B:P0} \rightarrow \Delta y_{B:P0} + \Delta y_{B:P0_{CAP}} + \Delta y_{B:P0_{HS}}$$

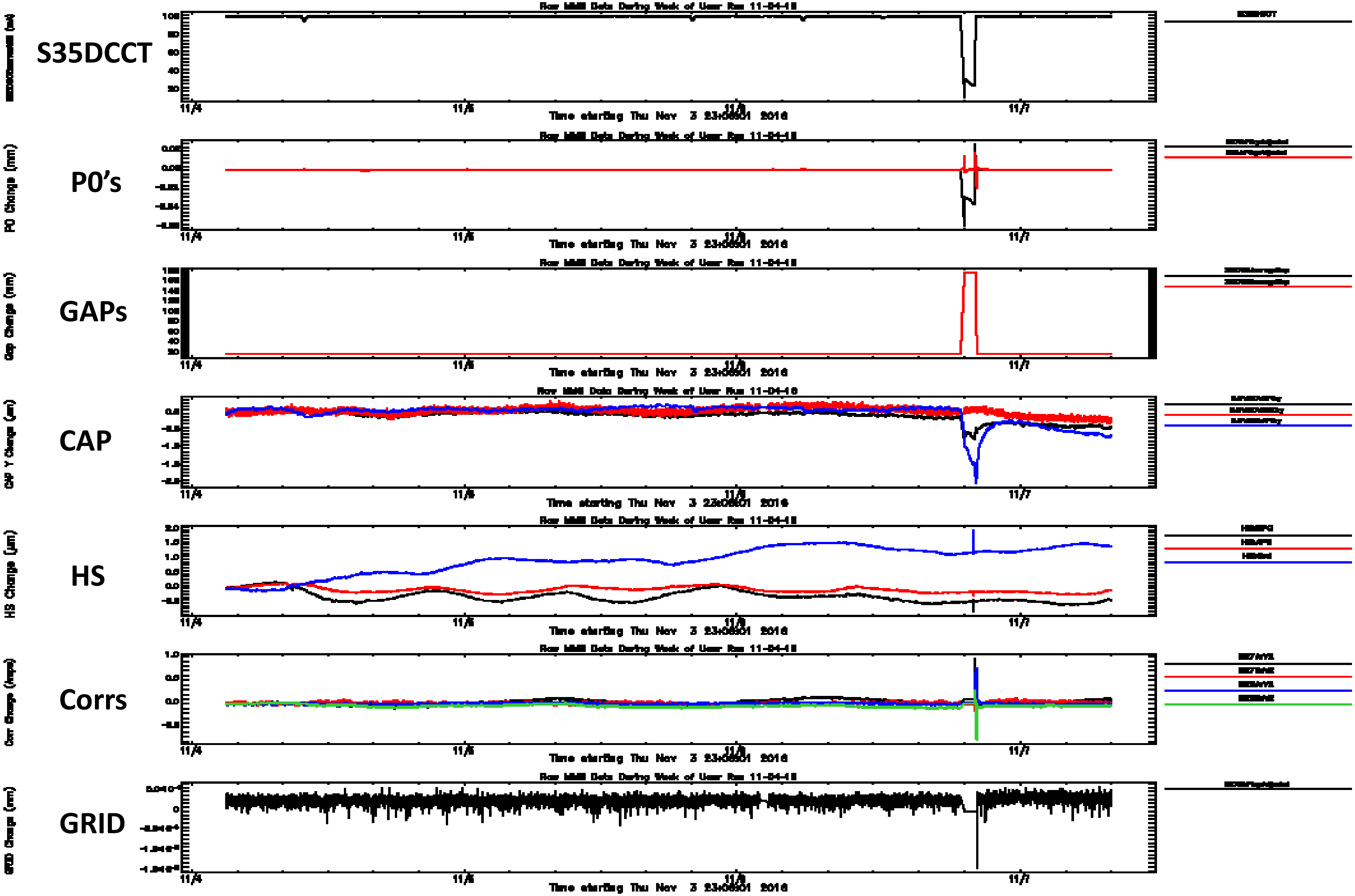
- Sector 27 geometry:



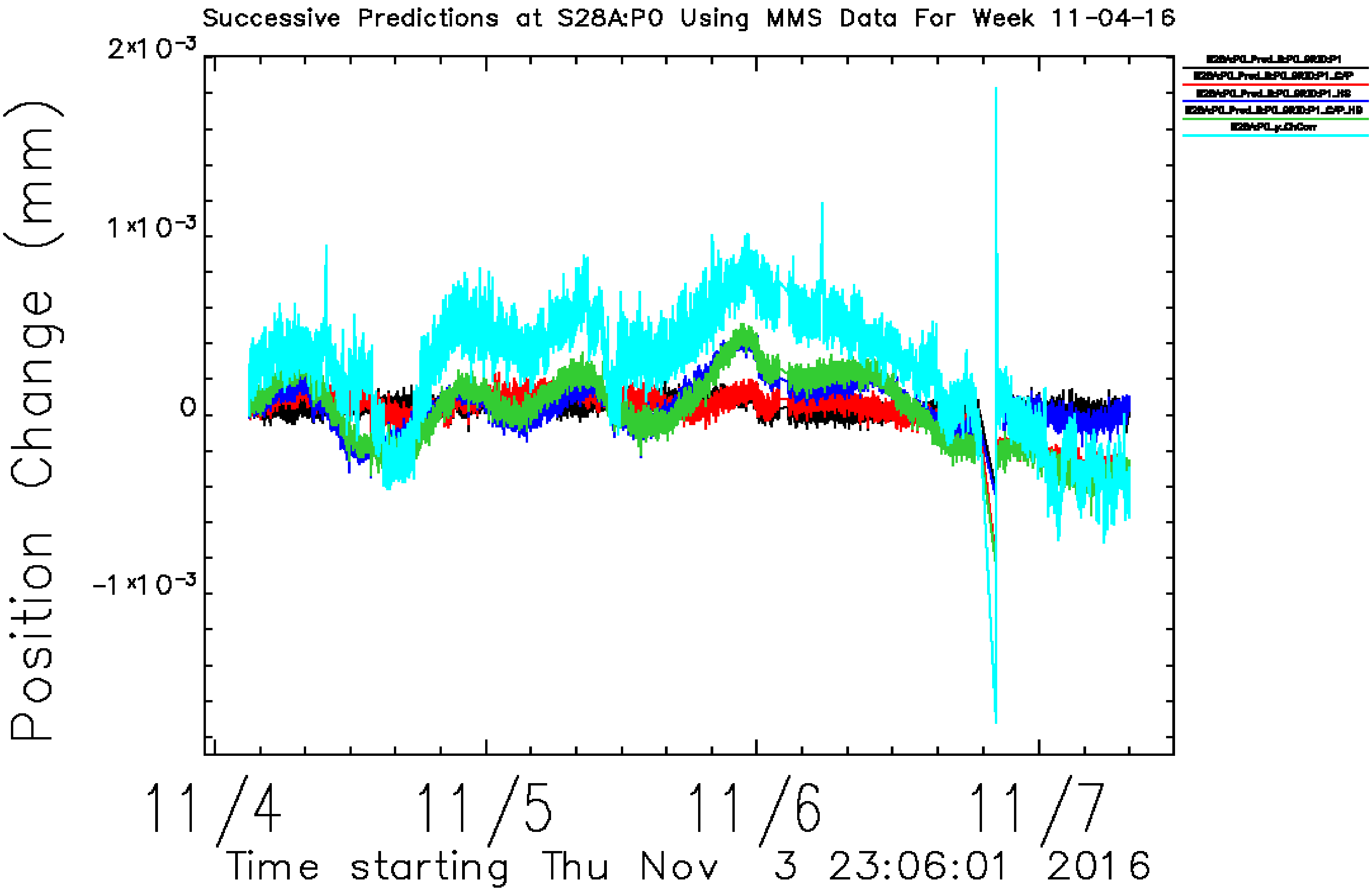

- Compare the position measurement change at the GRID to the prediction given by equations (1) – (3).

$$(4)\,\Delta y_{A:P0-Measured} \rightarrow \Delta y_{A:P0-Measured} + \Delta y_{A:P0_{CAP}} + \Delta y_{A:P0_{HS}}$$

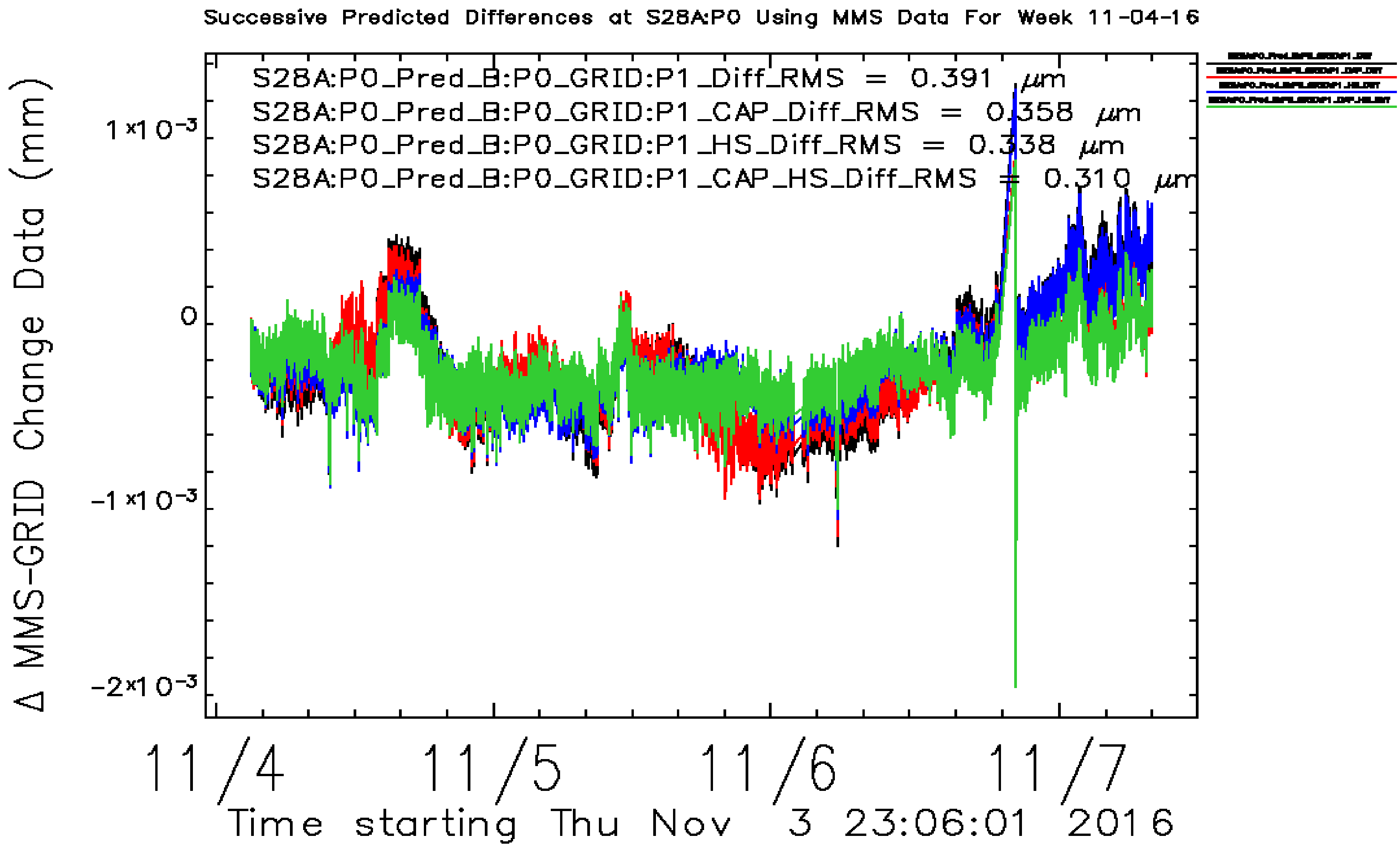
# Experiment Locking the Electron Beam at S27B:P0 and the GRID: Raw Data



# Experiment Locking the Electron Beam at S27BP0 and the GRID: Processed Data – S27B:P0 and GRID (successive corrections for HS and CAP motion) prediction at S28A:P0 corrected for CAP and HS motion



# Experiment Locking the Electron Beam at S27BP0 and the GRID: Processed Data – S27B:P0 and GRID (successive corrections for HS and CAP motion) prediction at S28A:P0 corrected for CAP and HS motion DIFFERENCES



# Experiment Locking the Electron Beam at S27B:P0 and the GRID: Conclusion

- Essentially the same as for the first experiment locking the beam at the P0s
- I would suspect systematic calibration factor errors for rf and X-ray bpms, capacitive and hydrostatic sensors could easily conspire to result in the 310 nm number when all three are used to predict the electron beam position at S28A:P0...
- Sector 27 now has many more bpms in it than datapool correctors
- Next data to mine is the same 3 bpms (S27B:P0, S28A:P0 and GRID)
  - Correct for Capacitative motion
  - Correct for Hydrostatic motion
  - Look at the corrected errors

# Experiment Using Standard Orbit Correction: P0 Prediction at GRID

- Used Hybrid, 102 mA top-up
- Predict change in X-ray beam position at the GRID assuming straight line optics this time with standard orbit correction running (no square matrix)
- Take into account HS and Capacitive sensor data at all three bpms
- Equations for the X-ray beam prediction at the GRID assuming the origin is in the middle of the two undulators:

$$(1)\,\Delta y_{GRID}=(\Delta y_{A:P0}-\Delta y_{B:P0})\frac{Lg}{Lu}+\Delta y_{A:P0}$$

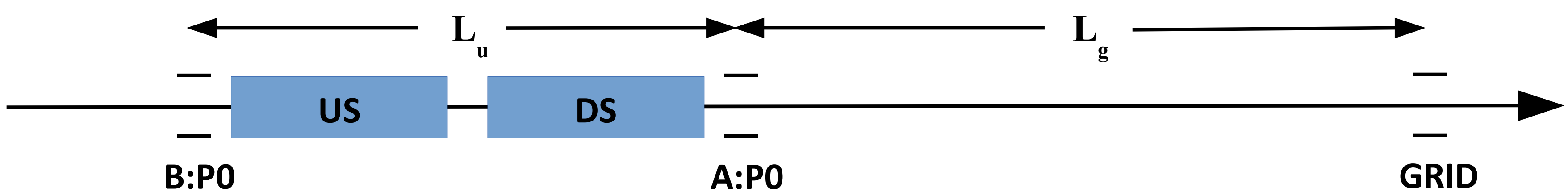
$$Lu=5.0\,m$$

$$Lg=16.1\,m$$

$$(2)\,\Delta y_{A:P0}\rightarrow\Delta y_{A:P0}+\Delta y_{A:P0_{CAP}}+\Delta y_{A:P0_{HS}}$$

$$(3)\,\Delta y_{B:P0}\rightarrow\Delta y_{B:P0}+\Delta y_{B:P0_{CAP}}+\Delta y_{B:P0_{HS}}$$

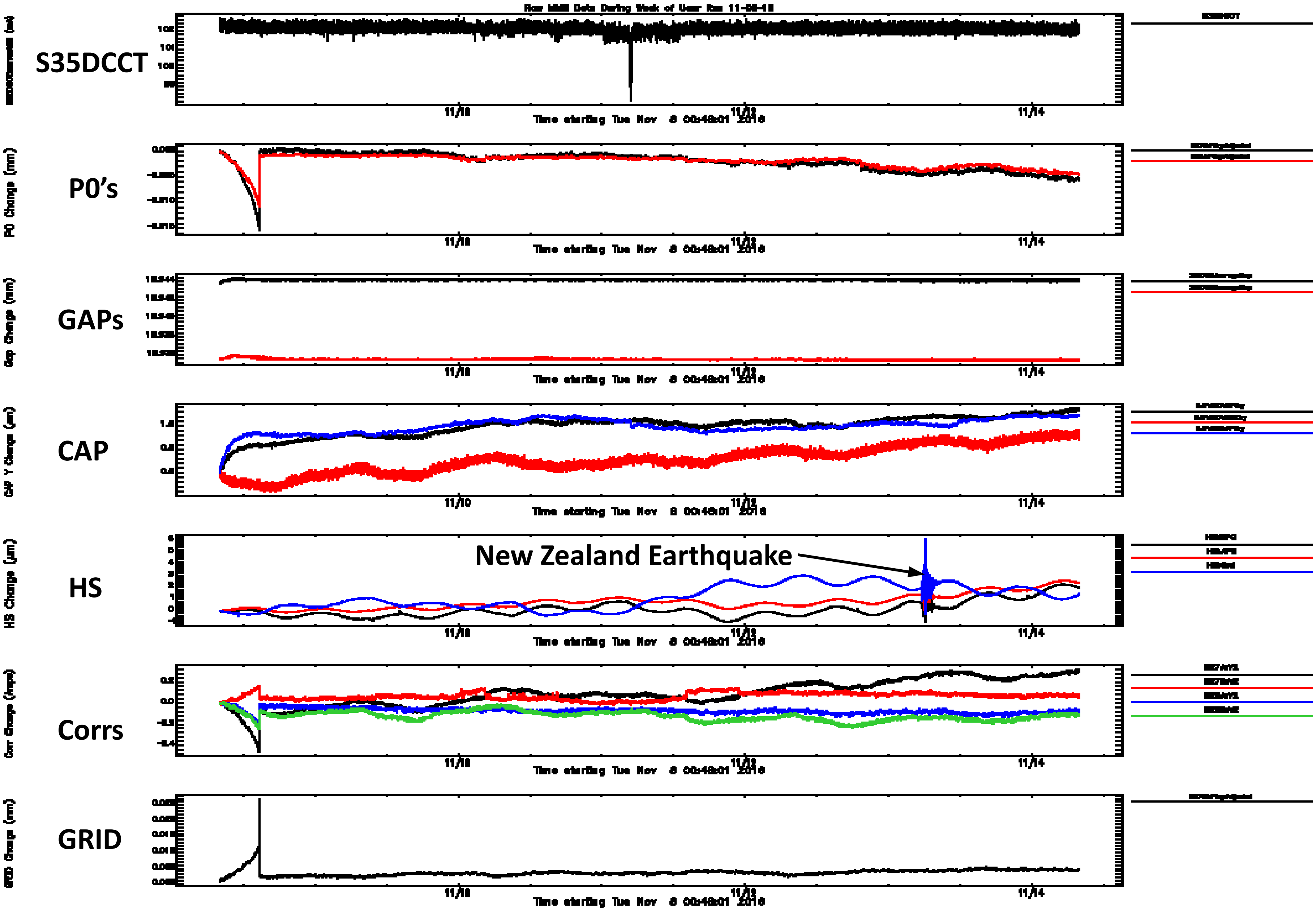
- Sector 27 geometry:




- Compare the position measurement change at the GRID to the prediction given by equations (1) – (3).

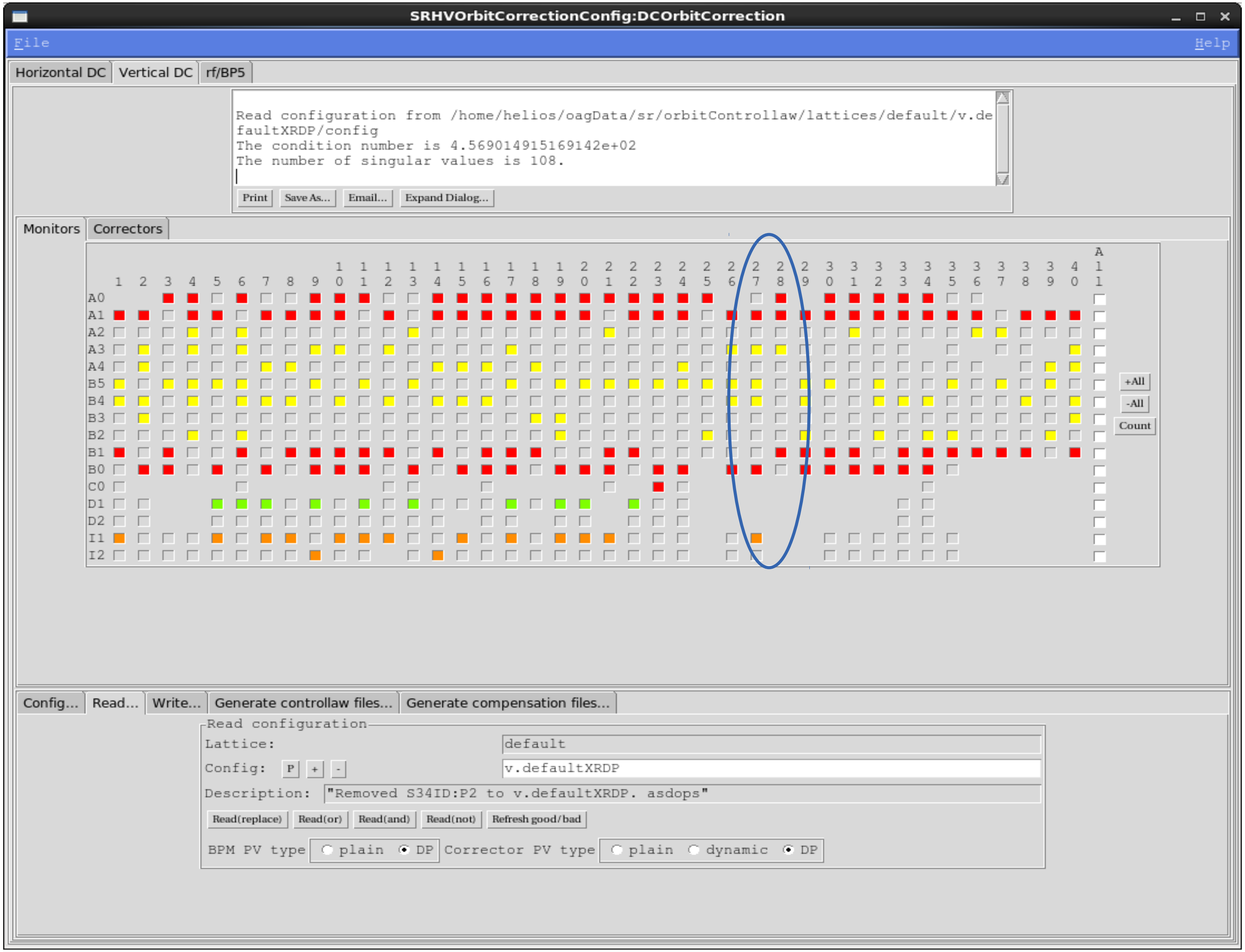
$$(4)\,\Delta y_{GRID-Measured}\rightarrow\Delta y_{GRID-Measured}+\Delta y_{GRID_{CAP}}+\Delta y_{GRID_{HS}}$$

# Experiment Using Standard Orbit Correction:  P0 Prediction at GRID Raw Data



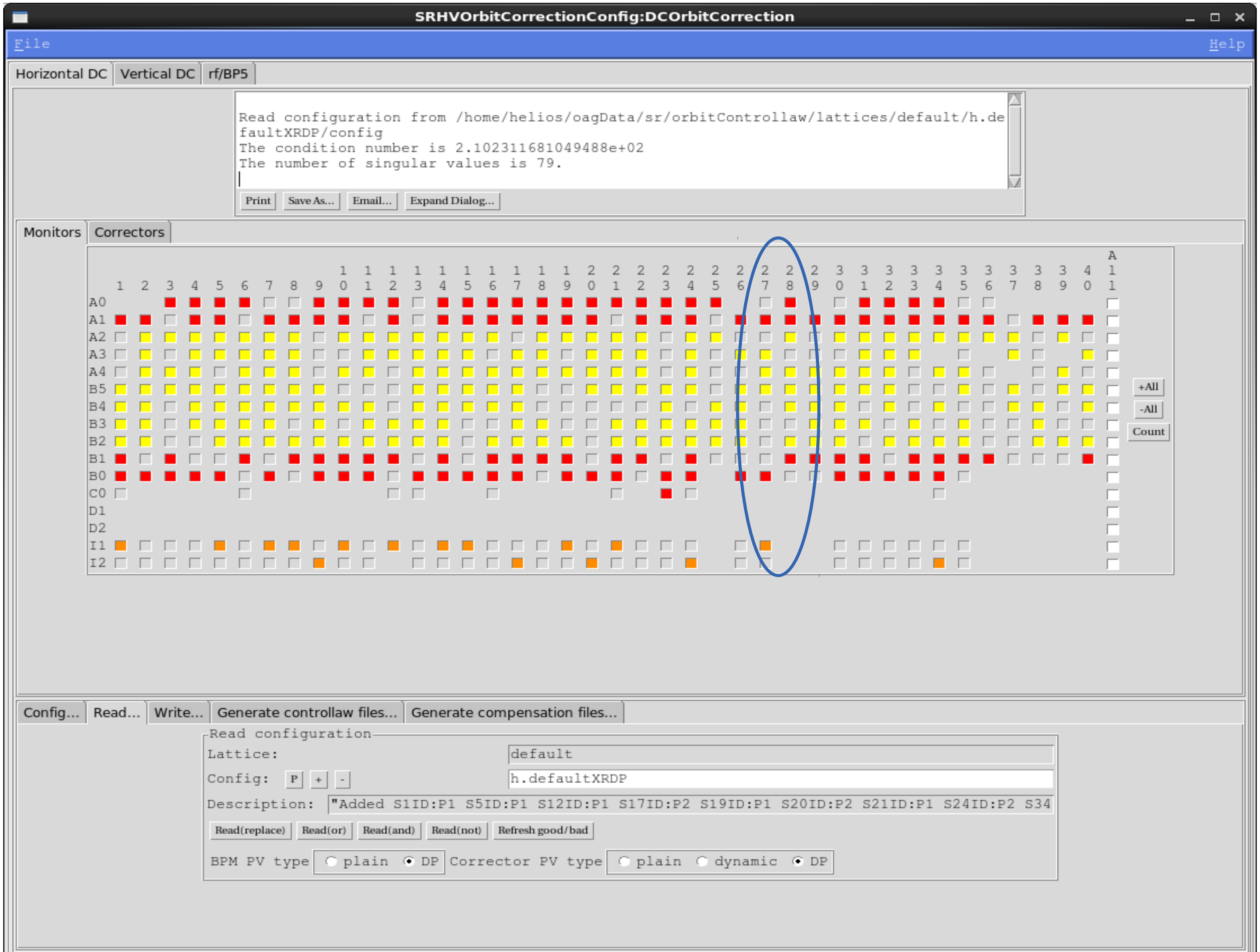
# Standard Datapool Orbit Correction Configurations:

- Standard Orbit Correction Configuration Vertical:

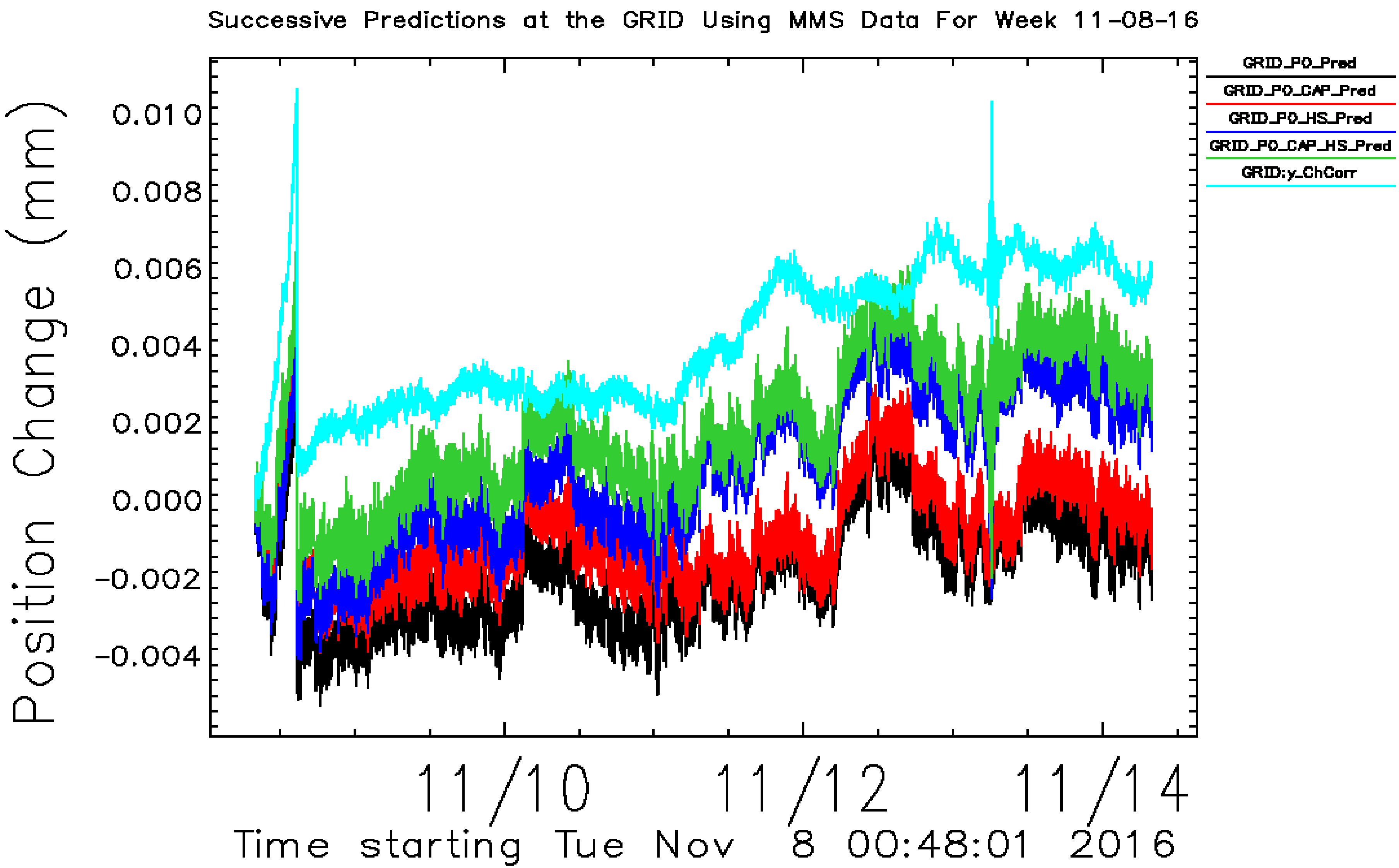


# Standard Datapool Orbit Correction Configurations:

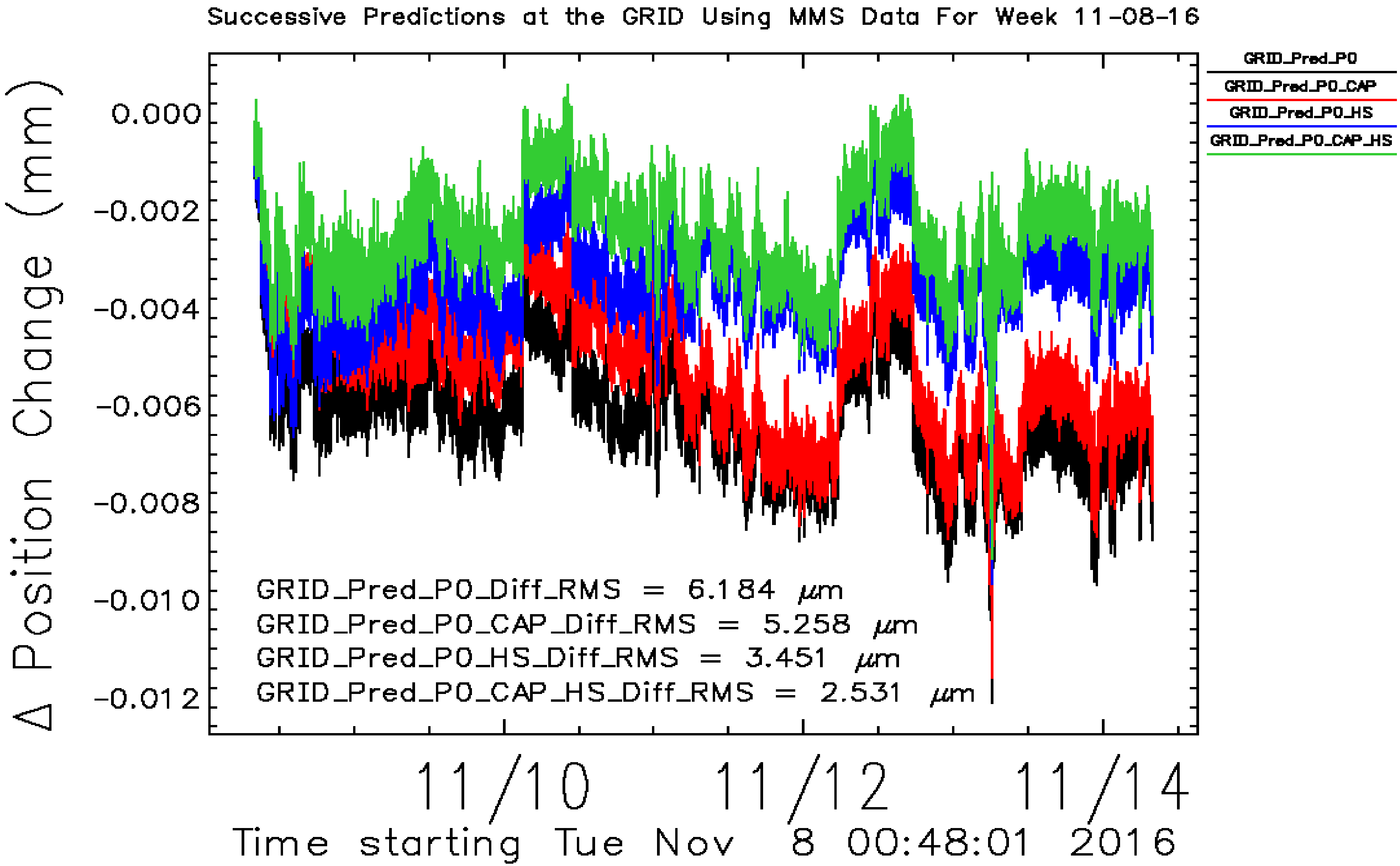
- Standard Orbit Correction Configuration Horizontal:



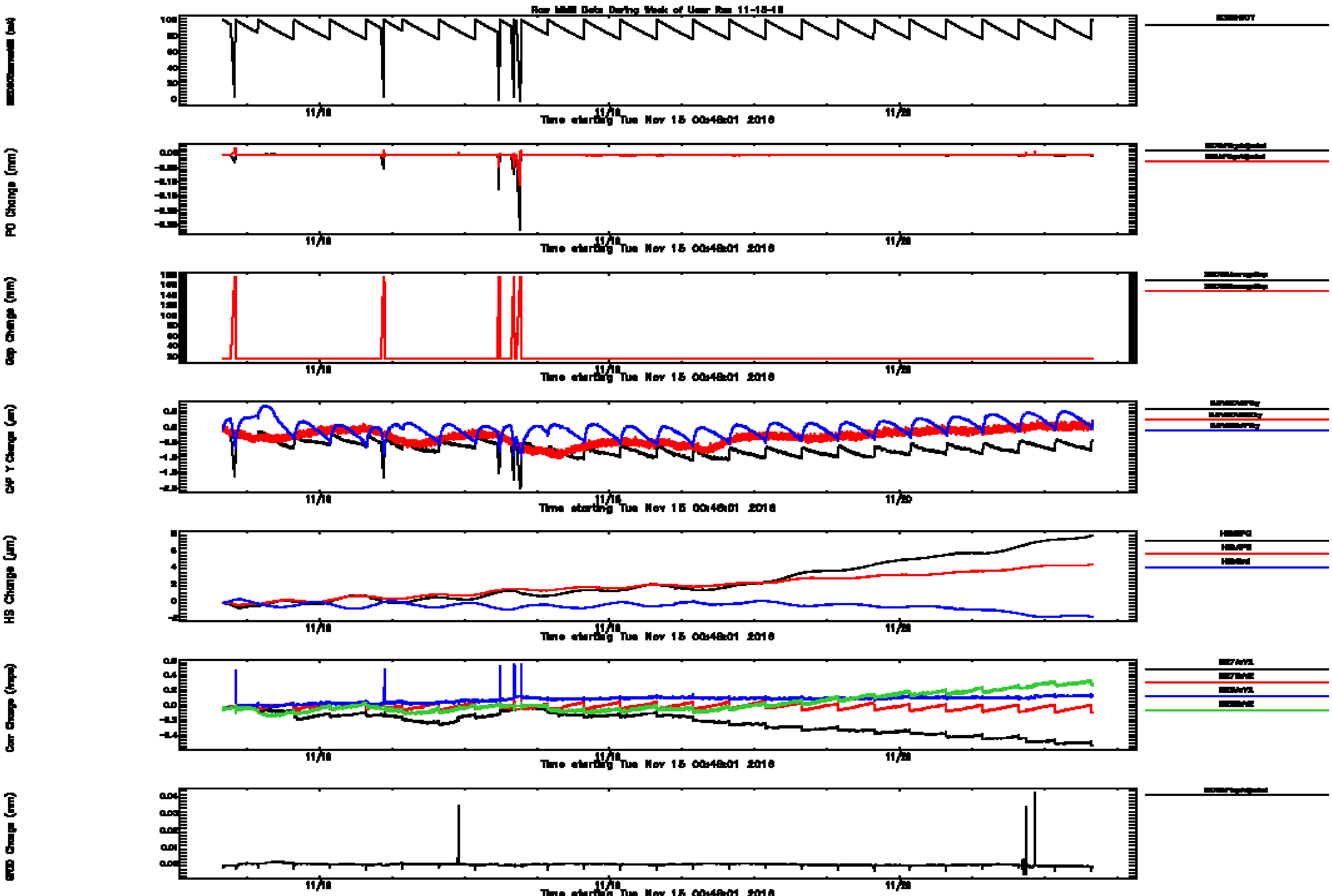
# Experiment Using Standard Orbit Correction: Processed Data – P0 (successive corrections for HS and CAP motion) Data Prediction at the GRID and GRID Corrected for CAP, HS motion



# Experiment Using Standard Orbit Correction: Processed Data – P0 (successive corrections for HS and CAP motion) Data Prediction at the GRID and GRID Corrected for CAP, HS motion DIFFERENCES



# Experiment Using Standard Orbit Correction: Using P0s to Predict Position at the GRID for 324 Singlets Raw Data:



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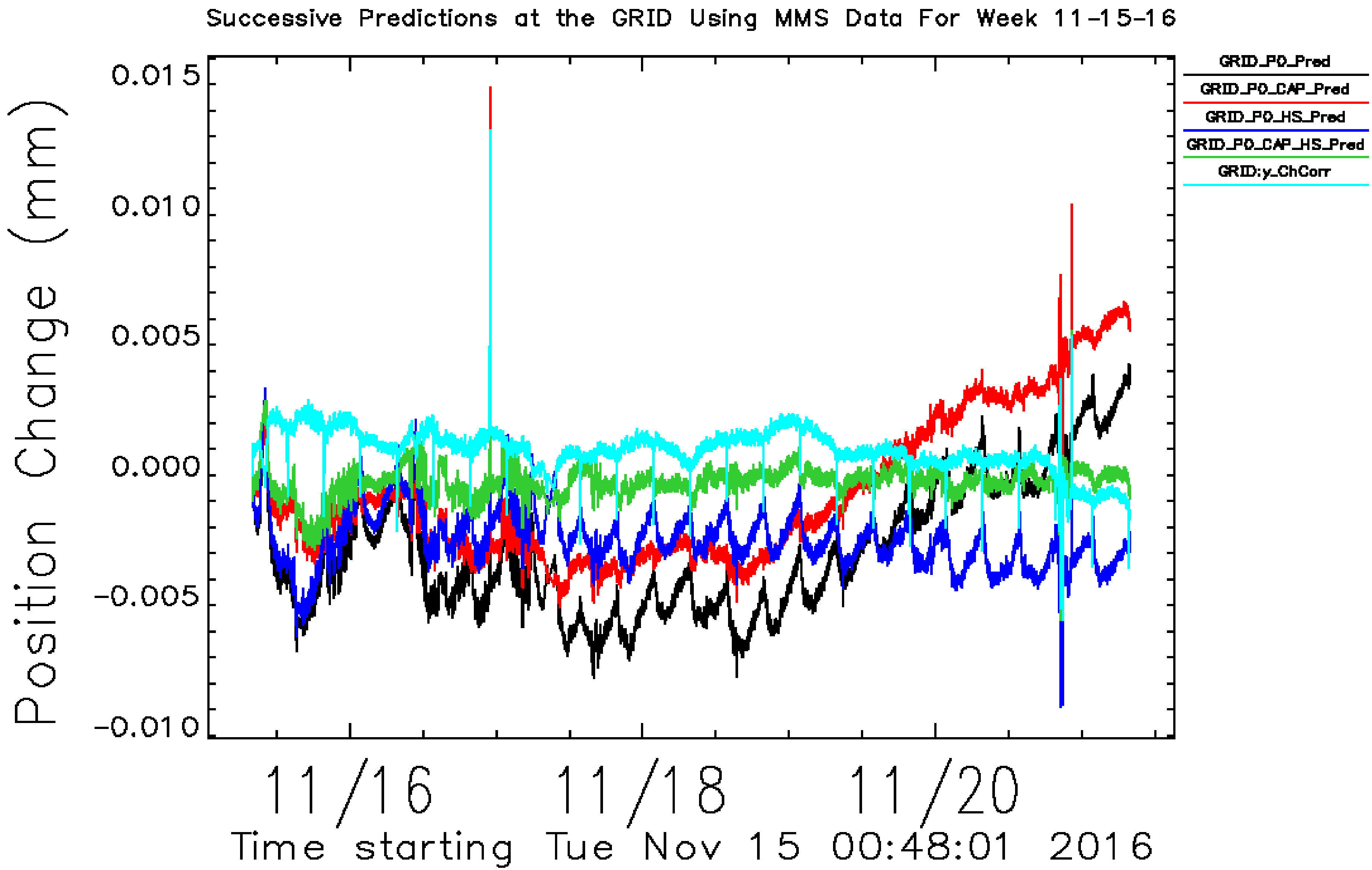
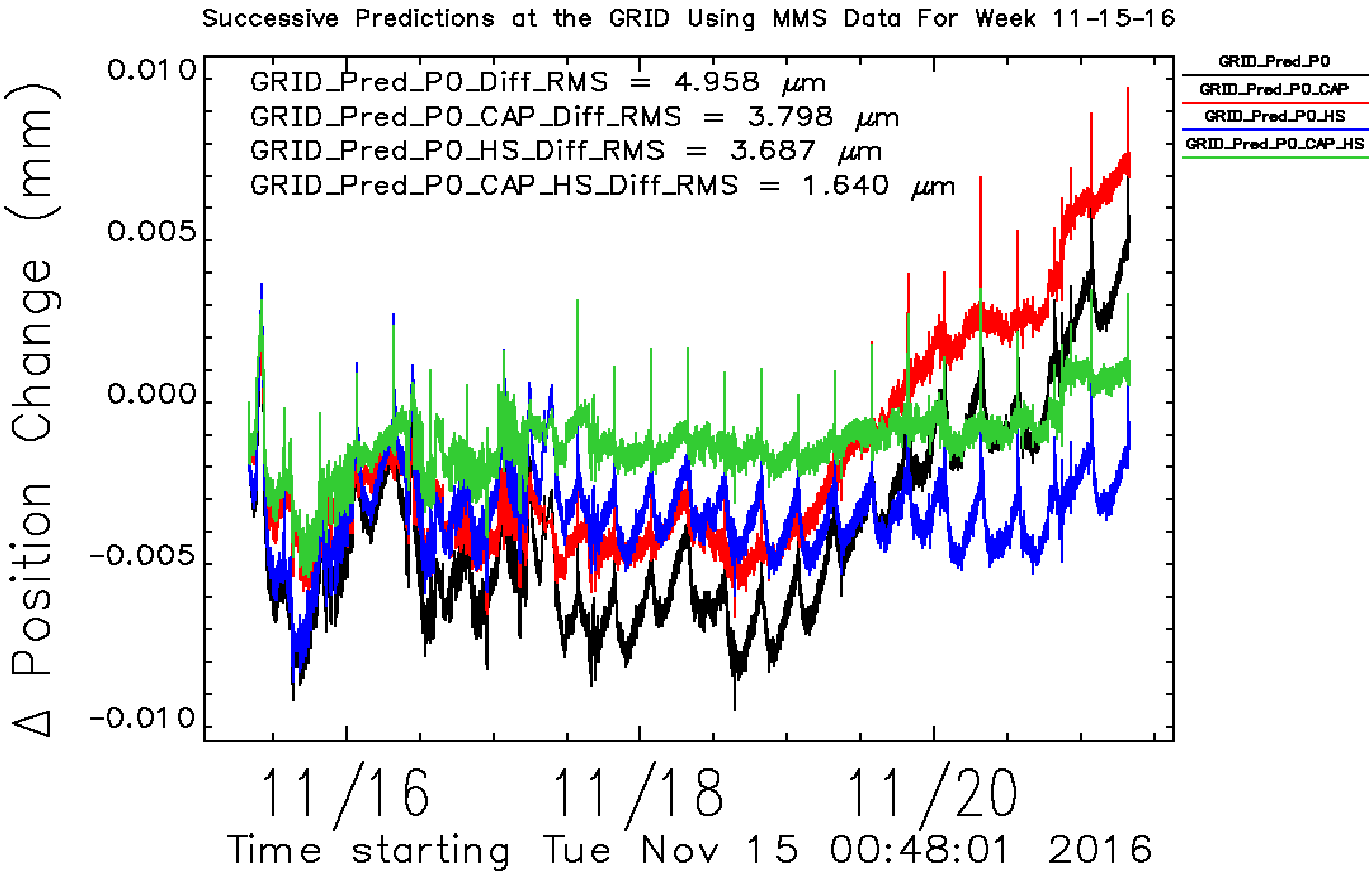


# Experiment Using Standard Orbit Correction: Using P0s to Predict Position at the GRID for 324 Singlets Processed Data DIFFERENCES:



# Experiment Using Standard Orbit Correction: Using P0s to Predict Position at the GRID Conclusion:

- Essentially the same conclusion as with the square matrix on slide 10
- MMS corrections are required to bring the prediction closer to the GRID measurement (corrected for GRID local mechanical motion)
- Note, however, the earthquake adds noise:
  - Few Hz earthquake signal is aliased due to the slow 30 seconds sample interval of the data logger
  - The few micron earthquake motion at a few Hz does not transfer to the mechanical structures holding the P0s and GRID (at least that is observable anyway)
- 324 Singlets:
  - Substantial “saw tooth” mechanical motion as detected on capacitive sensors
  - Substantial hydrostatic motion up to 8 microns
  - Mechanical correction of predicted position change corrects for large drift and “saw tooth” pattern

# Experiment Using Standard Orbit Correction: S27B:P0 and GRID Prediction at S28A:P0

- Used Hybrid, 102 mA top-up
- Predict change in electron beam position at S28A:P0 assuming straight line optics this time with standard orbit correction running (no square matrix)
- Take into account HS and Capacitive sensor data at all three bpms
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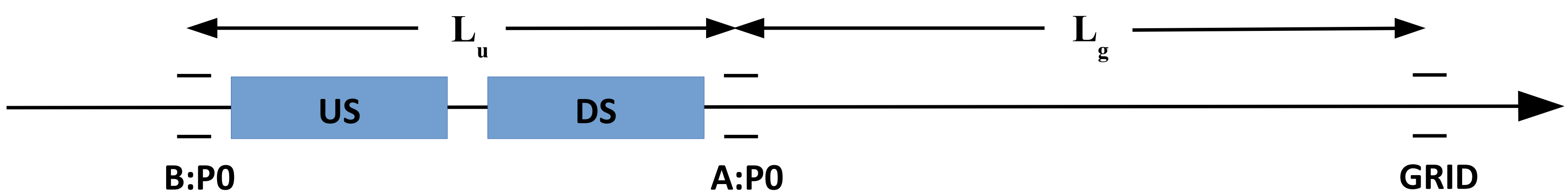
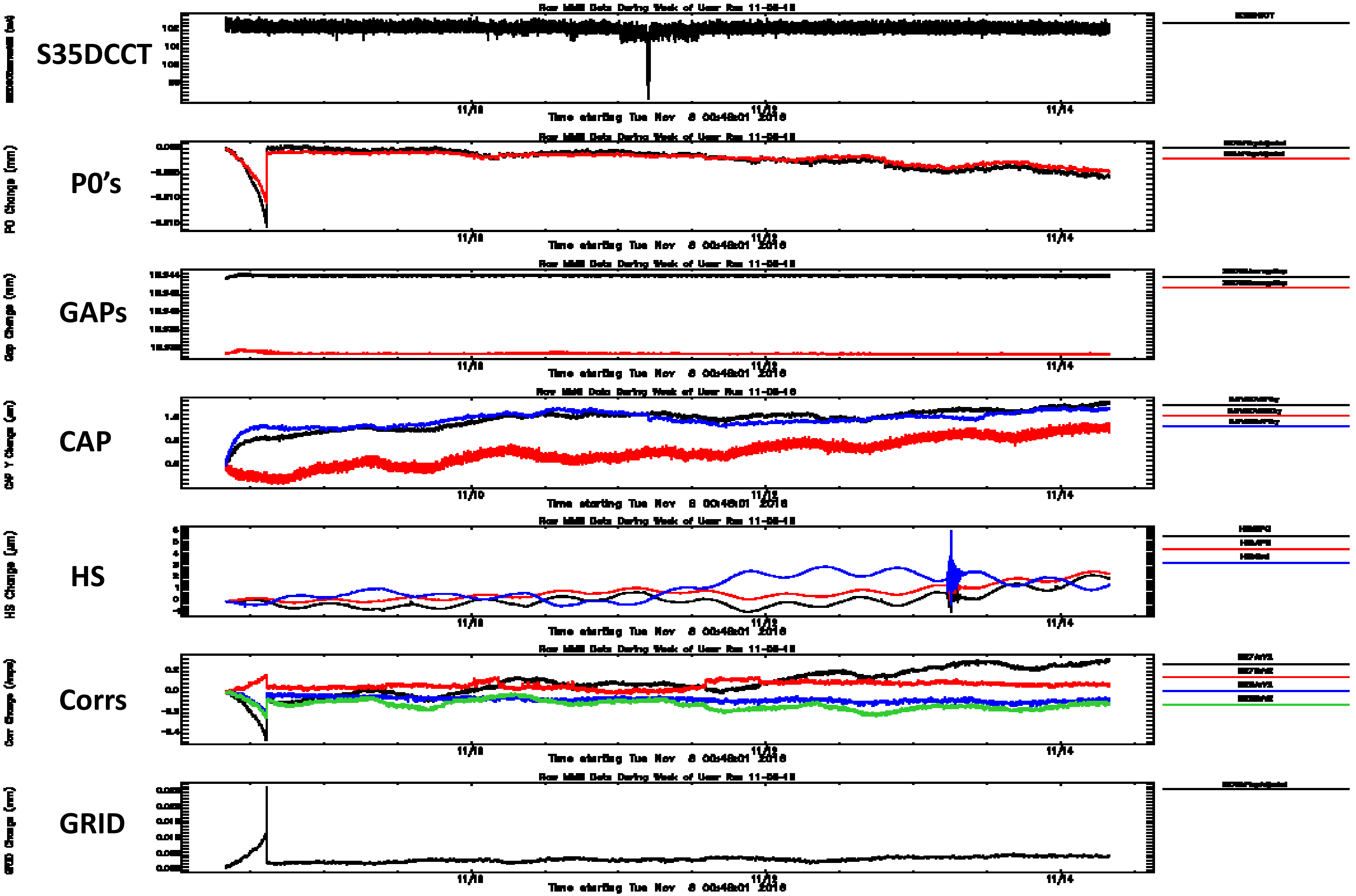
- Sector 27 geometry:



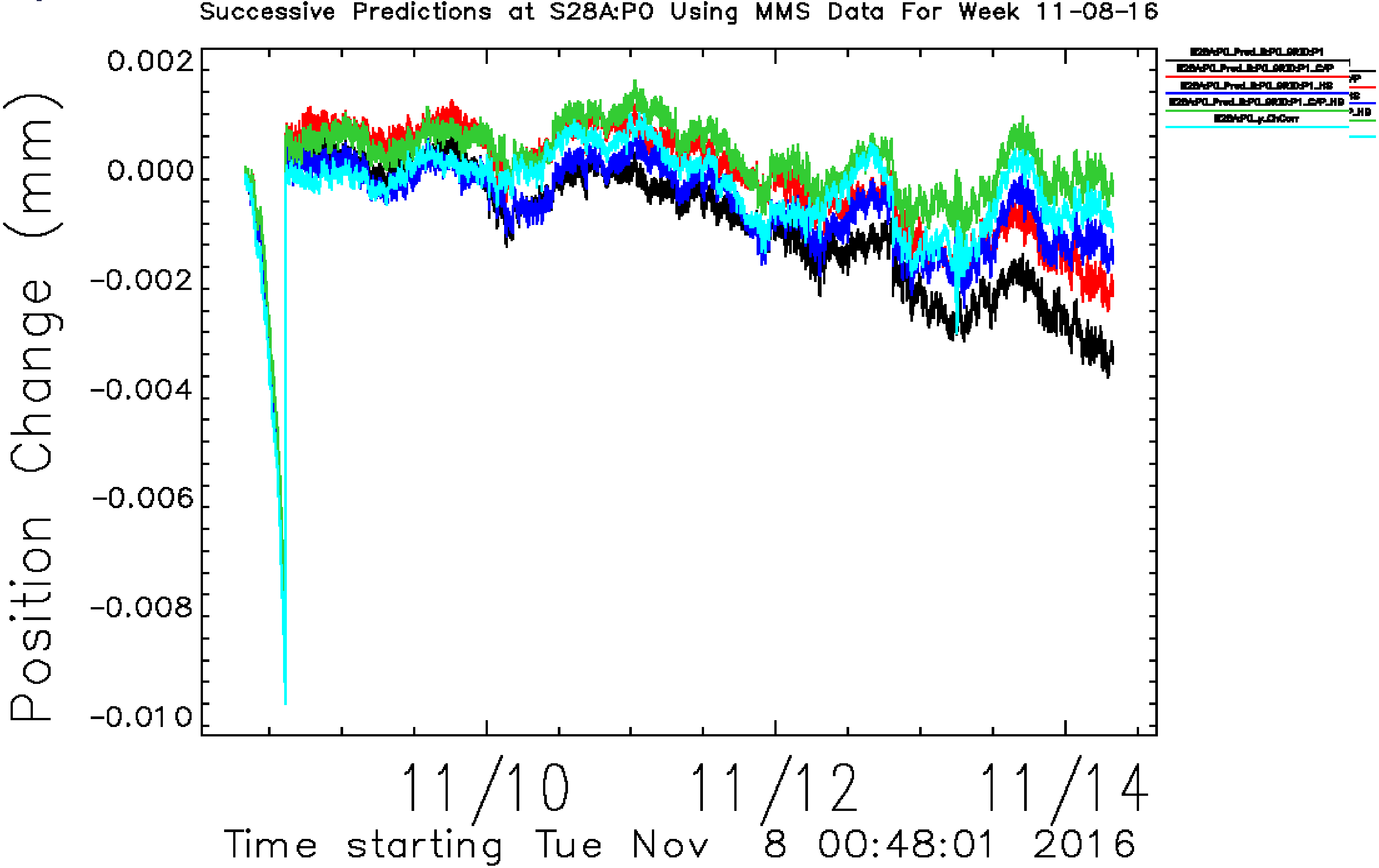

- Compare the position measurement change at the GRID to the prediction given by equations (1) – (3).

$$(4)\,\Delta y_{A:P0-Measured} \rightarrow \Delta y_{A:P0-Measured} + \Delta y_{A:P0_{CAP}} + \Delta y_{A:P0_{HS}}$$

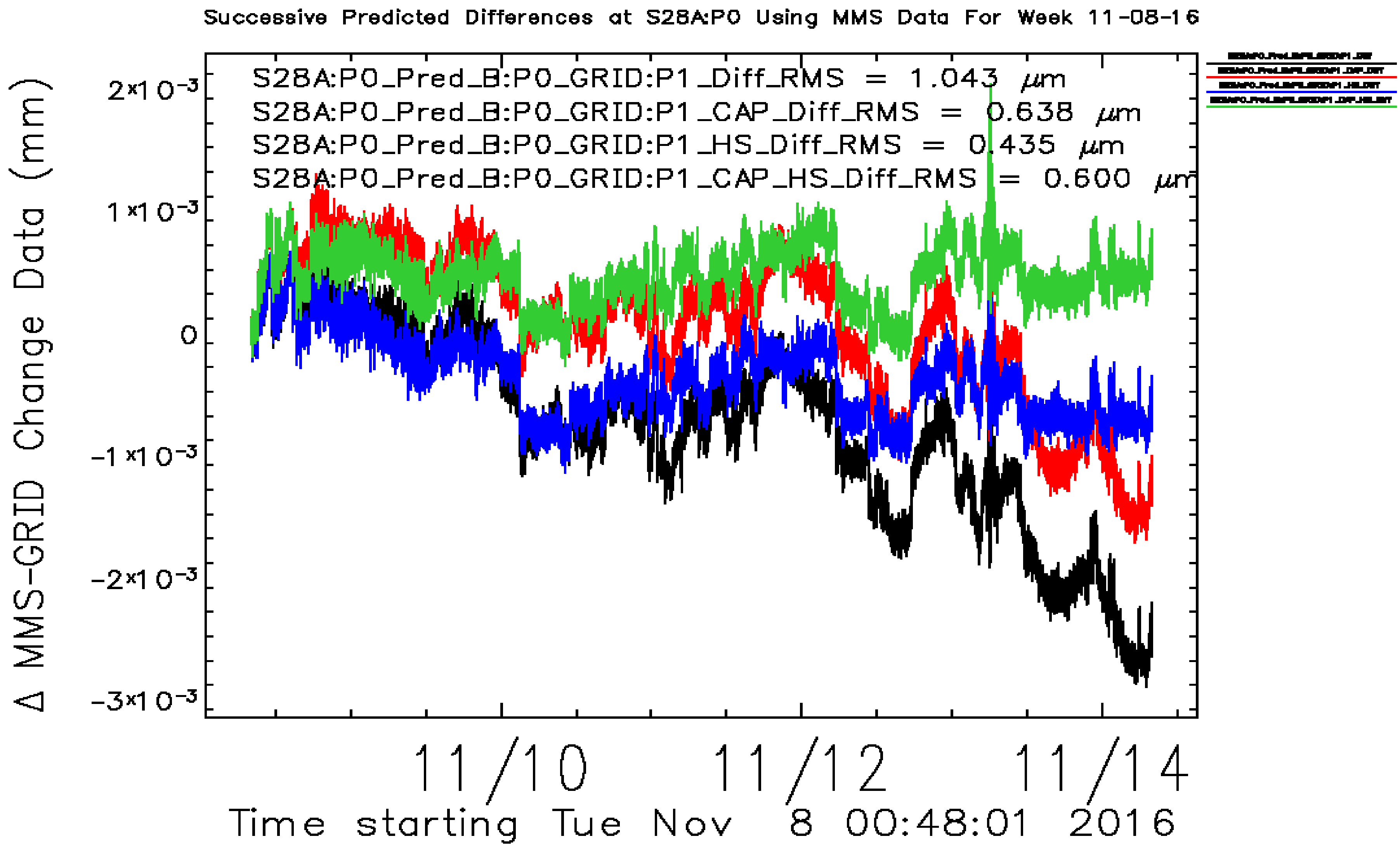
# Experiment using S27B:P0 and GRID Prediction at S28A:P0: Raw Data



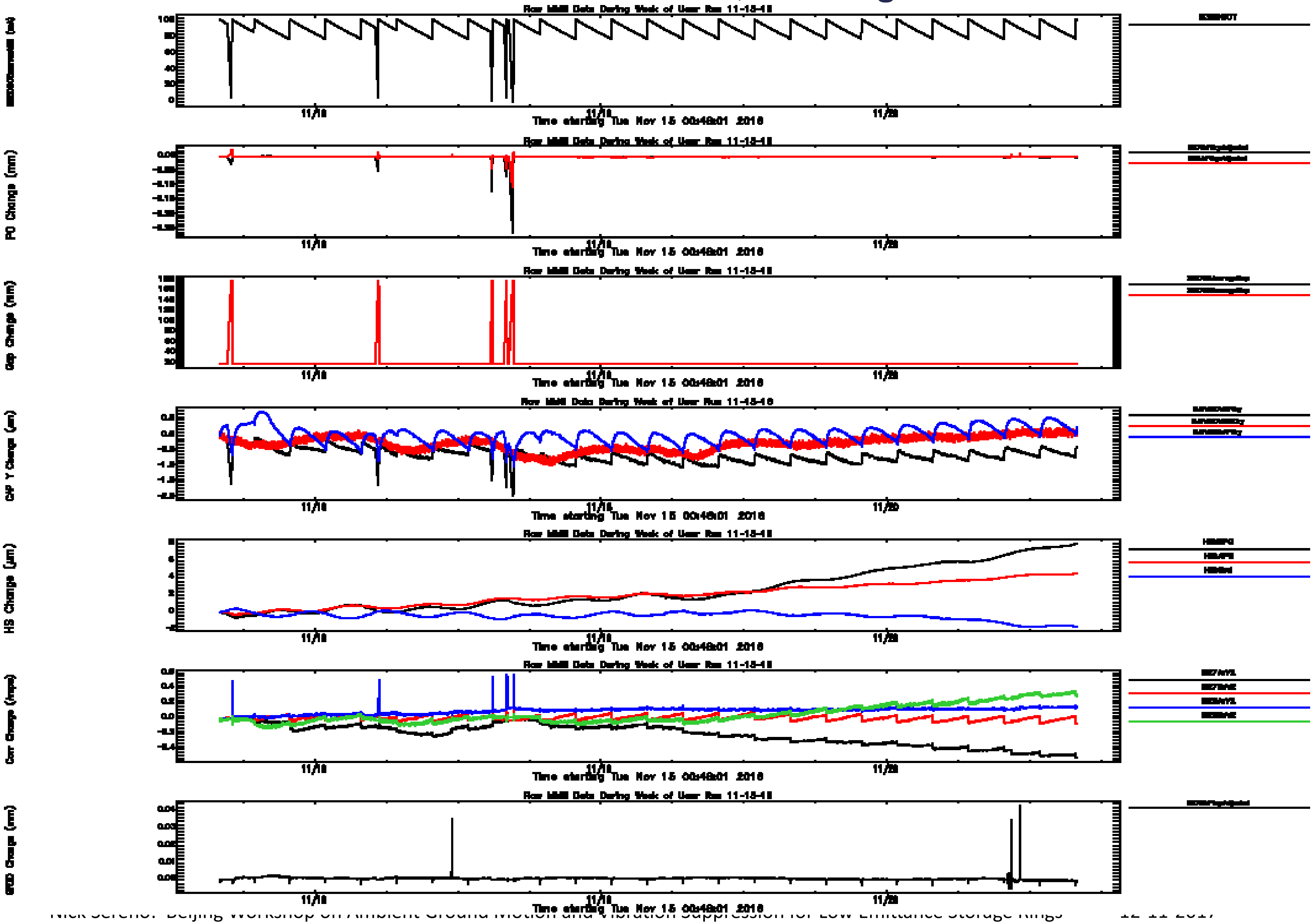
## Experiment using S27BP0 and the GRID for Prediction: Processed Data – S27B:P0 and GRID (successive corrections for HS and CAP motion) prediction at S28A:P0 corrected for CAP and HS motion



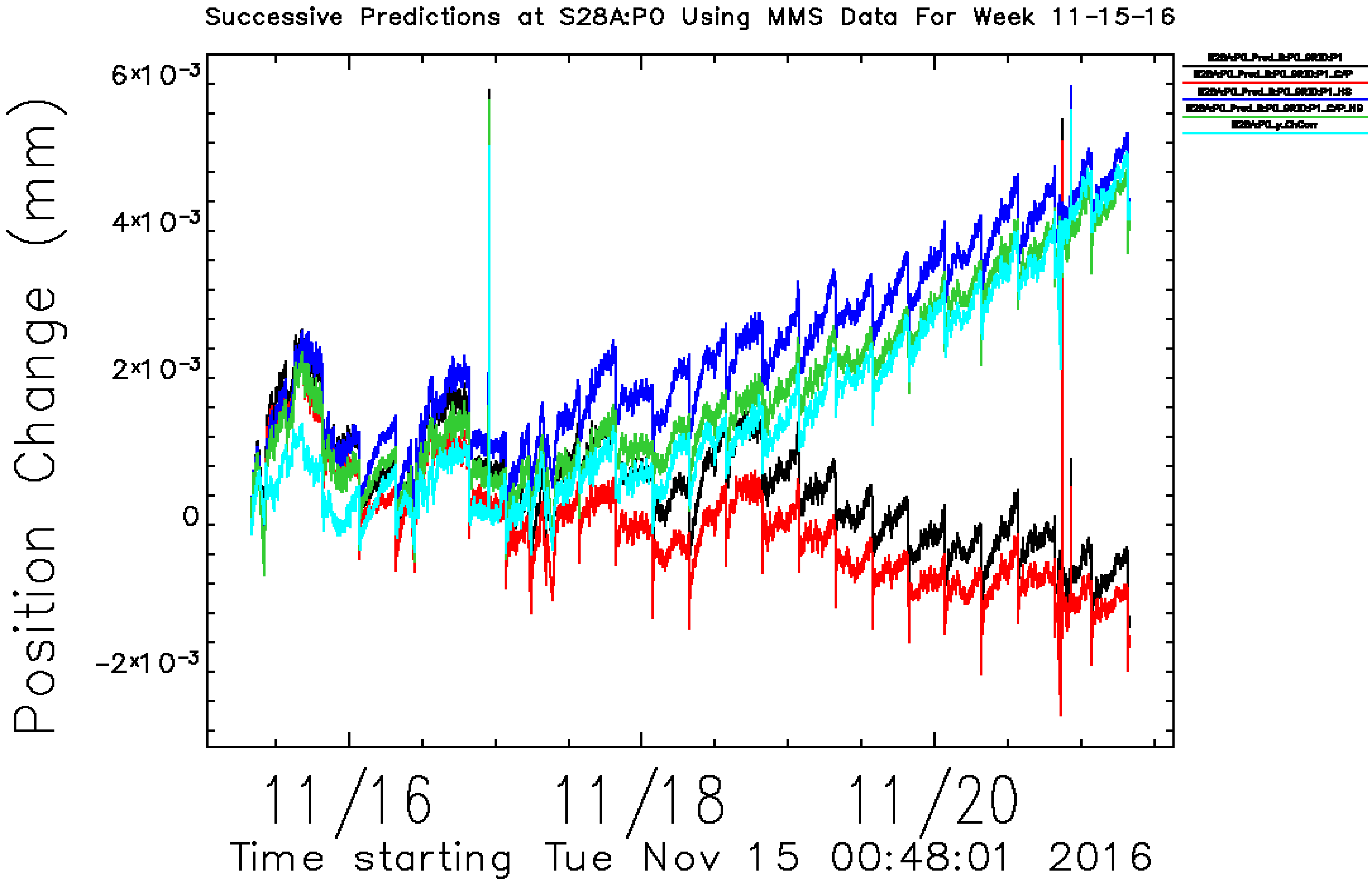
# Experiment using S27BP0 and the GRID for Prediction: Processed Data – S27B:P0 and GRID (successive corrections for HS and CAP motion) prediction at S28A:P0 corrected for CAP and HS motion DIFFERENCES



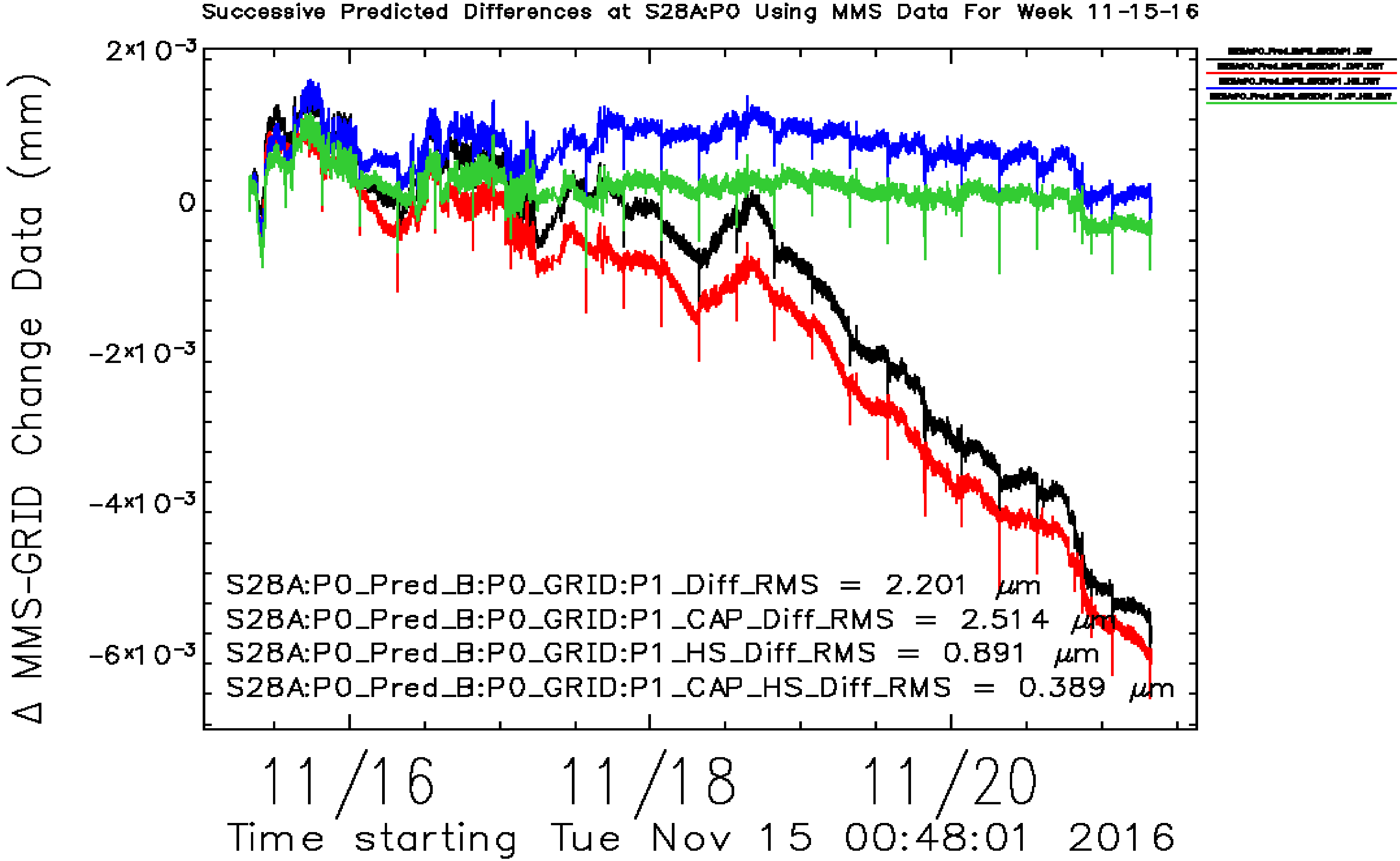
# Experiment Using Standard Orbit Correction:  Using the Position at S27B:P0 and the GRID to Predict Position at S28A:P0, 324 Singlets:  Raw Data



# Experiment Using Standard Orbit Correction: Using the Position at S27B:P0 and the GRID to Predict Position at S28A:P0, 324 Singlets: Processed Data



# Experiment Using Standard Orbit Correction: Using the Position at S27B:P0 and the GRID to Predict Position at S28A:P0, 324 Singlets: Processed Data DIFFERENCES

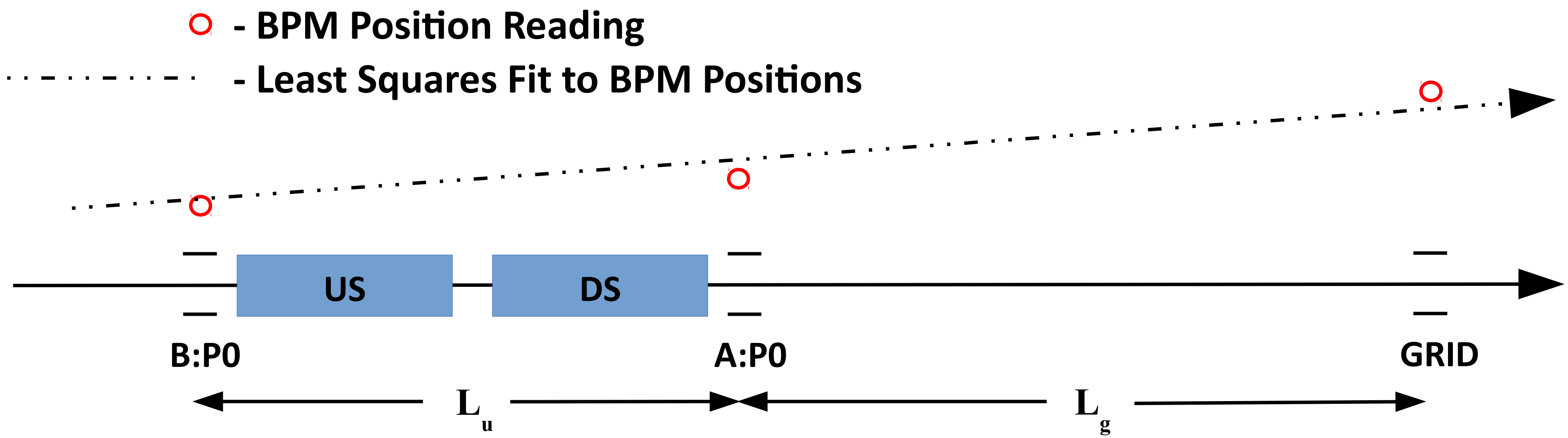


# Experiment Using Standard Orbit Correction: S27B:P0 and GRID Prediction at S28A:P0: Conclusion

- Essentially the same as for the first experiment locking the beam at S27B:P0 and the GRID
- MMS corrections are required to bring the prediction closer to the GRID measurement (corrected for GRID local mechanical motion)
- Interesting both predictions at S28A:P0 (using both square and non-square orbit feedback matrices slide 14) have a small net offset in the final difference
- 324 Singlets:
  - Substantial “saw tooth” mechanical motion as detected on capacitive sensors
  - Substantial hydrostatic motion up to 8 microns
  - Mechnanical motion compensation of predicted position at S28A:P0 is absolutely required to match measured motion change at S28A:P0

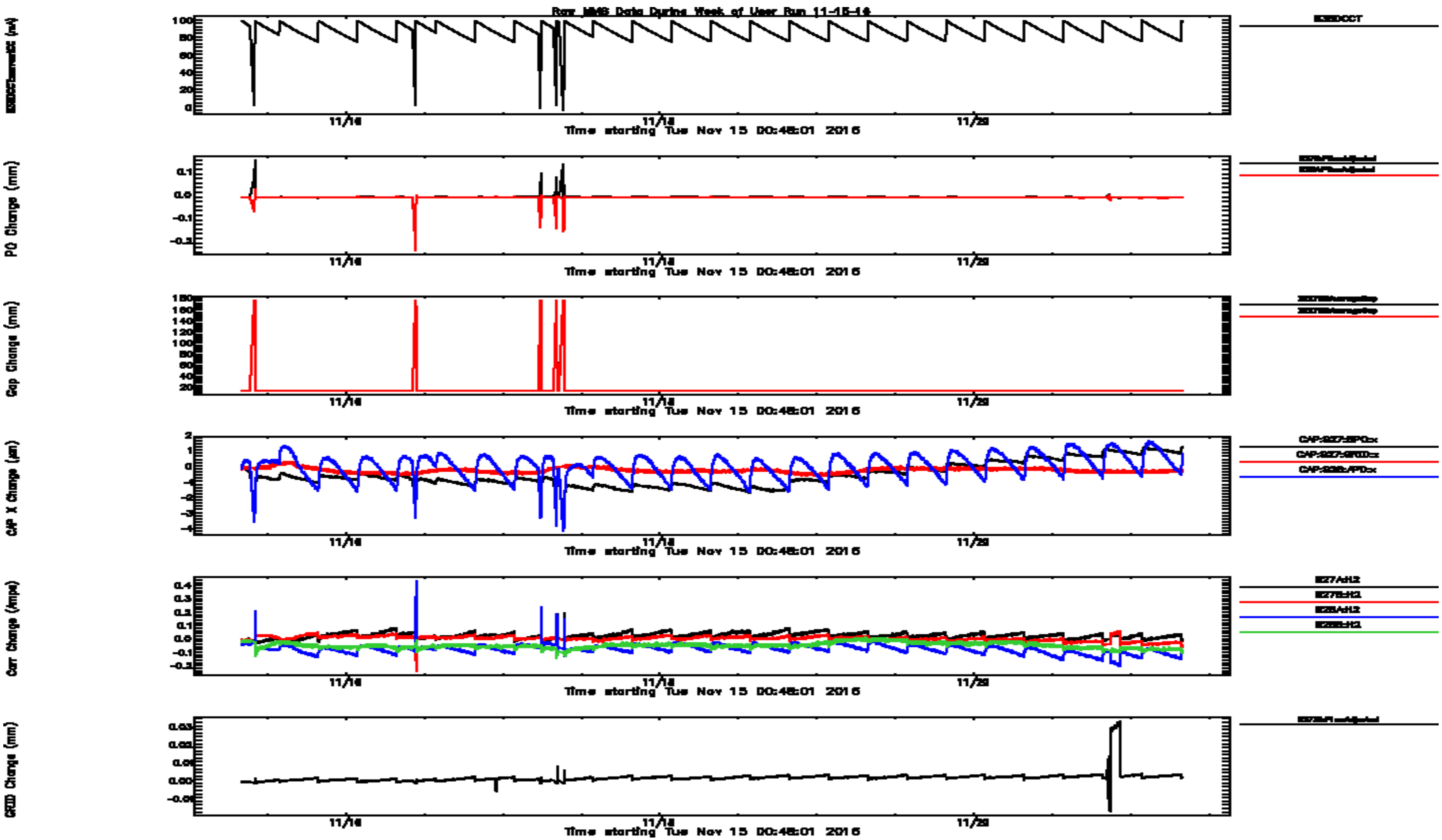
# Least Squares Fit to P0, GRID Position Change Data

- A least squares fit to these three bpms should reveal a smaller rms residual as CAP and HS motion is taken into account locally at each bpm
- Residual left over should be simply the rms orbit left over after rms orbit is minimized by orbit feedback (for an overdetermined system of more bpms than correctors)
- Procedure is similar to the prediction analysis:  successively correct for hydrostatic and capacitive motion and look at slope, interccept and standard deviation of the three residuals

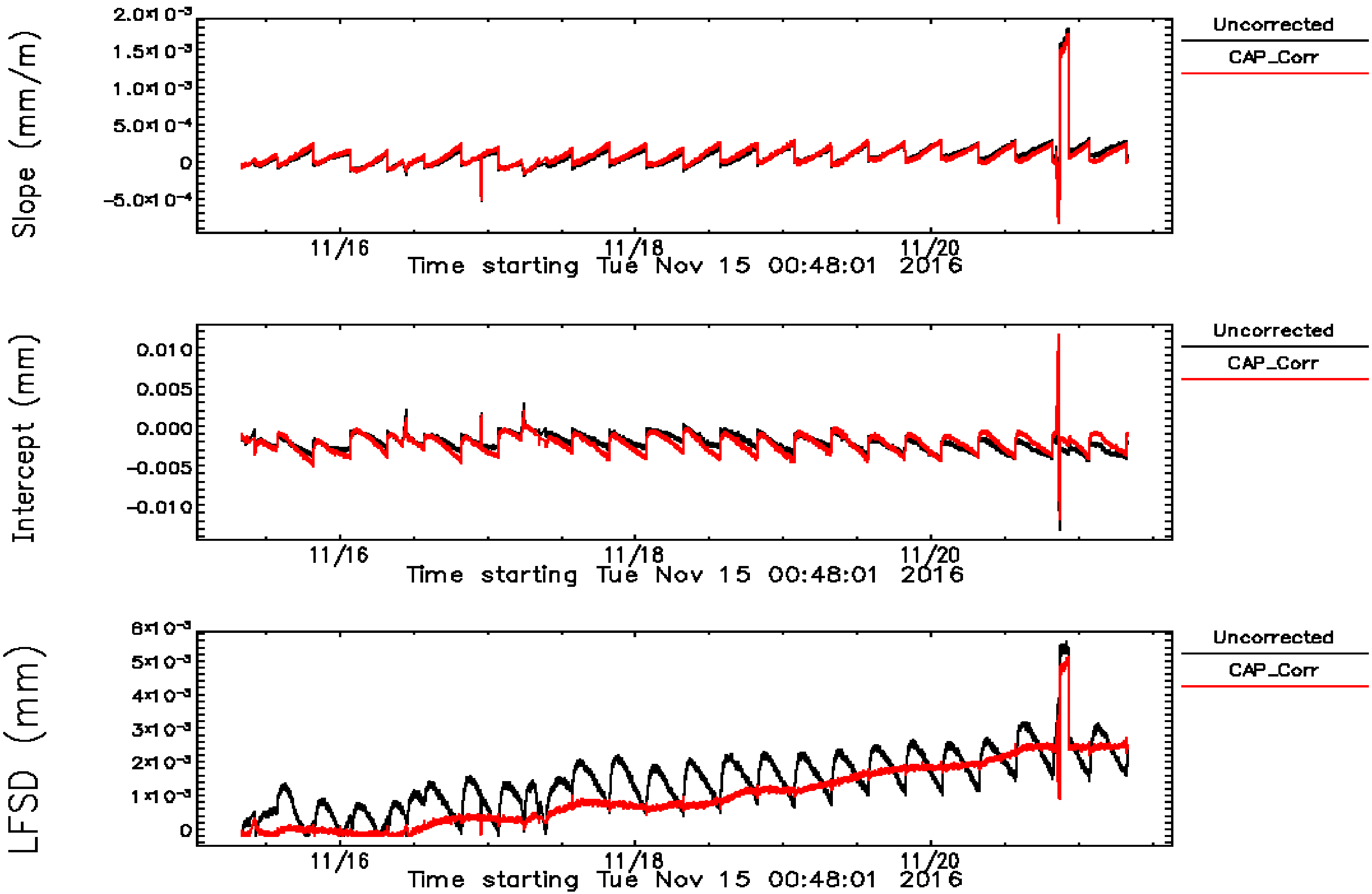


# Least Squares Fit to P0, GRID Position Change Data Horizontal Plane, 324 Singlets: Raw Data

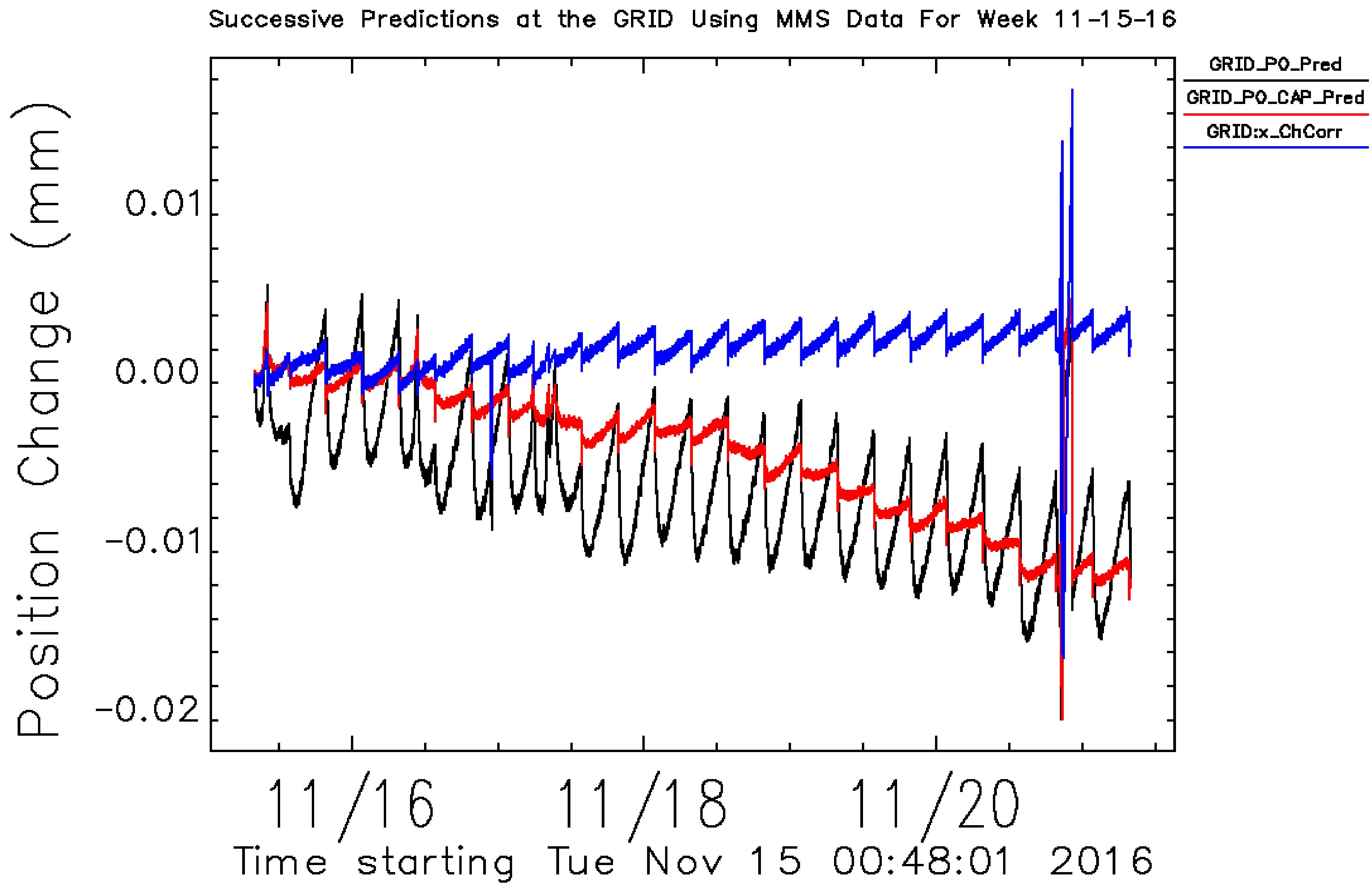
- A In this case, we investigate the lsq fit as we locally correct for only Capacitive motion at each BPM



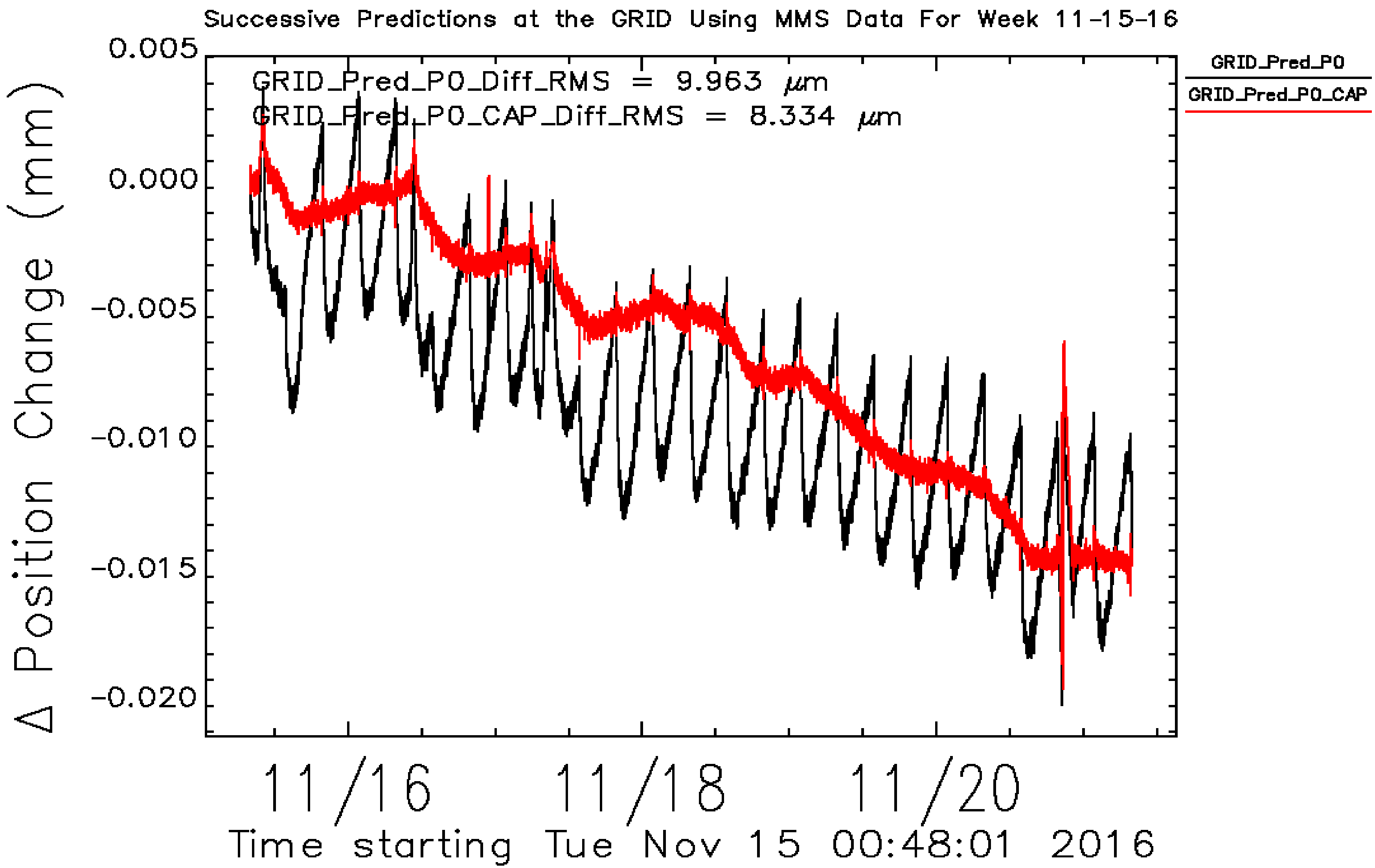
# Least Squares Fit to P0, GRID Position Change Data Horizontal Plane, 324 Singlets: Processed Data



# Prediction of GRID Position using P0s, GRID Corrected for Local CAP motion, Horizontal Plane, 324 Singlets: Processed Data



# Prediction of GRID Position using P0s, GRID Corrected for Local CAP motion, Horizontal Plane, 324 Singlets: Processed Data DIFFERENCES



# Least Squares Fit to P0, GRID Position Change Data Horizontal Prediction at GRID Using P0s

- The least squares fit analysis for vertical data shows smaller standard deviation of the residuals as CAP and HS data is added
- Interestingly, in the horizontal plane where only capacitive data is available, the lsq fit analysis shows the measured capacitive mechanical motion due to variation of 324 bunch beam current (presumably due to heating) is removed
- There is still a drift left in horizontal plane in the lsq fit analysis
- The prediction analysis also shows the same result: capacitive correction takes out mechanical motion due to variation in beam current
- There is a drift compared to predicted GRID position and measurement at the GRID
- This could be due to large number of horizontal bpms in datapool (rms corrected in sector 27 using 4 correctors and 13 bpms compared to ~7 bpms in the vertical plane)
- Main conclusion from these data and analysis: *Correction of bpm position changes due to mechanical motion can be made locally at each bpm, by adding in the changes in mechanical motion due to capacitive and hydrostatic measurement*