IMPROVING FERMI ORBIT DETERMINATION AND PREDICTION IN AN UNCERTAIN ATMOSPHERIC DRAG ENVIRONMENT

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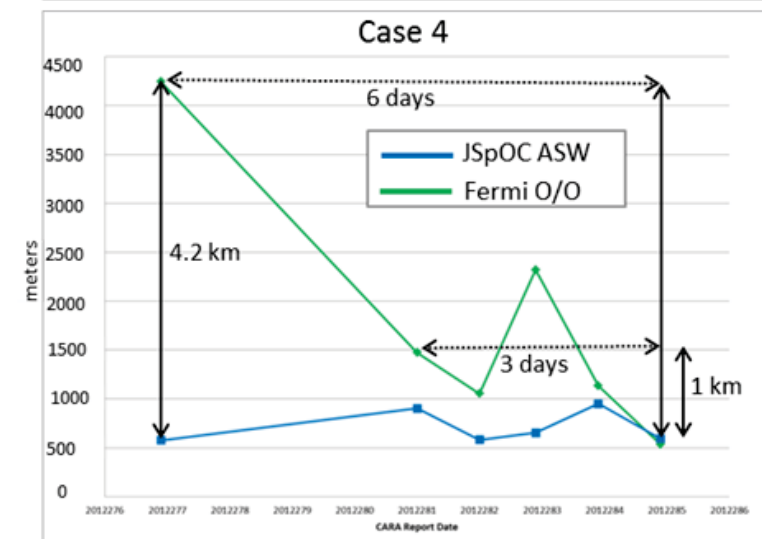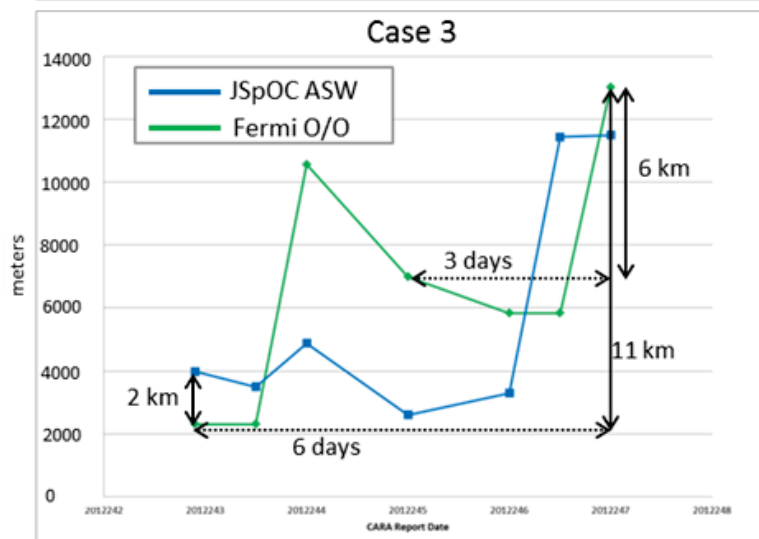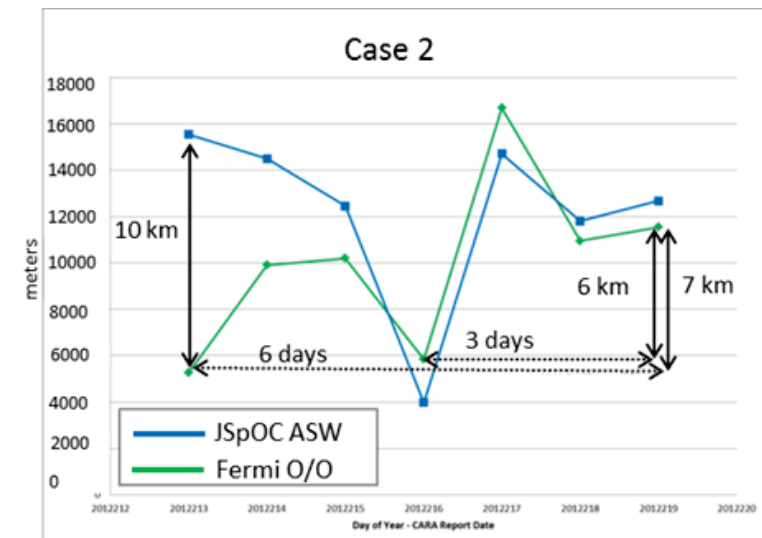a.i. solutions

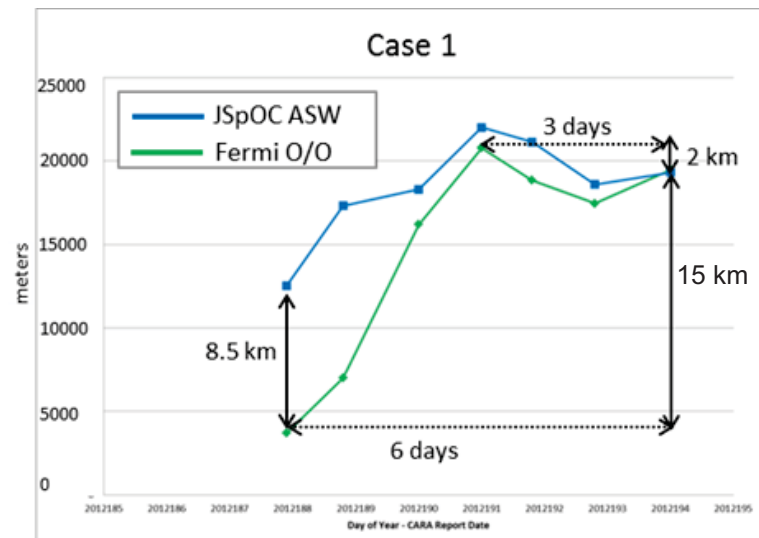**J. Russell Carpenter**
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# Fermi OD Background

Problem:

- Fermi Owner/Operator (O/O) & JSpOC miss distances often disagree; to maneuver or not to maneuver?
- Owner/Operator ODTK mods haven't resulted in consistent/repeatable improvement

Predictive Accuracy of Similar Low-LEO

- Hubble Space Telescope (HST) perigee altitude: ~550 km, Fermi perigee altitude: ~532 km
- In general: density models worse at higher altitudes, but drag uncertainty larger factor at lower altitudes
- HST exhibits relatively large position errors after 3 days of propagation
- Predictive ephems from August 2012 onward are from JSPoC ASW
  - 3-day predictive accuracy varies: 0.5 km to 5 km → similar or worse than Fermi predicts
  - 3-day mean predictive accuracy from 8/22/12 – 1/31/13 is 2.4 km

HST 3-Day Predictive Accuracy & F10.7 Value

Large errors at solar max: several days over 20 km error
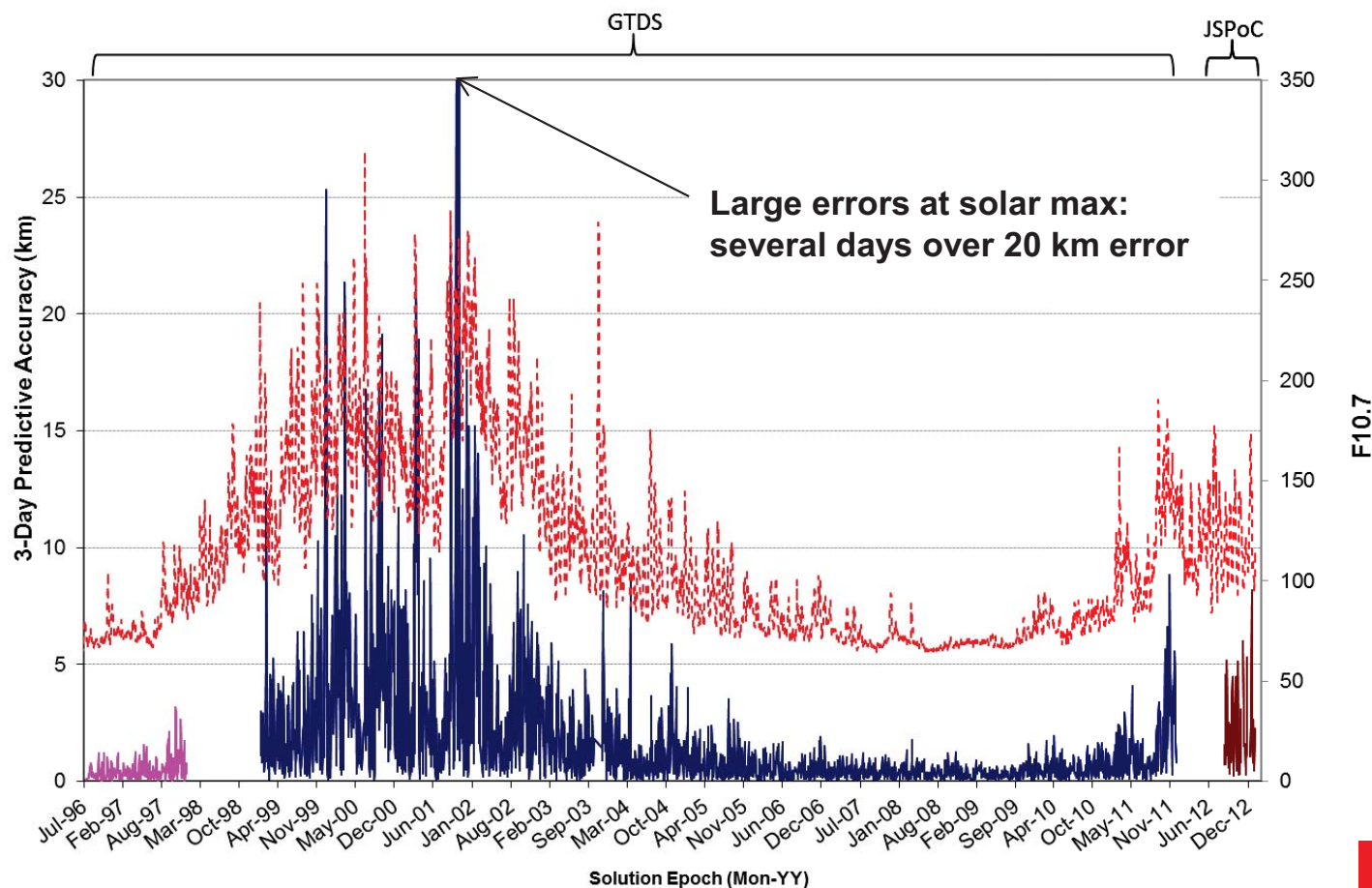
# Filter Tuning – Ground-based OD/Prediction

Optimization problem - maximize predictive accuracy (min. predictive-definitive overlap):

1. Investigated thinning measurement data
    - Thinning can allow density correction & ballistic coefficient to decay in absence of data
    - Varied between 1 sec & 20 minute thinning (1 min used operationally)

2. Varied point solution white noise sigma (2 – 15 m)

3. Adjusted initial C_D value (1.6 – 2.5)

4. Inspected different stochastic models for ballistic coefficient (BC):
    - O/O scenario uses Gauss-Markov
    - Vasicek allows for long and short term sigmas
    - Random walk allows for holding estimated value through prediction

5. Varied initial ballistic coefficient uncertainty
    - Tighten to reduce aliasing of atmospheric variations
    - Loosen w/ goal of more flexible estimating

6. Tested different density correction & BC estimate half life (HL) values

7. Adjusted density correction sigma scale (experimental ODTK EKF setting)
    - Nominal setting is 1; Varied between 0.5 & 4

8. Tested different atmospheric density models (e.g.:Jacchia-Roberts, CIRA 1972)

9. Investigated interpolated or non-interpolated a_p, K_p geomagnetic indices for atm. density

10. Tested different integrators & min. step sizes

Filter Tuning

- Tuning indicated problem is mainly one of prediction
- Tuning focus was drag models & params: ballistic coefficient & atmospheric density correction estimation
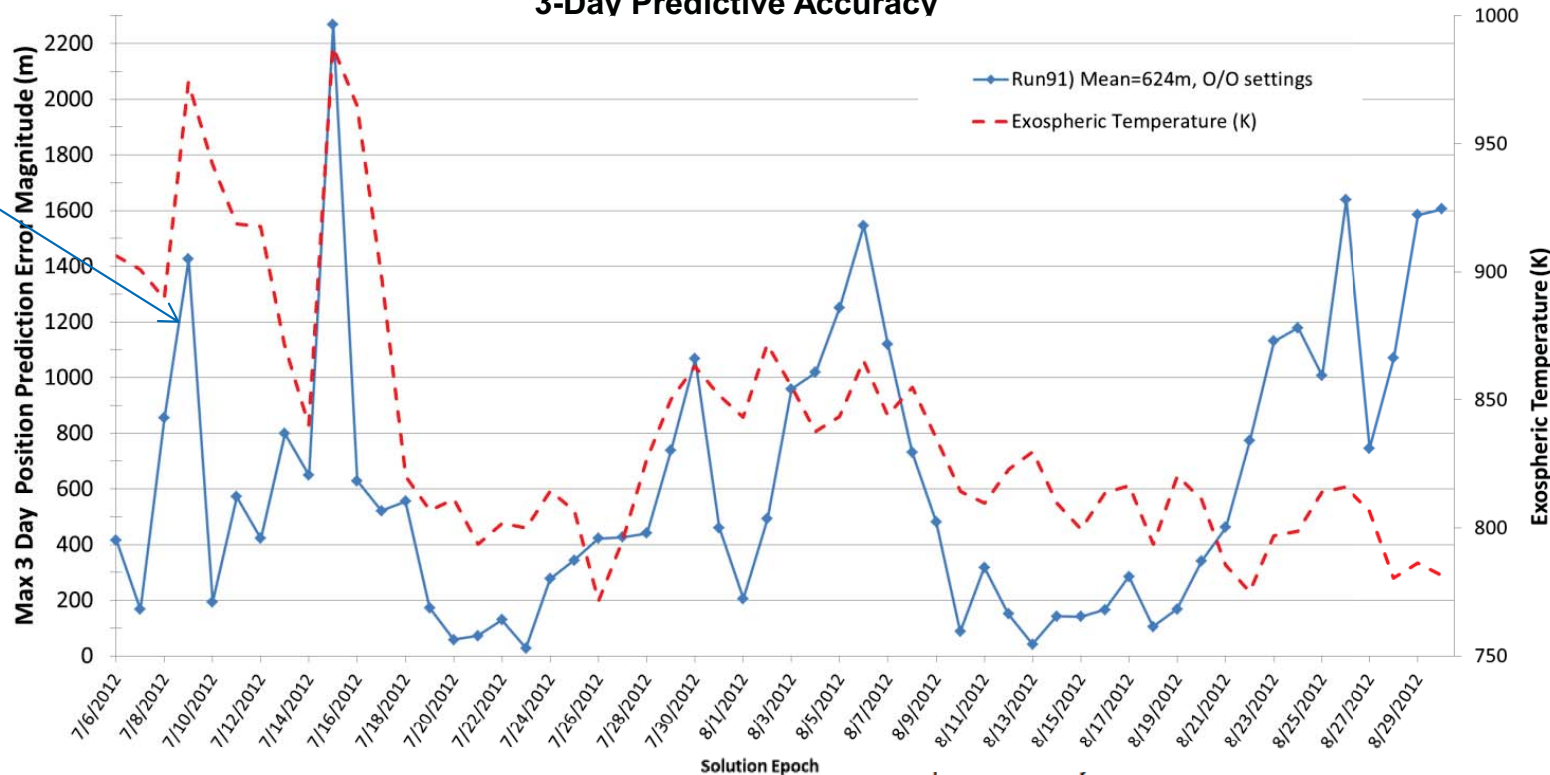

3-Day Predictive Accuracy of FDF ODTK Tuning Runs
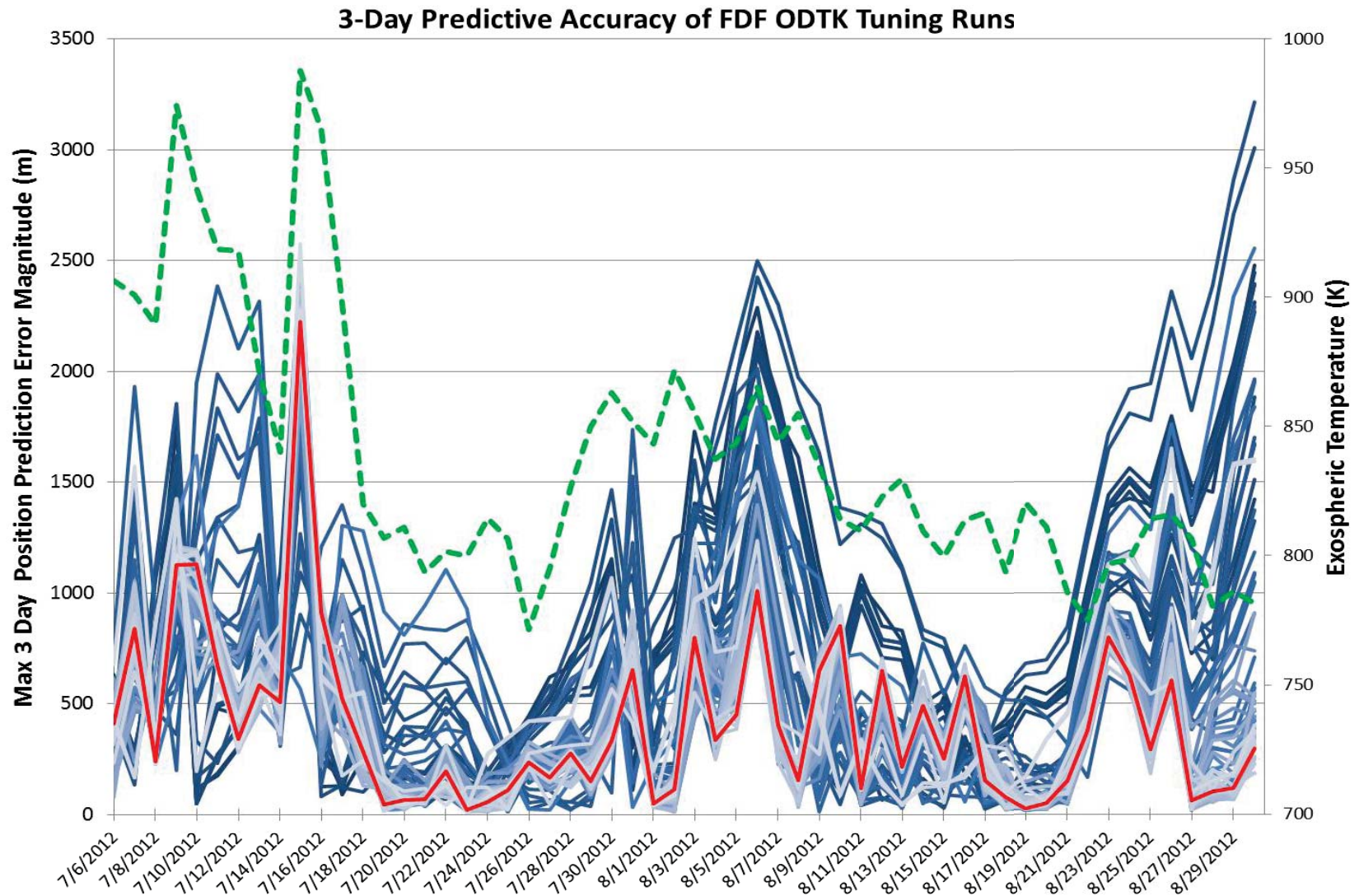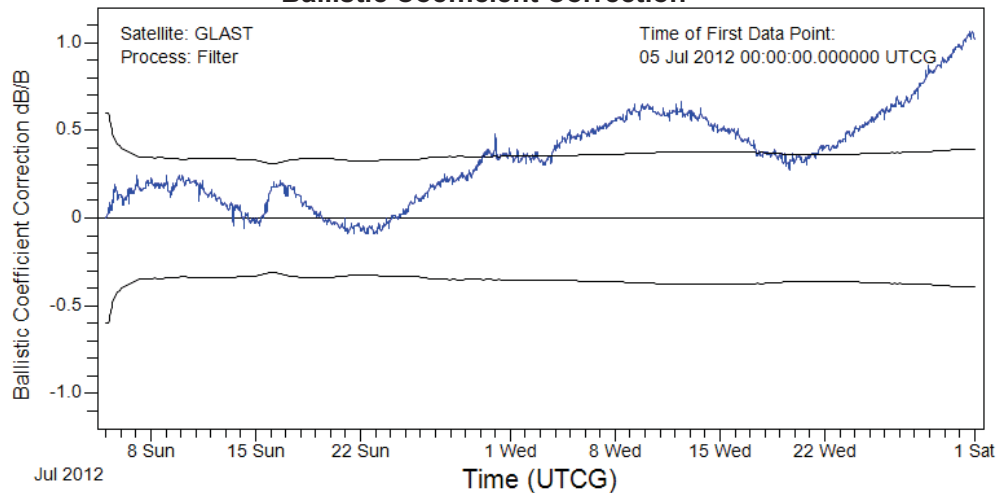
Filter Tuning – O/O ODTK Settings

Run 91: O/O settings

- 1min data frequency
- Gauss-Markov BC:
  - BC HL= 7 days
  - BC sigma = 0.3
- C_{D0} = 1.6
- Atm density HL = 180 min
- Density sigma scale = 1
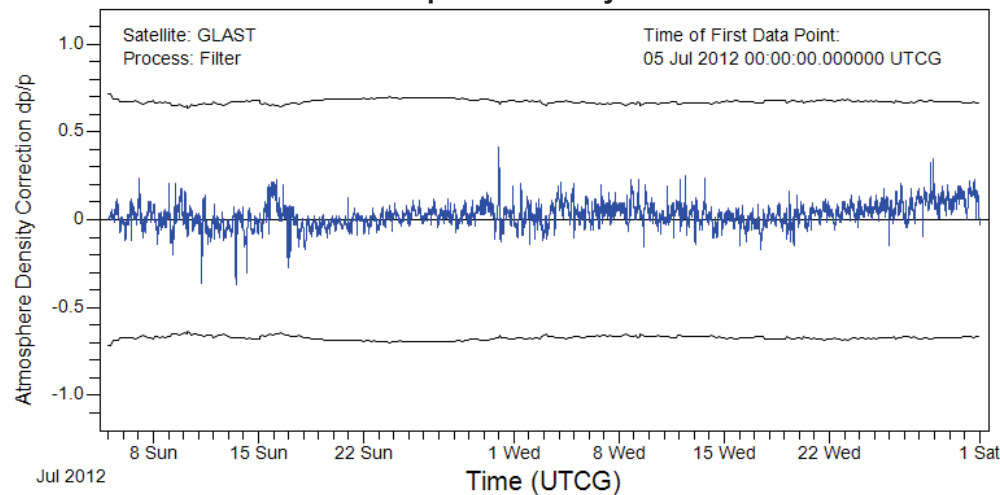- Mean 3 day error: **624 m**

3-Day Predictive Accuracy

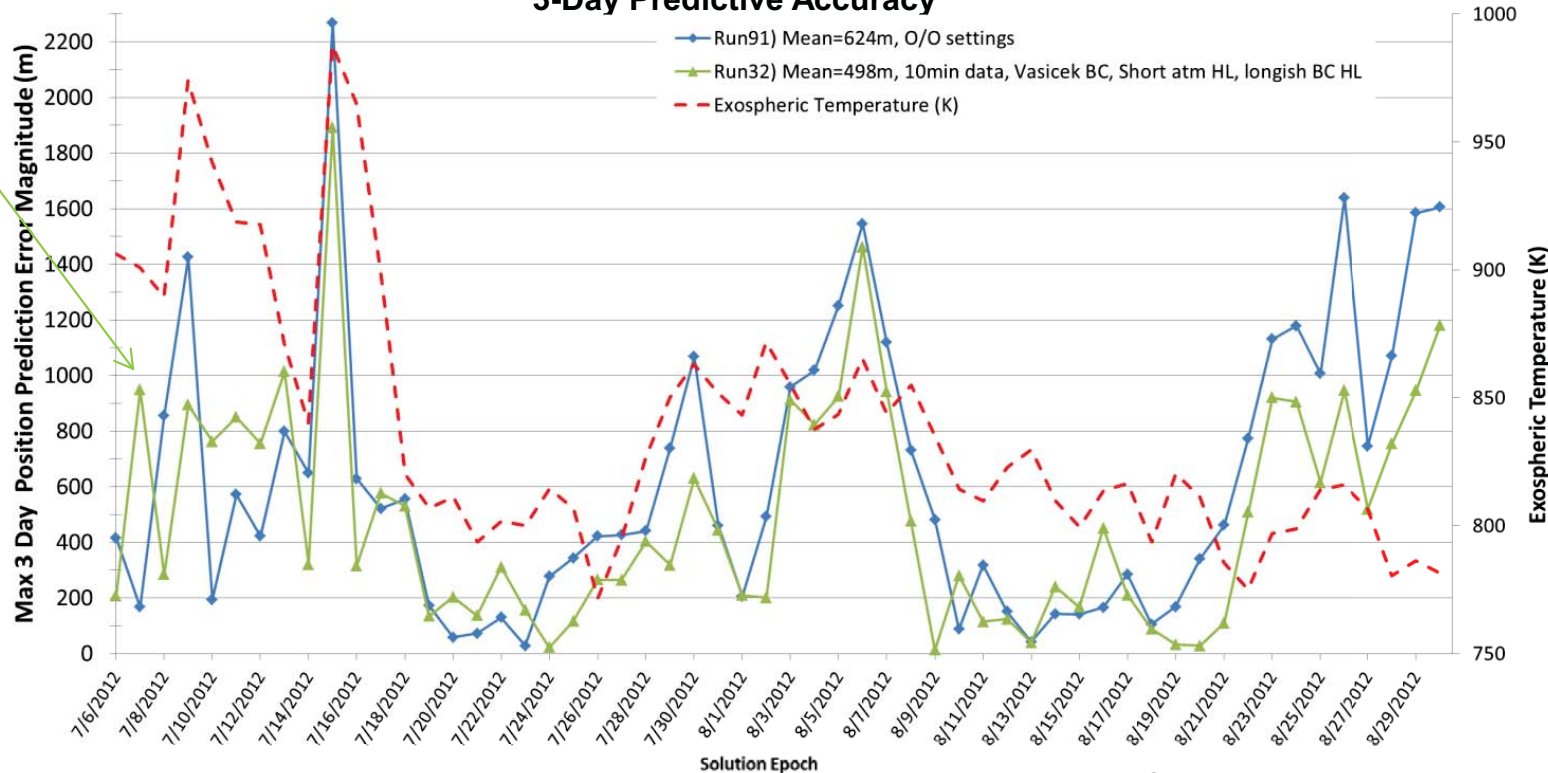Ballistic Coefficient Correction

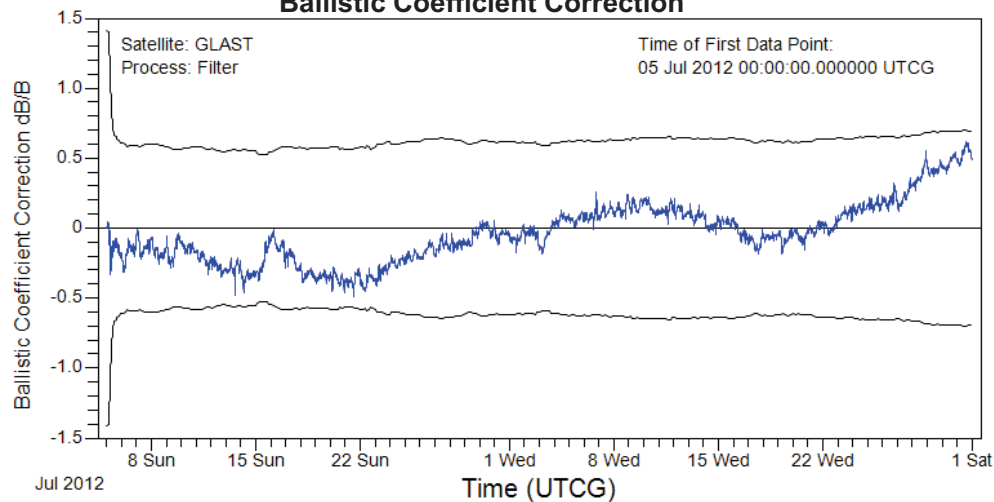Atmospheric Density Correction

Filter Tuning – Thinning Data

Run 32: Thinning data

- 10 min data frequency
- Vasicek BC:
  - BC short term HL= 2 days
  - BC short term σ = 0.5
  - BC long term σ = 0.5
- C_{D0} = 2.4
- Atm density HL = 360 min
- Density sigma scale = 1
- Mean 3 day error: **498 m**

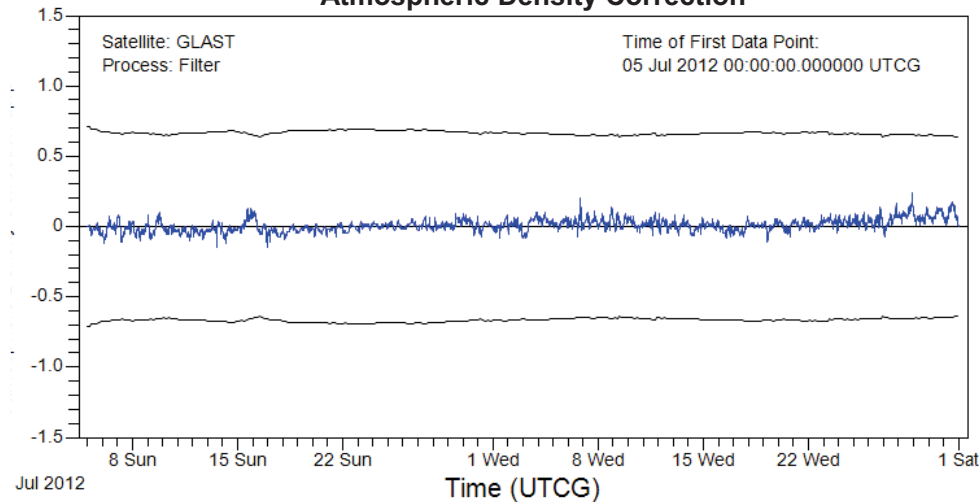3-Day Predictive Accuracy

Legend:
- Run91) Mean=624m, O/O settings
- Run32) Mean=498m, 10min data, Vasicek BC, Short atm HL, longish BC HL
- Exospheric Temperature (K)

Y-axis: Max 3 Day Position Prediction Error Magnitude (m) / Exospheric Temperature (K)
X-axis: Solution Epoch

Ballistic Coefficient Correction

Satellite: GLAST
Process: Filter
Time of First Data Point: 05 Jul 2012 00:00:00.000000 UTCG

GLAST Ballistic Coefficient Correction dB/B   dB/B +2 Sigma

Atmospheric Density Correction

Satellite: GLAST
Process: Filter
Time of First Data Point: 05 Jul 2012 00:00:00.000000 UTCG

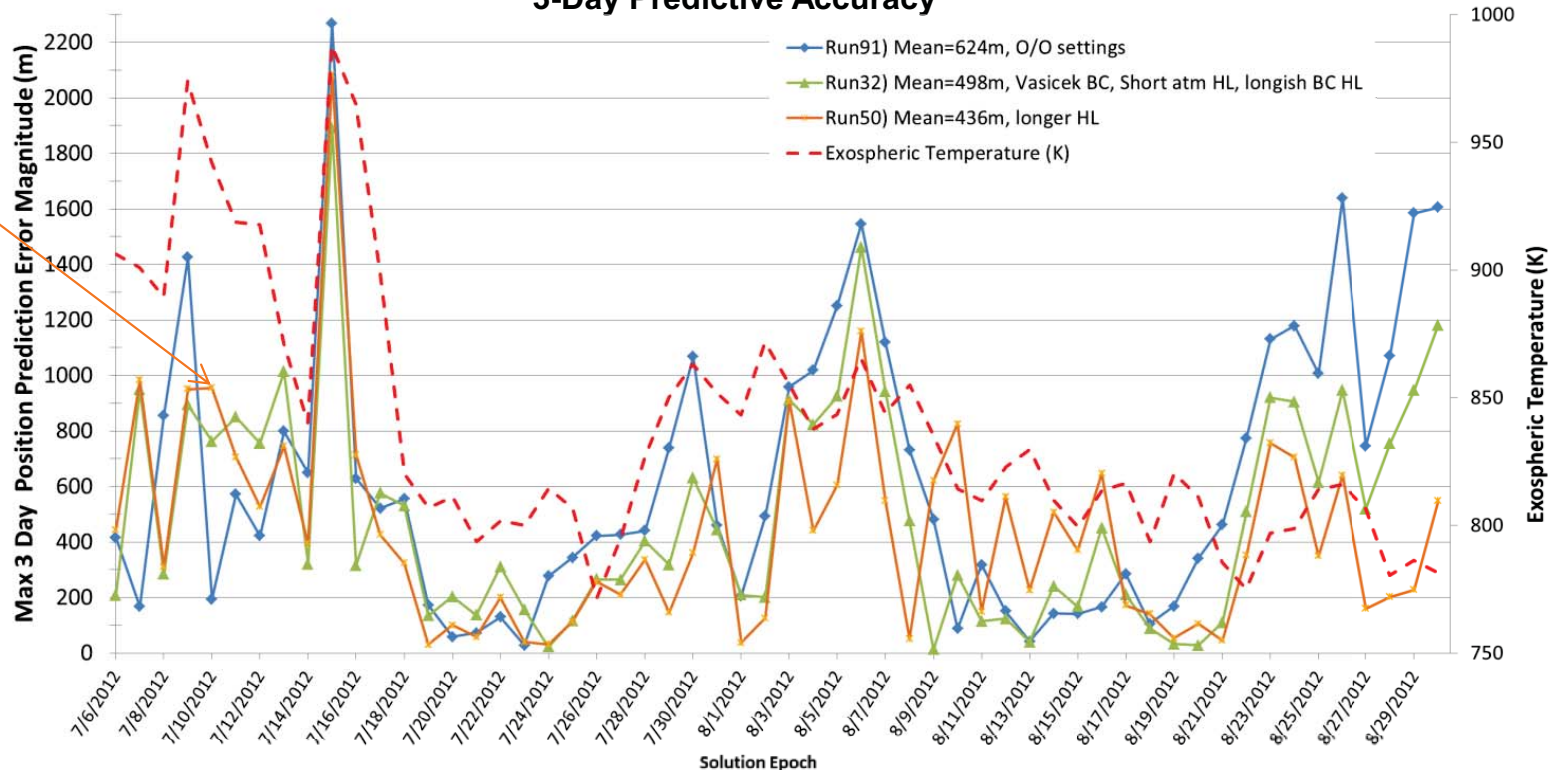GLAST Atmosphere Density Correction dp/p   GLAST dp/p +2 Sigma

Filter Tuning – Longer Half Lives
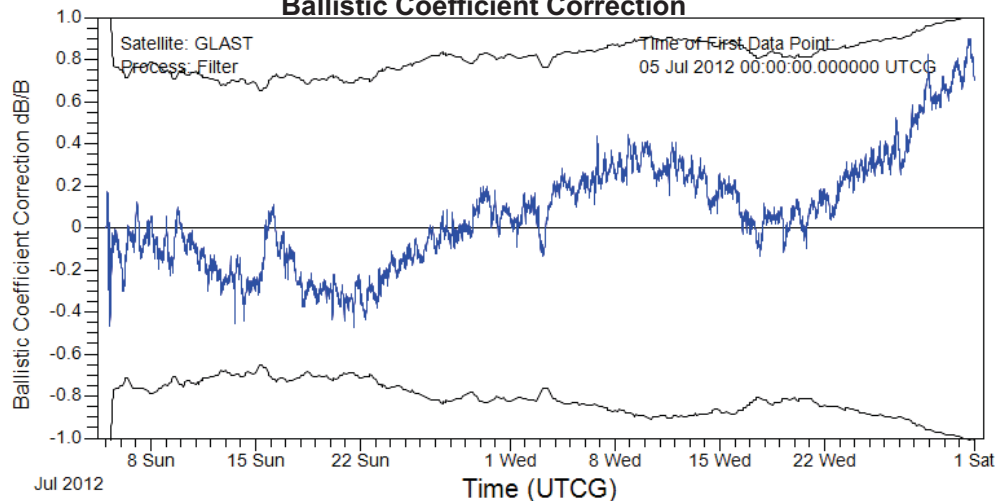
Run 50: 10 min data

- 10 min data frequency
- Vasicek BC:
  - **BC HL = 7days**
  - BC short-term σ = 1
  - BC long-term σ = 1
- C_{D0} = 2.2
- **Atm density HL= 1 day**
- Density sigma scale = 1
- Mean 3 day error: **436 m**

Thinning allows longer half life in stochastic models while still allowing the filter to innovate

3-Day Predictive Accuracy

- Run91) Mean=624m, O/O settings
- Run32) Mean=498m, Vasicek BC, Short atm HL, longish BC HL
- Run50) Mean=436m, longer HL
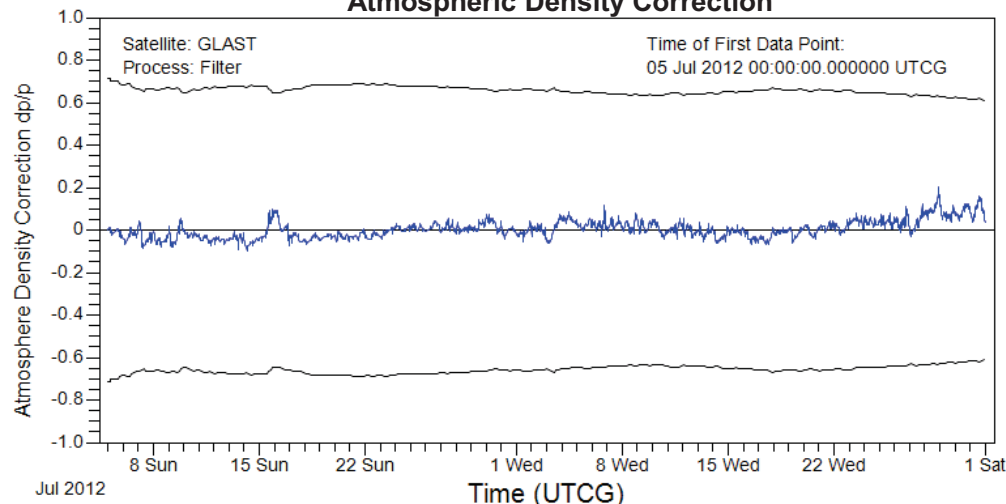- Exospheric Temperature (K)

Ballistic Coefficient Correction

GLAST Ballistic Coefficient Correction dB/B   dB/B +2 Sigma

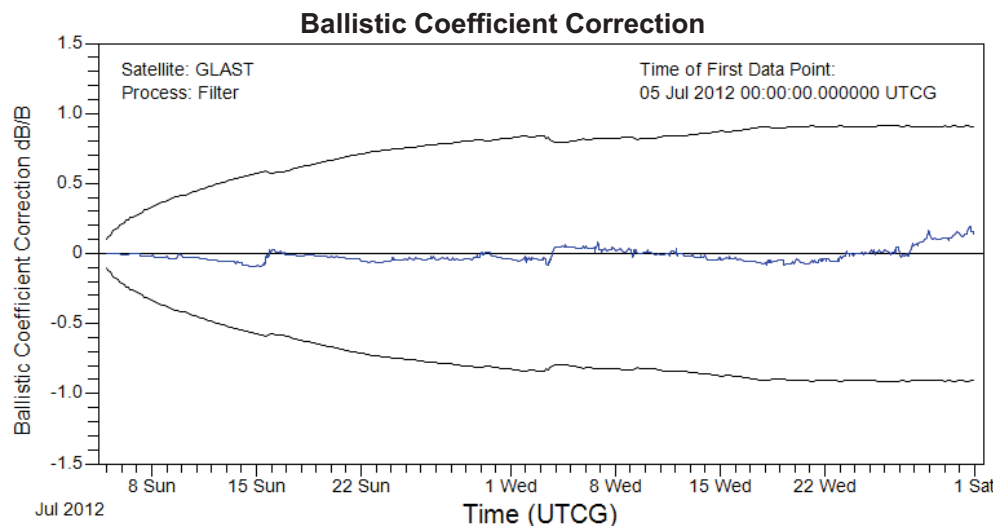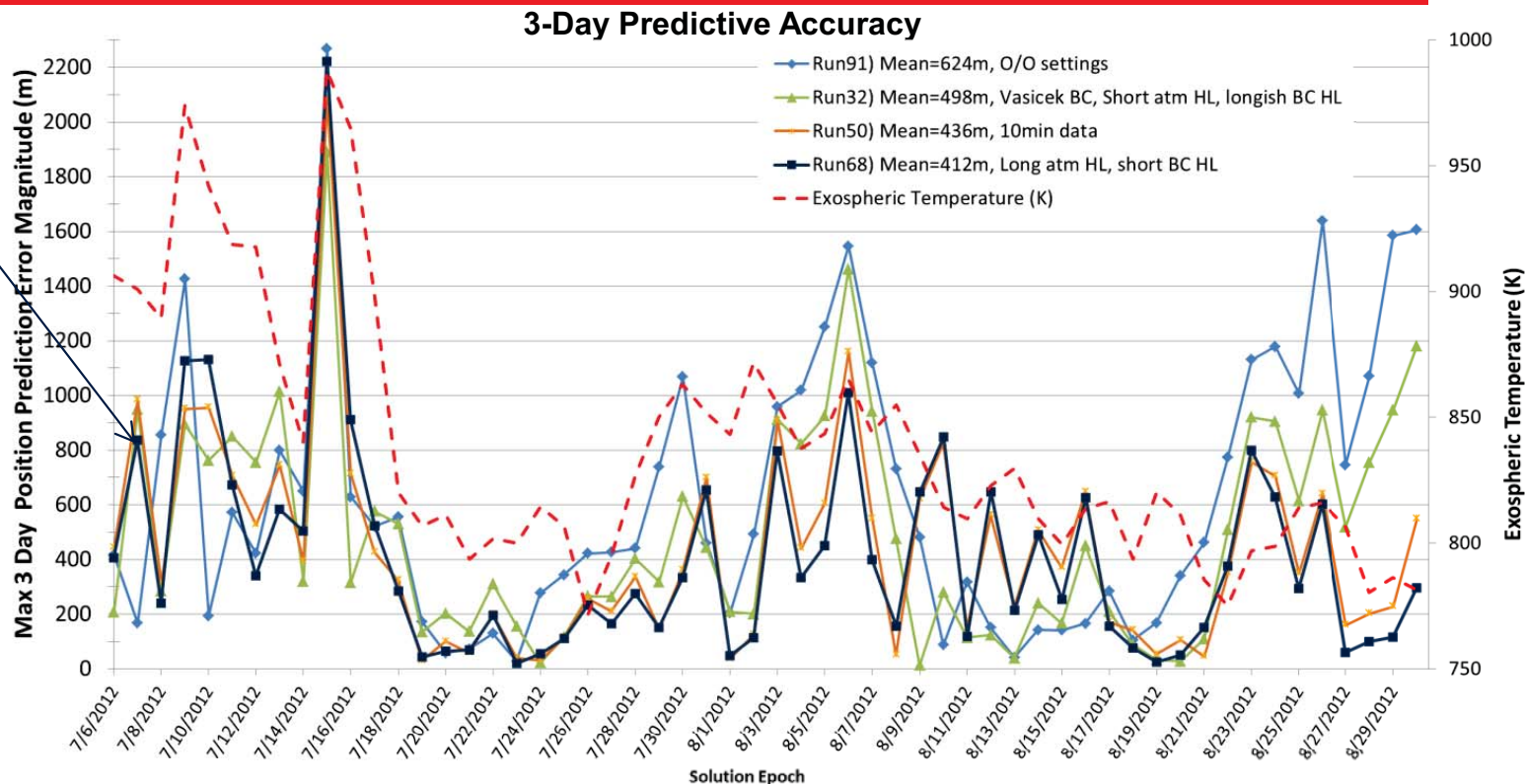Atmospheric Density Correction

GLAST Atmosphere Density Correction dp/p   GLAST dp/p +2 Sigma

Filter Tuning – BC & Atm Density Models
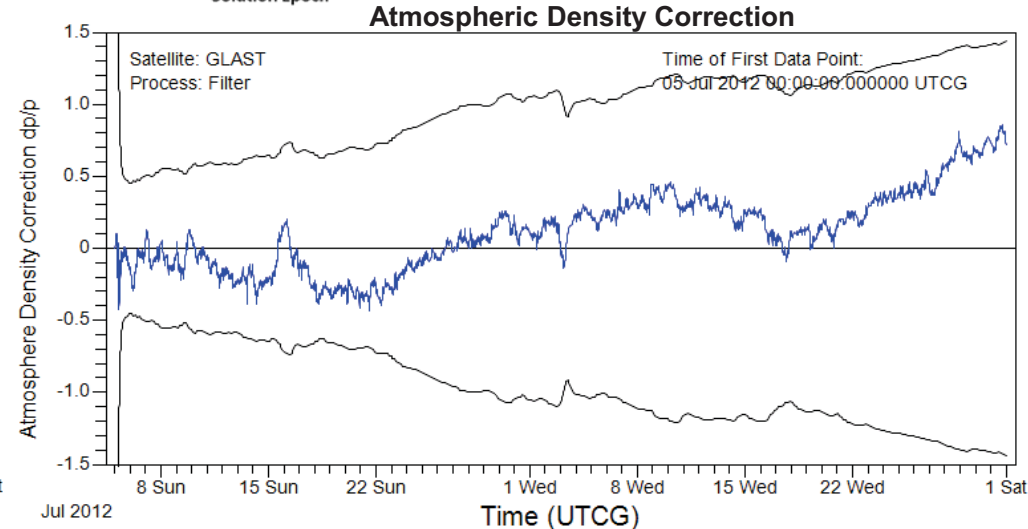
Run 68: Model HL adjusting

- 10 min data frequency
- Random walk BC
  - BC σ = 0.05
  - BC diffusion coef. = 3E-4
- C_{D0} = 2.15
- Atm density HL= 10 days
- **Density sigma scale = 3**
- Mean 3 day error: **412 m**

34% improvement in 3-day predictive accuracy from O/O settings over tuning period

3-Day Predictive Accuracy

- ◆ Run91) Mean=624m, O/O settings
- ▲ Run32) Mean=498m, Vasicek BC, Short atm HL, longish BC HL
- — Run50) Mean=436m, 10min data
- ■ Run68) Mean=412m, Long atm HL, short BC HL
- - - Exospheric Temperature (K)

Ballistic Coefficient Correction

Satellite: GLAST
Process: Filter
Time of First Data Point: 05 Jul 2012 00:00:00.000000 UTCG

GLAST Ballistic Coefficient Correction dB/B   dB/B +2 Sigma

Atmospheric Density Correction

Satellite: GLAST
Process: Filter
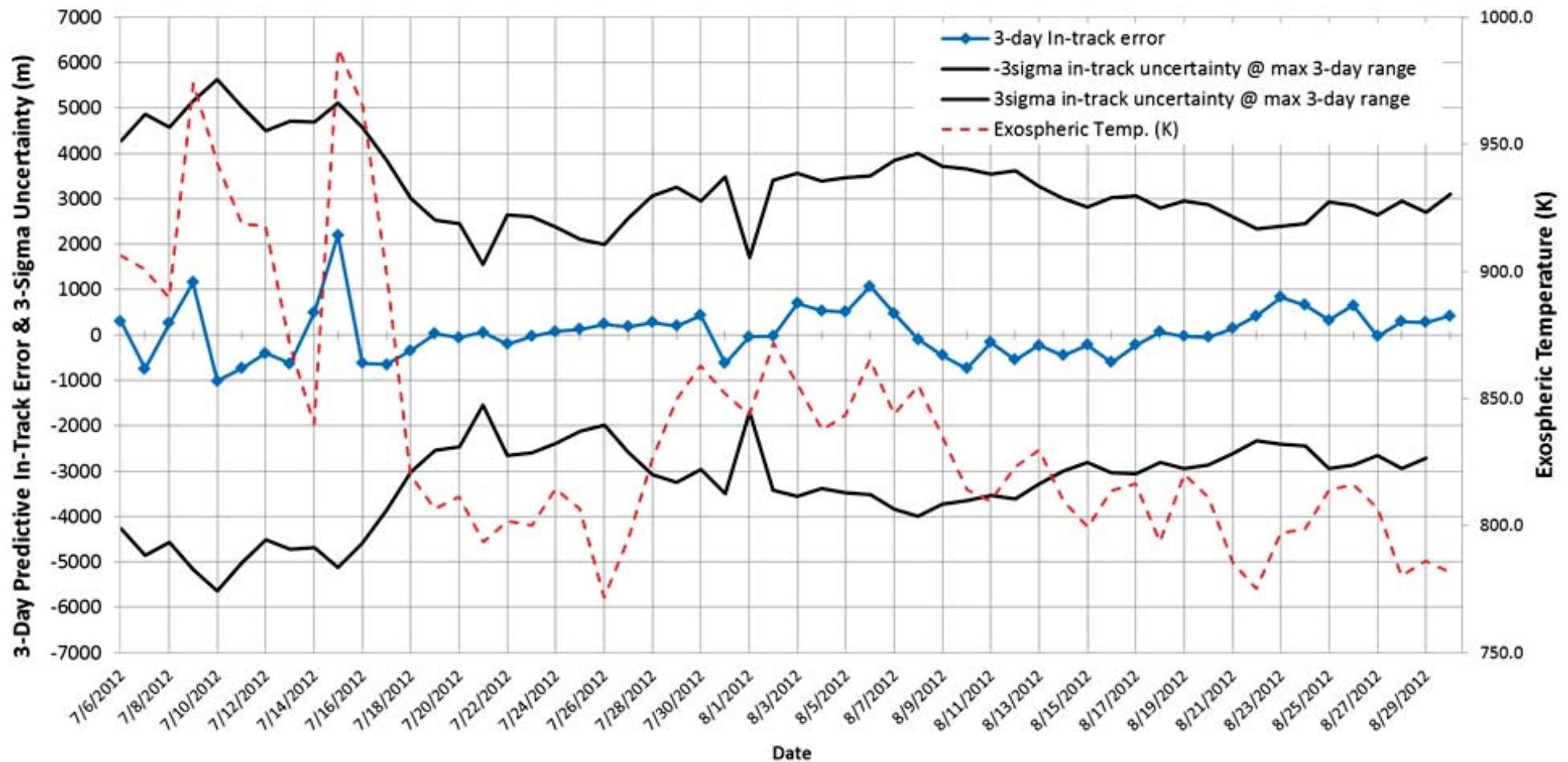Time of First Data Point: 05 Jul 2012 00:00:00.000000 UTCG

GLAST Atmosphere Density Correction dp/p   GLAST dp/p +2 Sigma
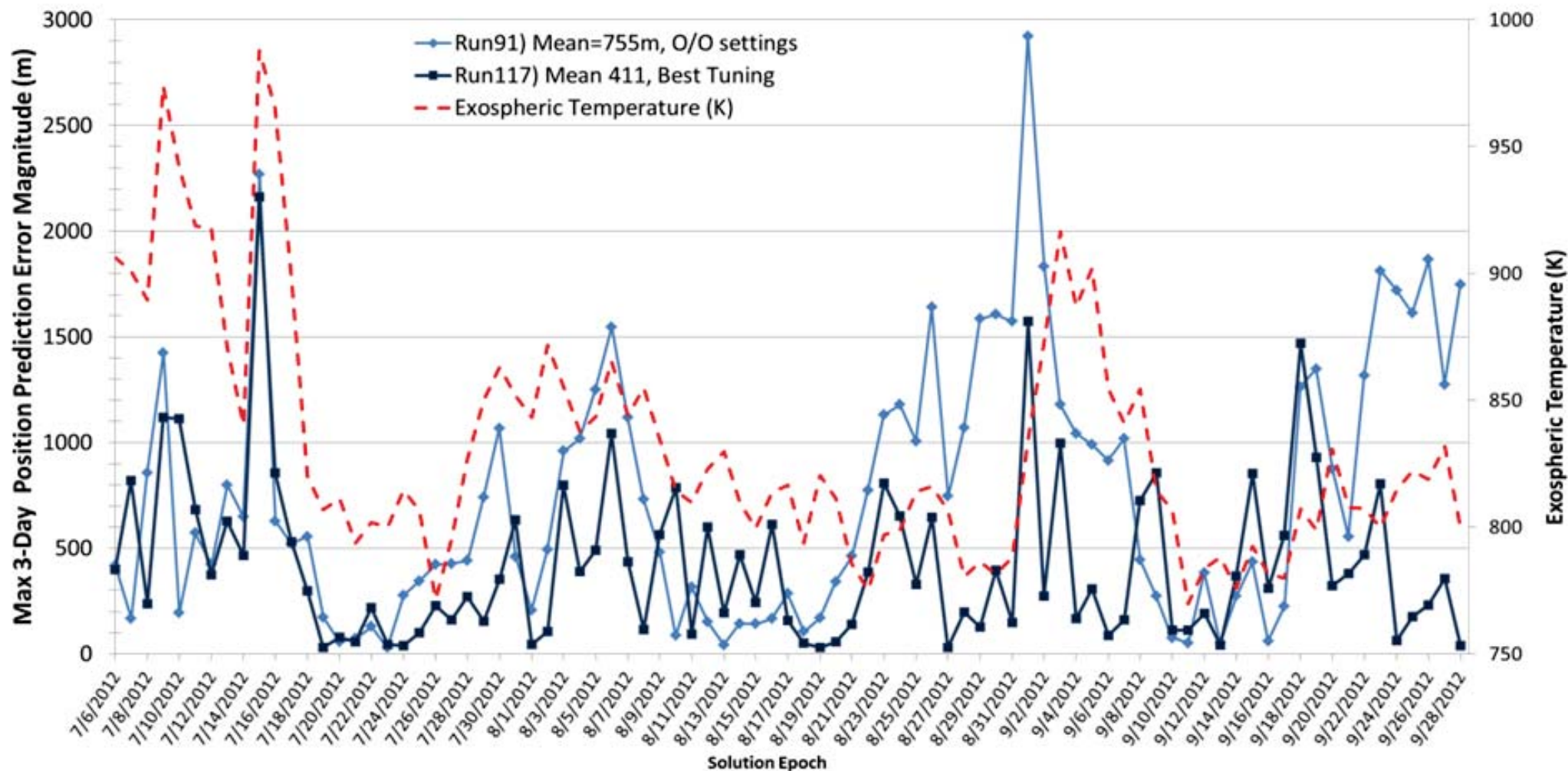
Representative In-Track Error

3-Day Predictive Accuracy: In-Track Error & 3σ Uncertainty

3-Day Predictive Accuracy (7/6 – 9/30)

	O/O ODTK Settings	Run99	Improvement
Mean (m)	755	425	45%
Maximum (m)	2923	2164	26%
Standard deviation (m)	609	390	36%

Summary of Tuning Results

1. Propagation is highly sensitive to drag modeling & uncertainty
   - Driven by Fermi's low altitude
   - In-track position error is the largest contributing factor in predictive error
   - Drag modeling parameters are the key to tuning given Fermi's low altitude

2. Tuning emphasis on BC & density correction stochastic models & associated half lives (HL)

3. Random walk BC & long (~10 days) atm. density correction HL works well
   - In context of best predictive accuracy; Gauss-Markov or Vasicek BC model may produce better definitive accuracy
   - Allows estimated values to be carried through prediction
   - Comparable results when BC HL is short & density correction HL is long OR when estimating only density correction
   - When BC HL is shorter than density correction HL, density correction estimate absorbs more of drag variation

4. Large atmospheric density correction sigma scale can be effective
   - When atm density correction HL is long relative to BC HL, pumping up uncertainty improves predictive accuracy

5. Thinning data can help prediction accuracy, allowing for innovation in filter with long density correction half life

6. Measurement white noise sigma of 7.5 m is a good compromise

7. C_{D0} of 2.2 is effective - Can be modified to some degree w/out detriment depending on model

8. Tuning provided improved mean predictive accuracy for July-Oct '12 data
   - 36% improvement for 6-day predictions
   - 43% improvement for 3-day predictions
   - 50% improvement for 1-day predictions

Conclusion

- Problem is more of a prediction issue than an OD issue
  - Fermi altitude is relatively low → drag is relatively high
  - Difficult to predict long periods at high accuracy given uncertain & variable atm. density (drag model does not match reality)
  - Expect inconsistency in predictive capability given variability of atm. density

- Prediction accuracy not off-base relative to satellites with similar altitude
  - Fermi predictive accuracy is better than HST for similar dates

- Improvements in predictive accuracy of O/O OD expected w/ recommended mods
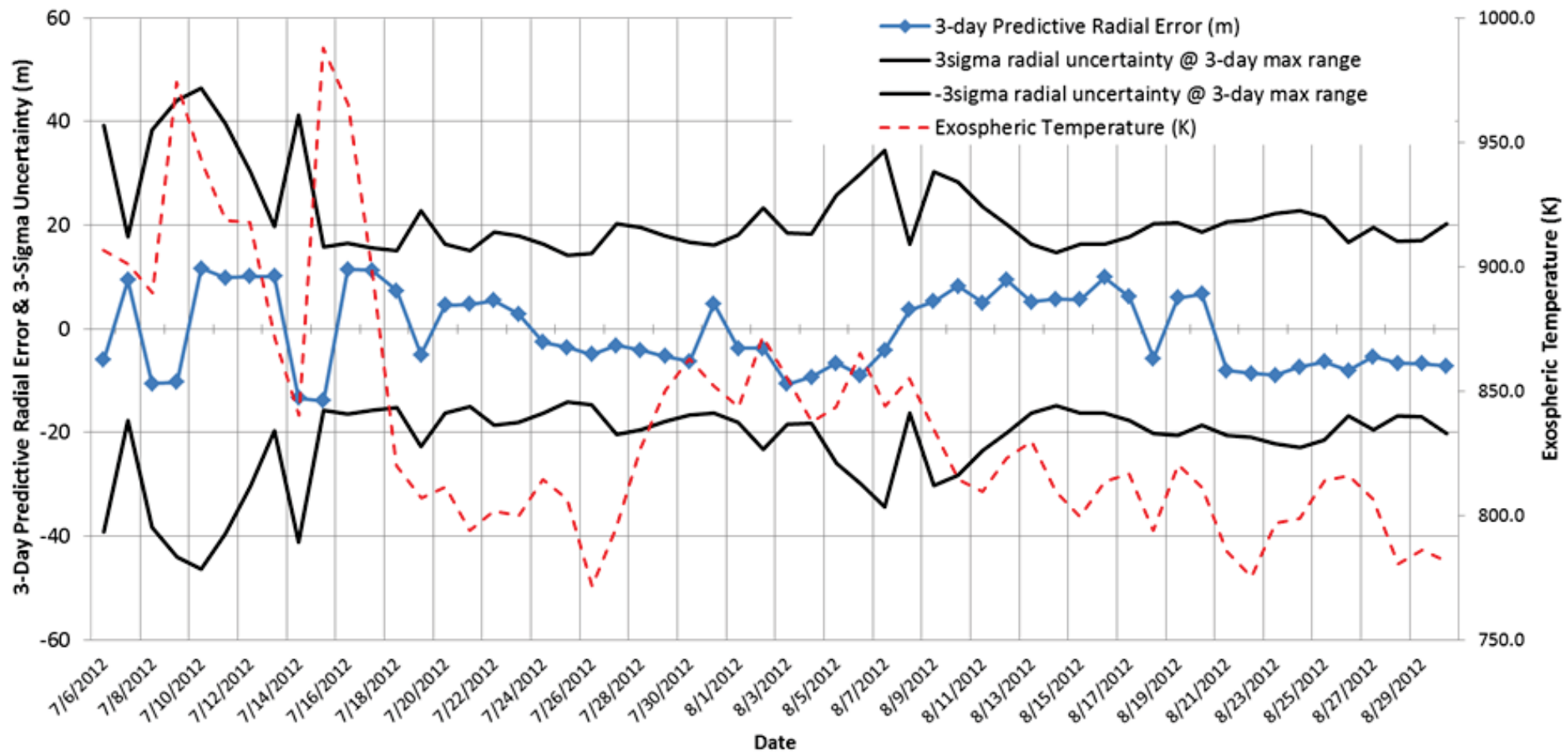 - Extensive tuning produced substantial improvement
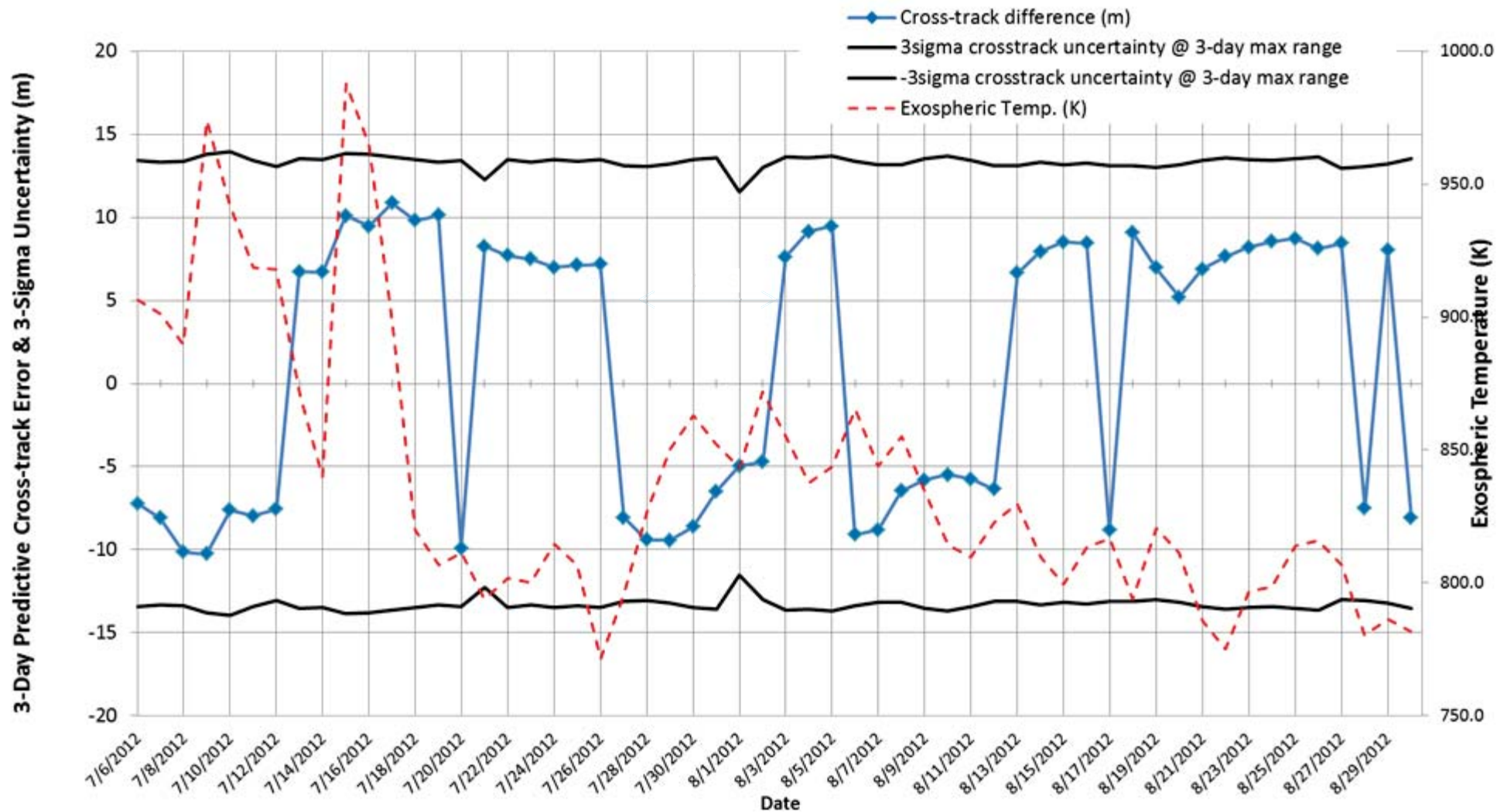
Backups

Representative Radial Error

3-Day Predictive Accuracy: Radial Error & 3σ Uncertainty

Representative Cross-Track Error

## 3-Day Predictive Accuracy: Cross-Track Error & 3σ Uncertainty

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Operational OD Recommendations

- Use ODTK restart feature to retain estimated atm. density model correction & BC
  - Automate with FDF OD process where possible

- Update ballistic coefficient & atmospheric density models based on tuning results
  - Use long HL for atm density correction model (~10 days) & short Gauss-Markov HL for BC (~5 hrs)
  - Adjust density correction sigma scale from 1 to 3
  - Increase nominal C_D from 1.6 to 2.2 (keeping drag area at 14.18 m^2)

- Thin measurement data rate from 1/min to 1/10 min
  - Allows estimated density correction to be carried through prediction w/out stiffening filter

- Implement updates in gravity model
  - Currently 40x40 → change to 70x70

- Increase variational equation degree and order
  - Currently degree 2, order 0 → change to degree 5, order 5

- Move to interpolated values of a_p geomagnetic index (cubic spline)

- Tighten measurement noise sigma from 15 m to 7.5 m
 - If not running from restart value may need to be larger than 7.5 m

Hubble JSPoC Predictive Accuracy

- Predictive ephems from previous plot are from JSPoC ASW from August 2012 onward
- 3-day predictive accuracy varies between 0.5 km to 5 km → similar or worse than Fermi predicts
- 3-day mean predictive accuracy from 8/22/12 – 1/31/13 is 2.35 km

HST 3-Day Predictive Accuracy & F10.7 Solar Flux
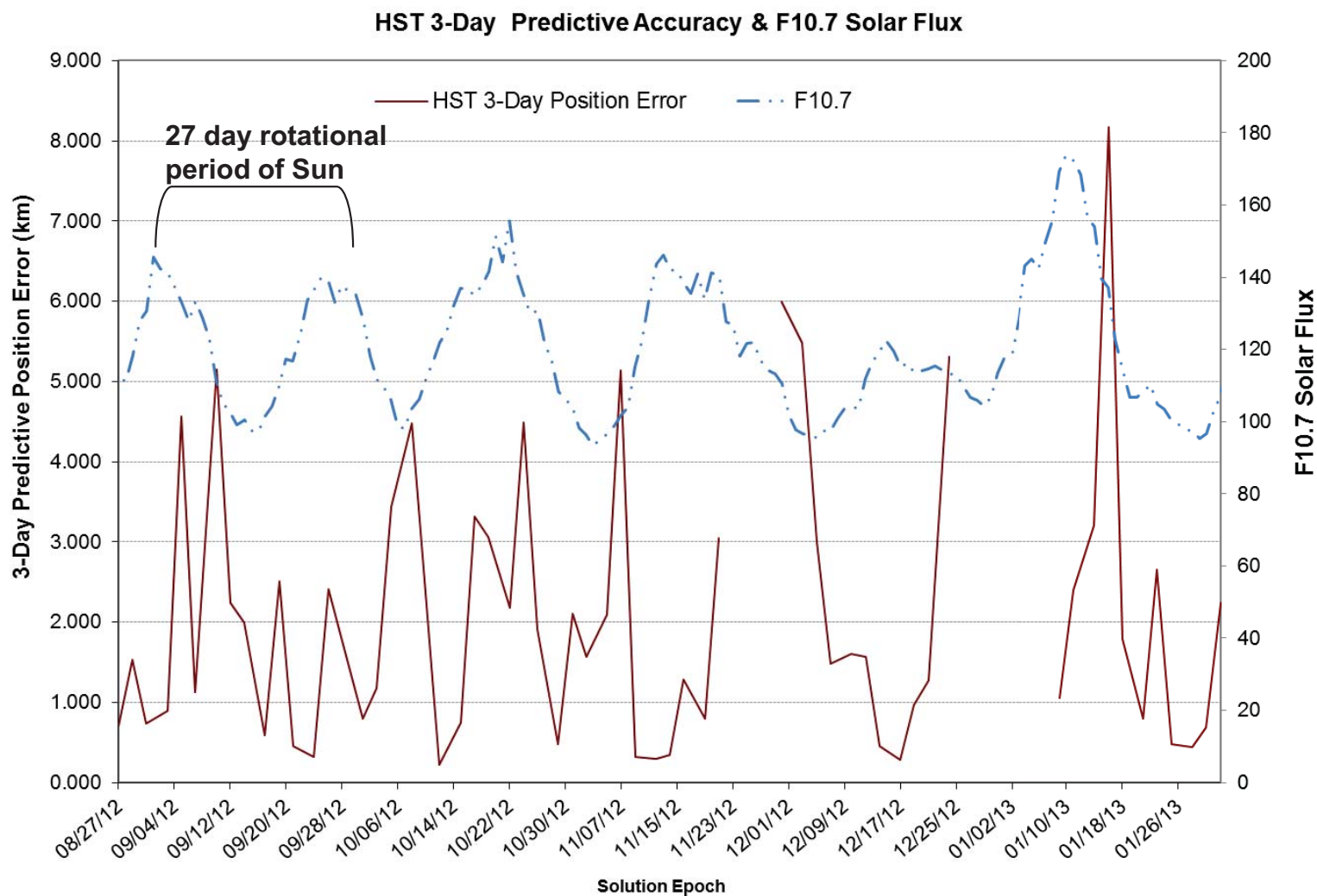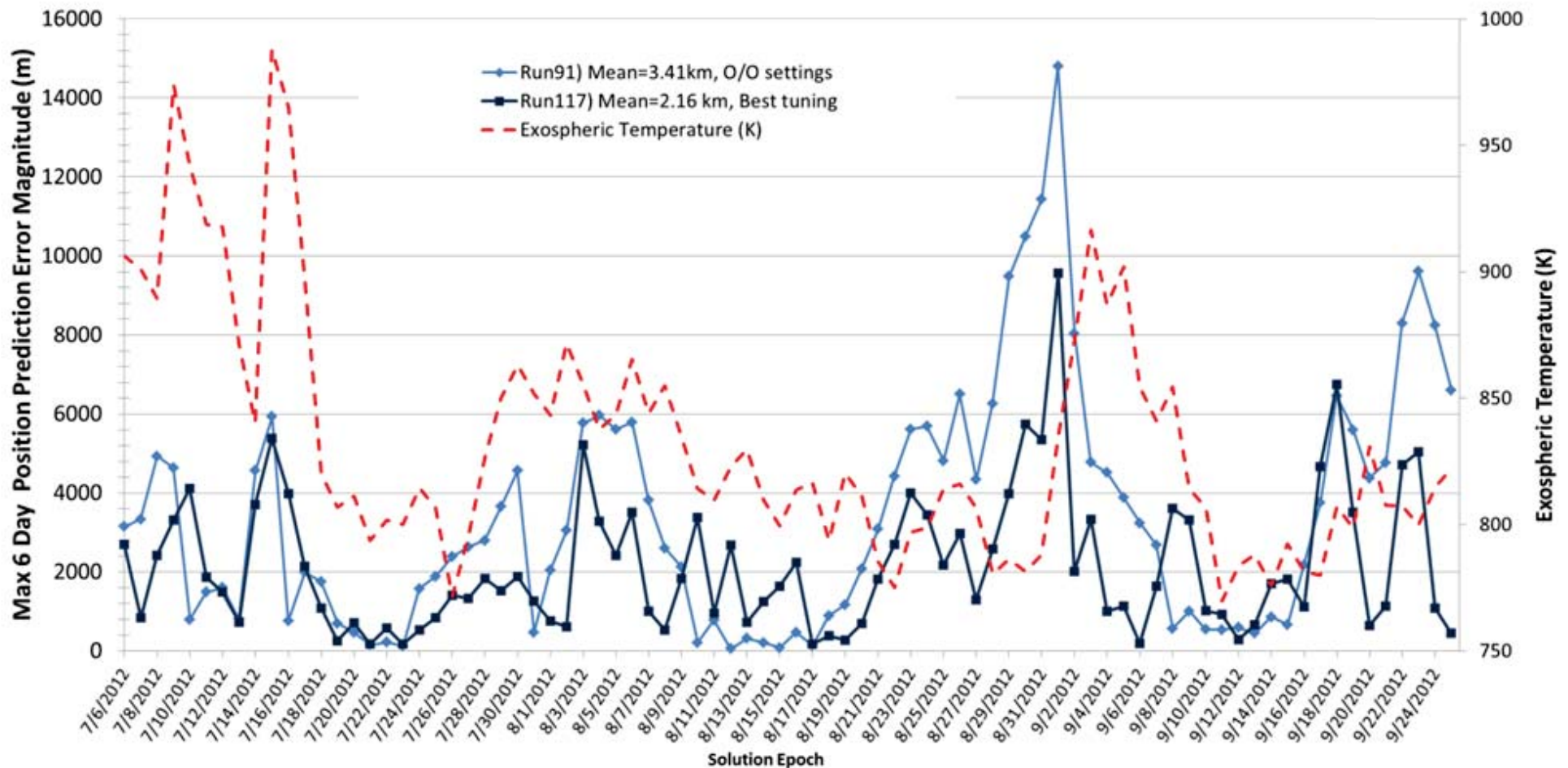
Representative Prediction Error Evolution

- Main contributor to prediction error is in-track component
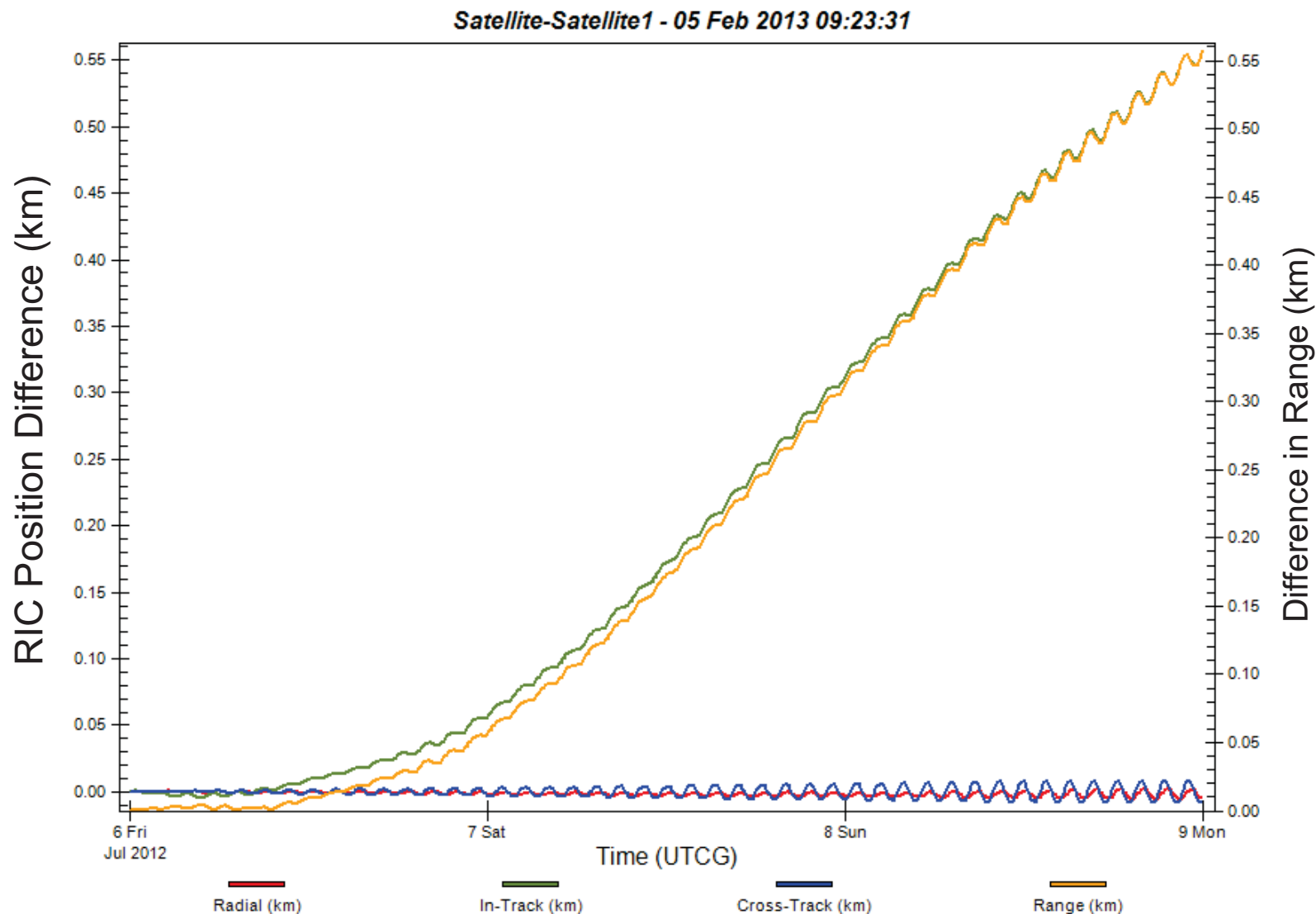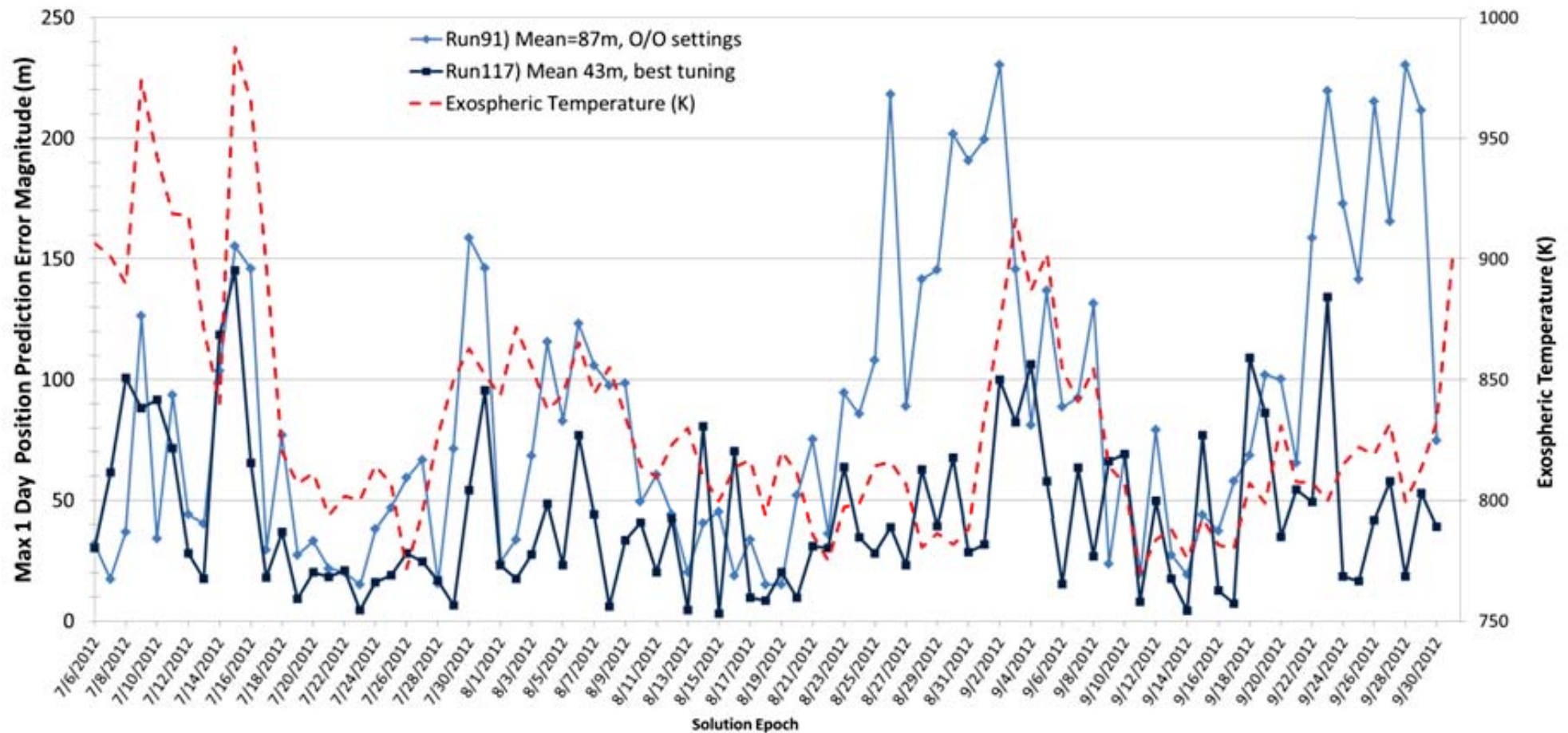
6-Day Predictive Accuracy

6-Day Predictive Accuracy

	O/O ODTK Settings	ODTK Run117	Improvement
Mean (m)	3412	2161	37%
Maximum (m)	14809	9571	35%
Standard deviation (m)	3007	1751	42%

1-Day Predictive Accuracy

1-Day Predictive Accuracy

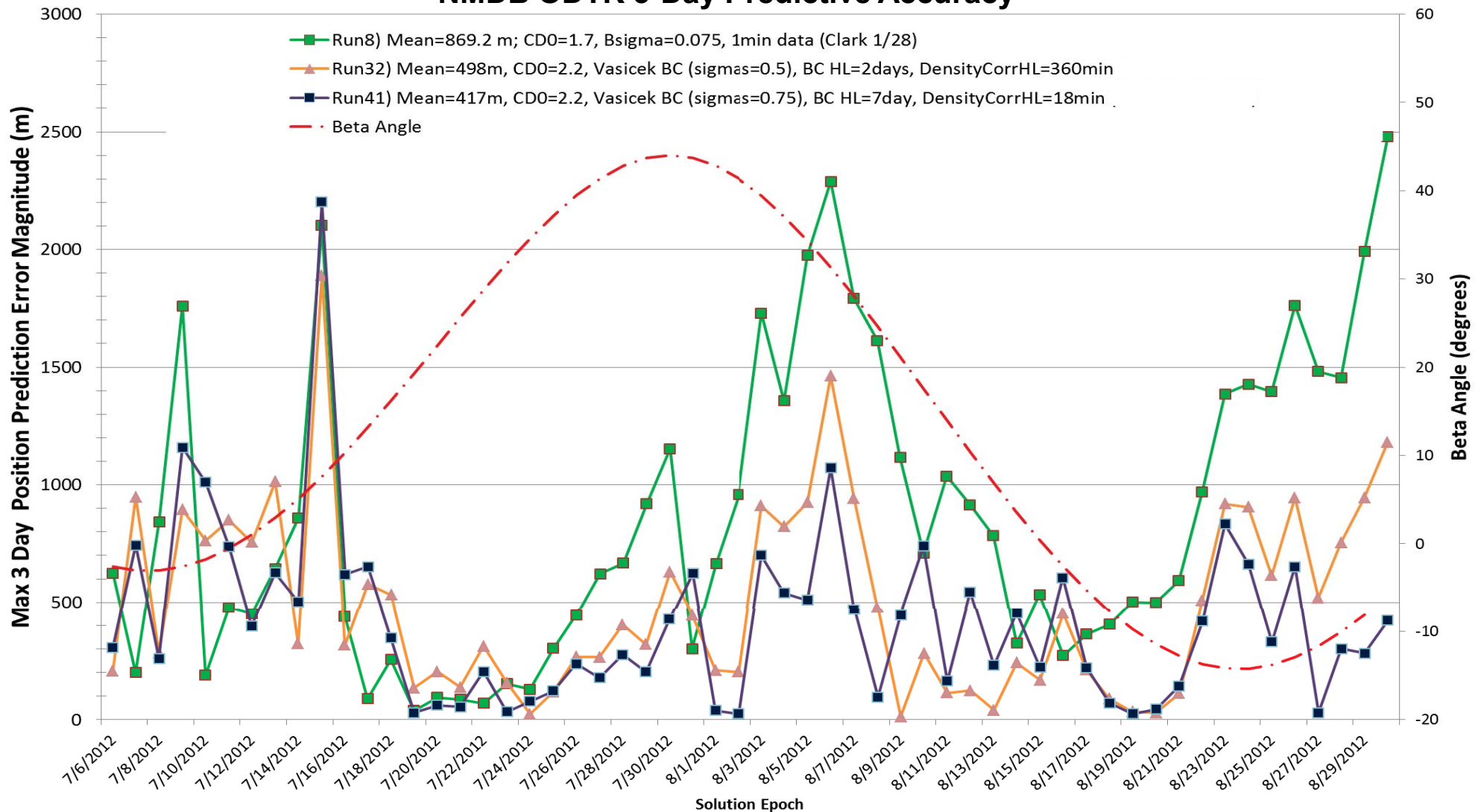|	O/O ODTK Settings	ODTK Run117	NMDB Improvement
Mean (m)	87	43	50%
Maximum (m)	230	145	37%
Standard deviation (m)	61	32	46%

O/O and JSPoC Predictive Accuracy

- Received several days of JSPoC ASW ephems in Jan/Feb '13 via CARA
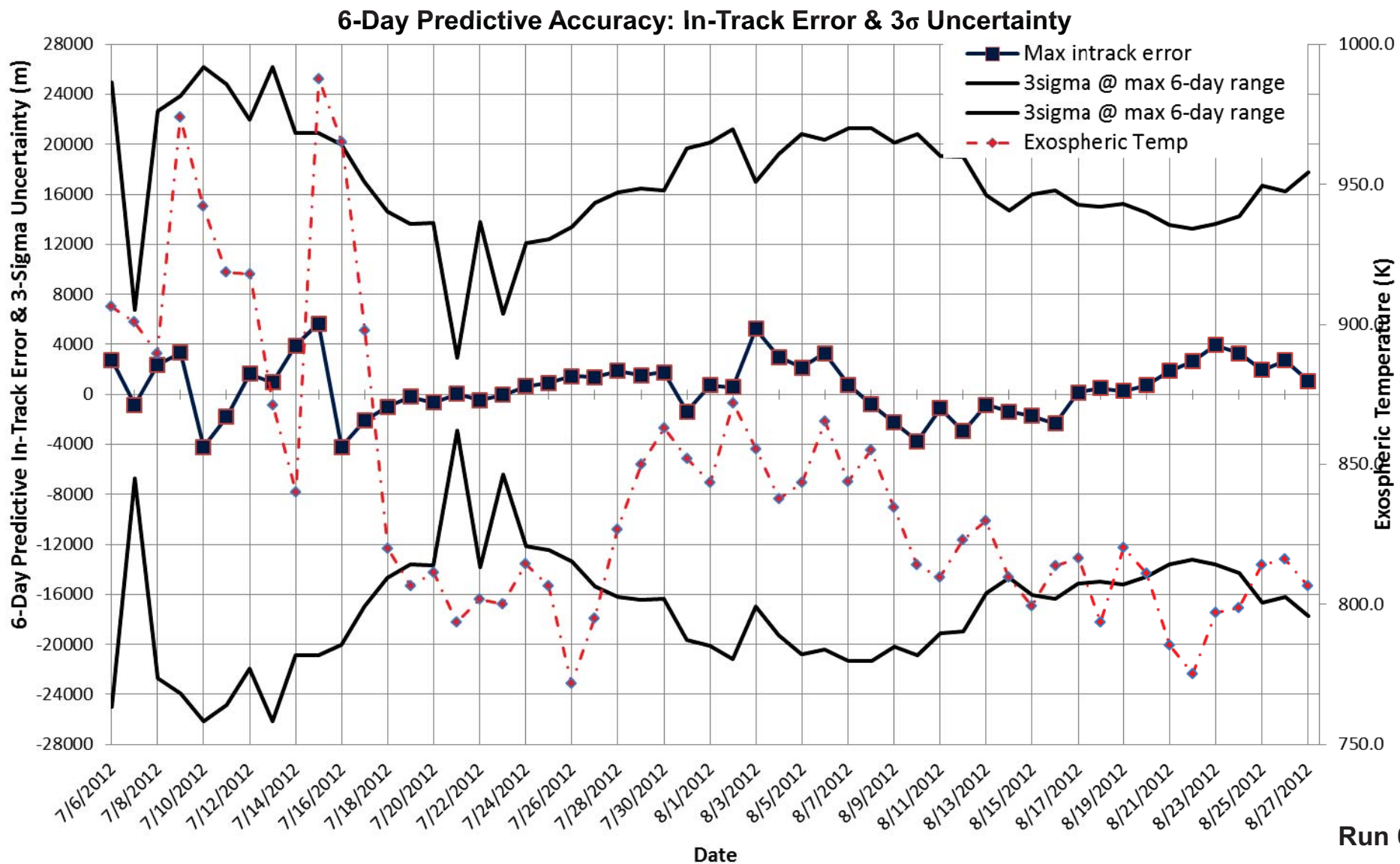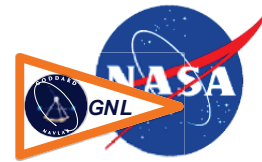- 4 3-day predictive accuracy data generated & compared against ODTK (O/O, NMDB) & GTDS

3-Day Predictive Accuracy Compare (2013 Data)
O/O ODTK, NMDB ODTK, JSPoC, FDF GTDS
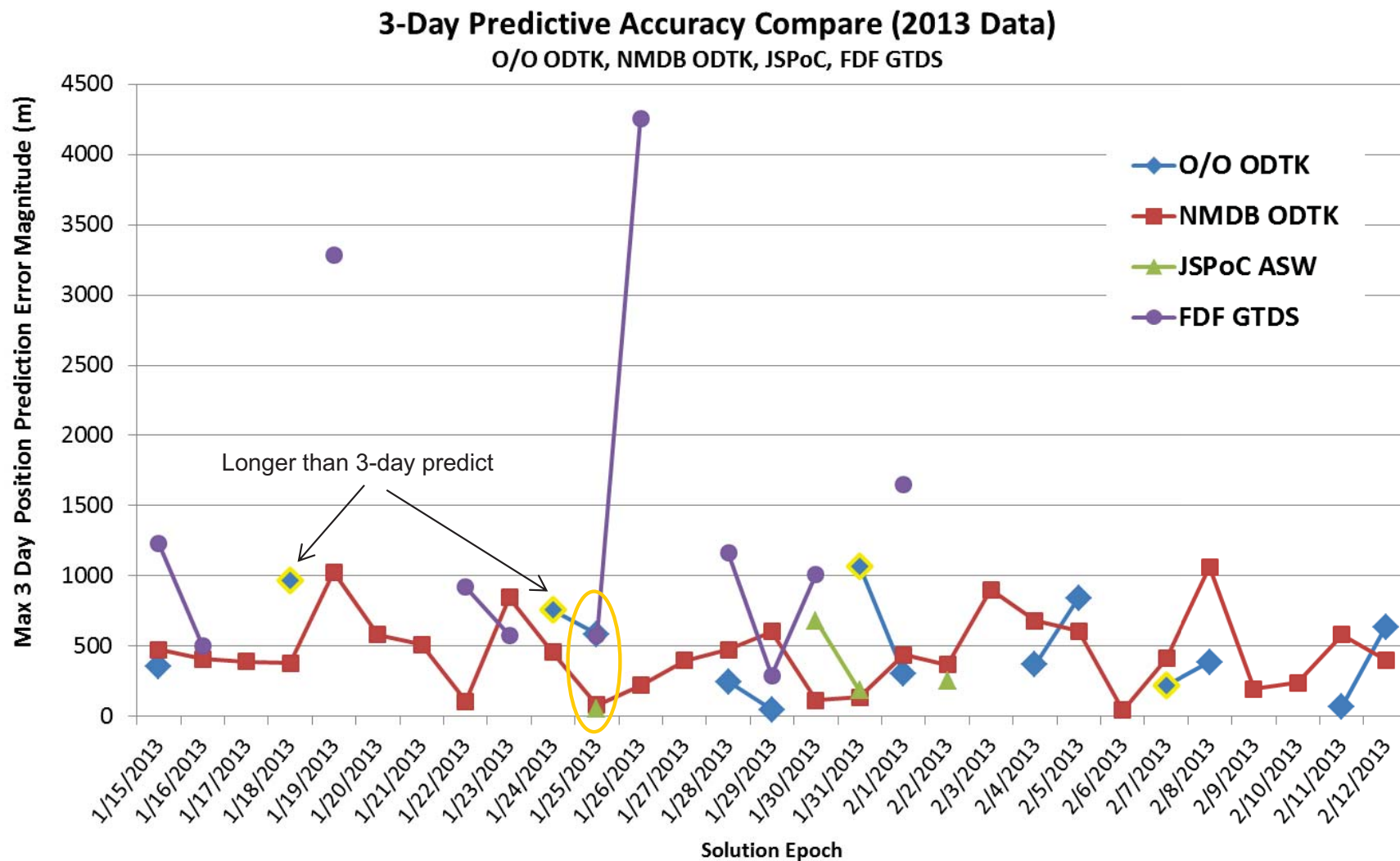
Beta Angle Correlation Investigation

NMDB ODTK 3-Day Predictive Accuracy

- Run8) Mean=869.2 m; CD0=1.7, Bsigma=0.075, 1min data (Clark 1/28)
- Run32) Mean=498m, CD0=2.2, Vasicek BC (sigmas=0.5), BC HL=2days, DensityCorrHL=360min
- Run41) Mean=417m, CD0=2.2, Vasicek BC (sigmas=0.75), BC HL=7day, DensityCorrHL=18min
- — · Beta Angle

• No obvious correlation between beta angle & predictive accuracy

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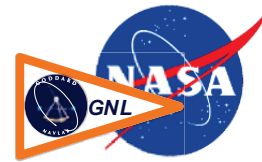6-Day Predictive Accuracy: In-Track Error & 3σ Uncertainty

Run 68

6-Day Predictive Accuracy: Radial Error & 3σ Uncertainty

Run 68

Representative 6-Day Cross-Track Error

6-Day Predictive Accuracy: Cross-Track Error & 3σ Uncertainty