Solari

A Commercial Data Assimilative Thermospheric Density Model

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Community Space Weather Modeling and Data Assimilation Workshop

September. 11, 2025

SPACE ENVIRONMENT TECHNOLOGIES

Enabling Human Evolution Into Space

Objective

Develop a commercially available data assimilative density model utilizing multiple measurement types that provides a global density nowcast and 2- to 3-day forecast with corresponding uncertainties to LEO satellite operators

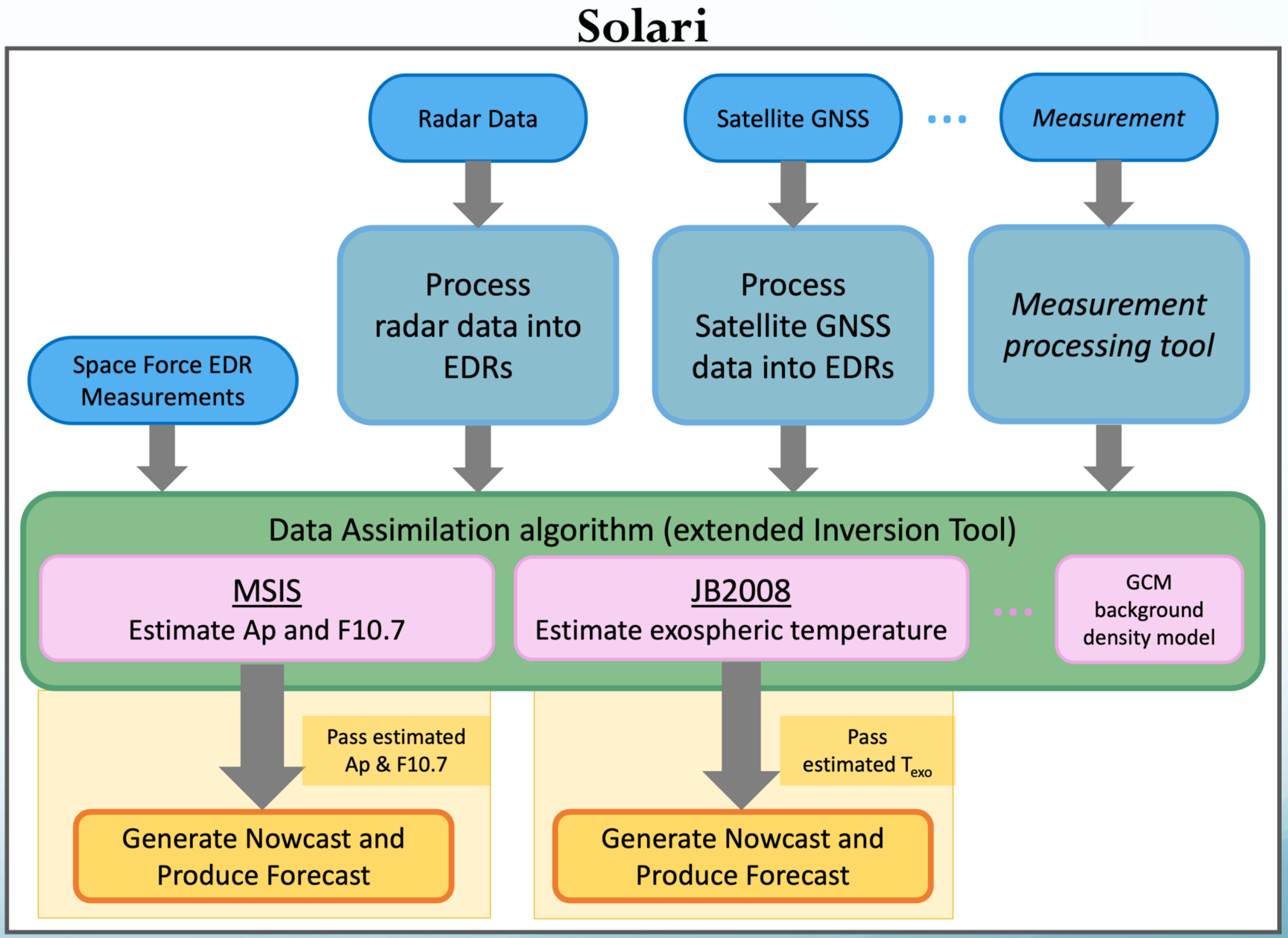
HASDM	Solari
• Single measurement source • Immutable/fixed model • No density uncertainty quantification • Operational density output restricted to US government use only	• Multiple measurement types/data sources • Flexible architecture • Produces density uncertainty • Commercially available density output

Project Status

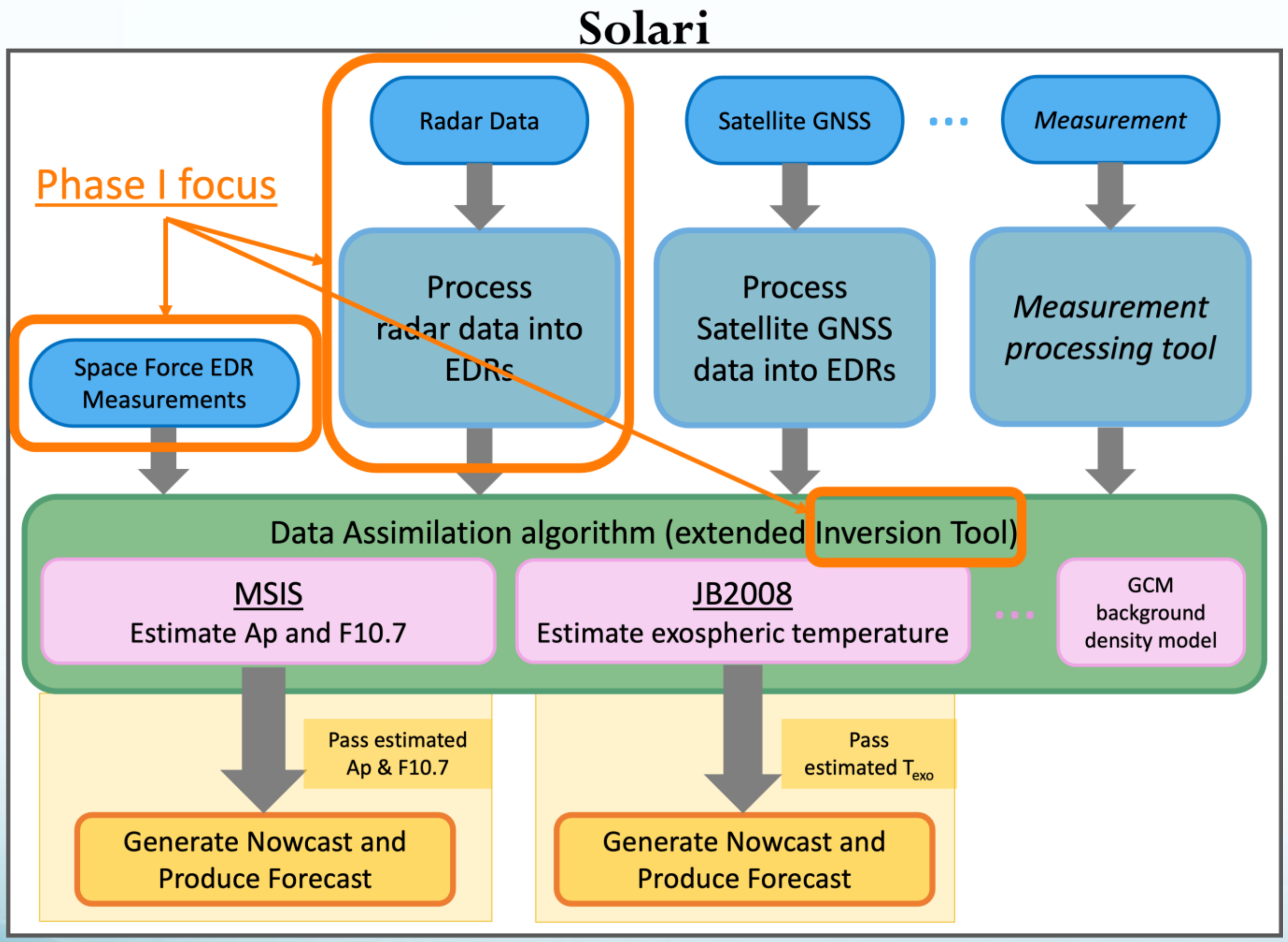
- Completed 6-month NASA SBIR Phase I Feb. 2025
- 2-year Phase II began August 2025

Solari Architecture

- Measurements:
  - Space Force EDRs
  - LeoLabs range & range-rate
  - Future: Satellite GNSS, Nitric oxide, etc.
- Two output data channels:
  - MSIS
  - JB2008
  - Future: ex. TIE-GCM



NASA SBIR Phase I



Period of Performance:
August 2024 – February 2025 (6 months)

Focus of Phase I:

- Test & validate inversion tool
- Feasibility study of radar data processing tool

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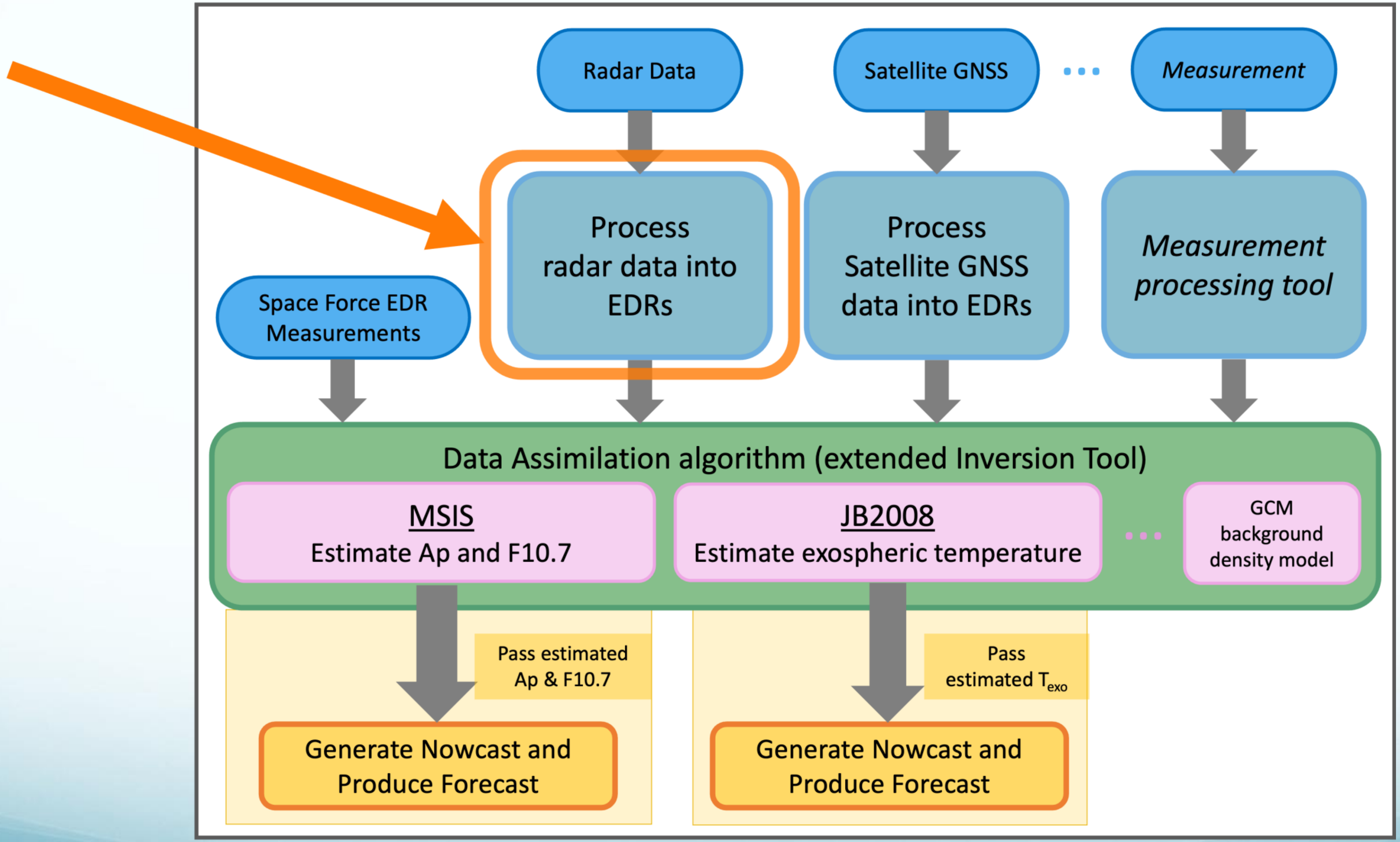
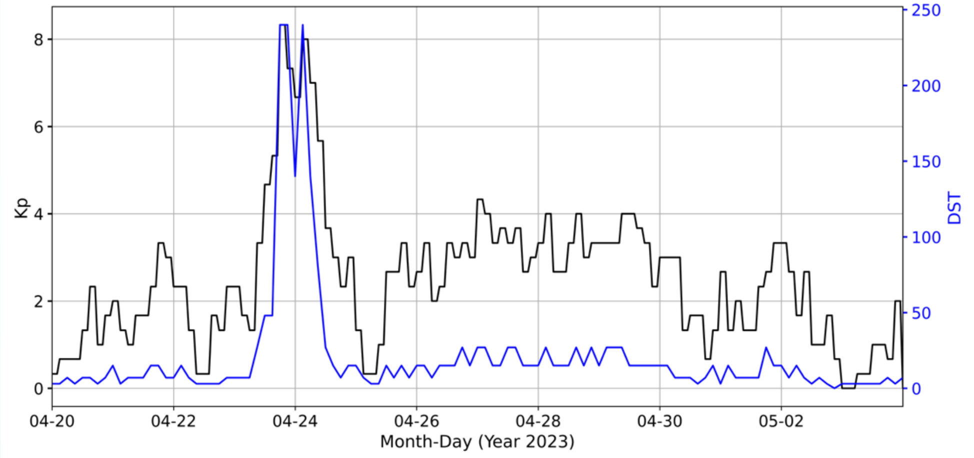


Radar Data
Satellite GNSS
Measurement
Process radar data into EDRs
Process Satellite GNSS data into EDRs
Measurement processing tool
Space Force EDR Measurements
Data Assimilation algorithm (extended Inversion Tool)
MSIS
Estimate Ap and F10.7
JB2008
Estimate exospheric temperature
GCM background density model
Pass estimated Ap & F10.7
Pass estimated T_{exo}
Generate Nowcast and Produce Forecast
Generate Nowcast and Produce Forecast

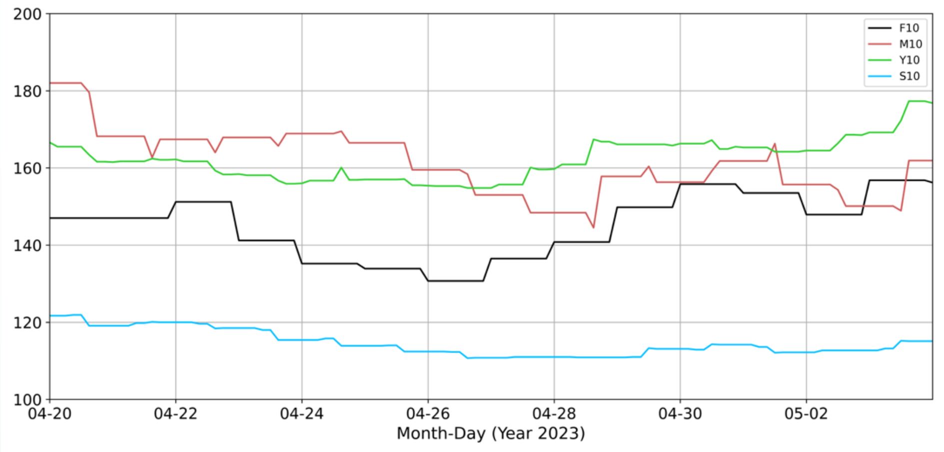
LeoLabs Phase I Data

- Measurements: Two weeks of LeoLabs range and range-rate of multiple calibration satellites
- Dates: April 20 – May 3, 2023

Geomagnetic Indices



Solar Indices



Select satellites for which LeoLabs data was obtained

Name	Kosmos 660	Kosmos 807	Kosmos 1238	Explorer VII
NORAD ID	7337	8744	12138	22
AMR	0.005	0.005	0.005	0.011
Min/Max Altitude [km]	383/1134	370/1139	404/1394	489/657
Eccentricity	0.05	0.05	0.07	0.01
Inclination [deg]	83	83	83	50

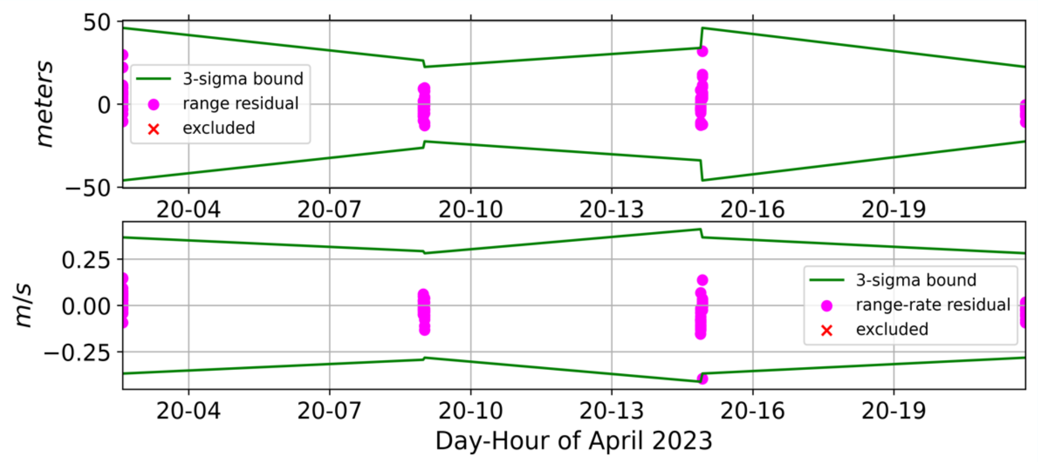
Radar Data Feasibility Study

Radar data processing sequence:

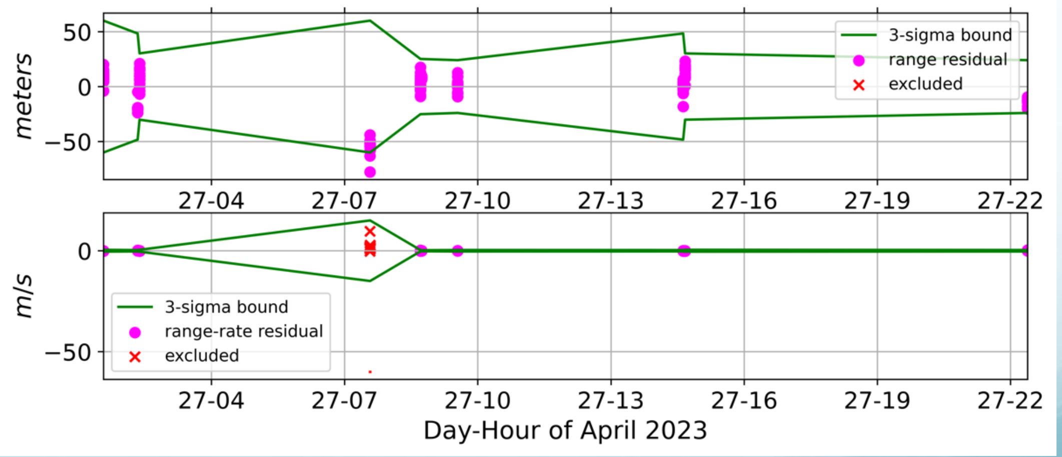
1. Batch filter: processes measurements to obtain position & velocity solution
   - Batch processes one day of LeoLabs measurements at a time
   - Uses Orekit astrodynamics toolkit
   - Batch is iterated until the solution converges
2. Extract Energy Dissipation Rates (EDR) from ephemeris solution
3. Validation of EDRs via comparison to Space Force EDRs and Omitron's independent processing of LeoLabs data

<ins>Batch results</ins>:

- Batch does not always converge using this <1-day fitspan
- All range-rate measurements the Poker Flat Incoherent Scatter Radar (PFISR) in Alaska have a reported measurement uncertainty that is too high to be used in the Batch



Batch range and range-rate measurement residuals for Kosmos 660 on April 20, 2023



Batch range and range-rate measurement residuals for Kosmos 660 on April 27, 2023

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Radar Data Feasibility Study

Radar data processing sequence:

1. Batch filter: processes measurements to obtain position & velocity solution
2. Extract Energy Dissipation Rates (EDR) from ephemeris solution
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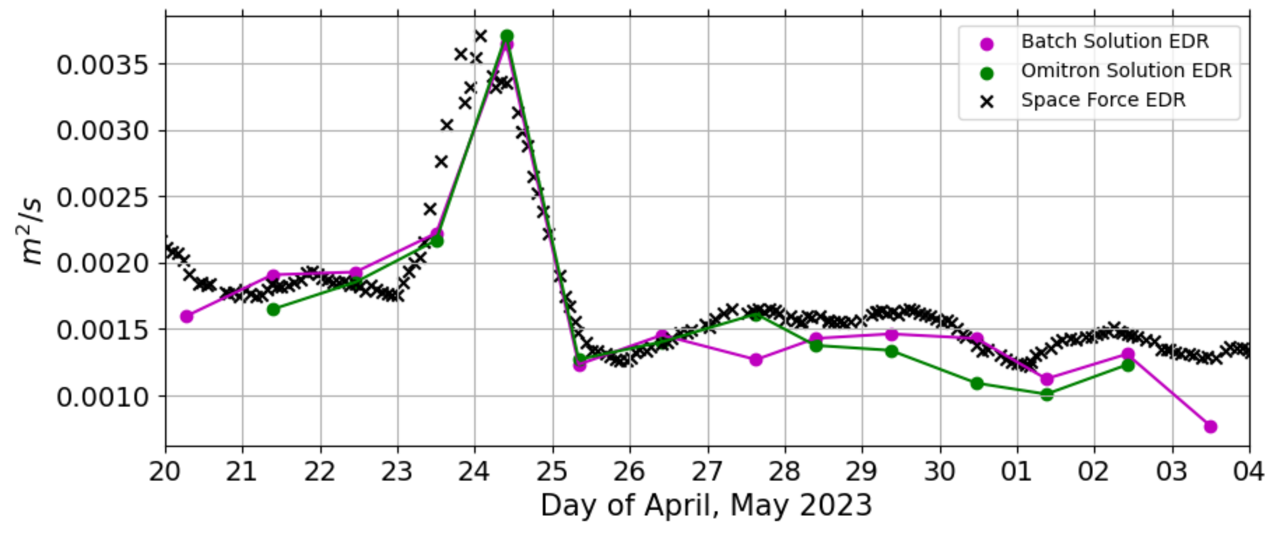
Orbit energy is computed:

$$\xi = \frac{v^2}{2} - \omega_{Earth}^2 \frac{x^2 + y^2}{2} - \frac{\mu}{r} - U_{nonSpherical}$$

Then EDR is computed: $EDR = {}^{\Delta\xi}/_{\Delta t}$

Plot:

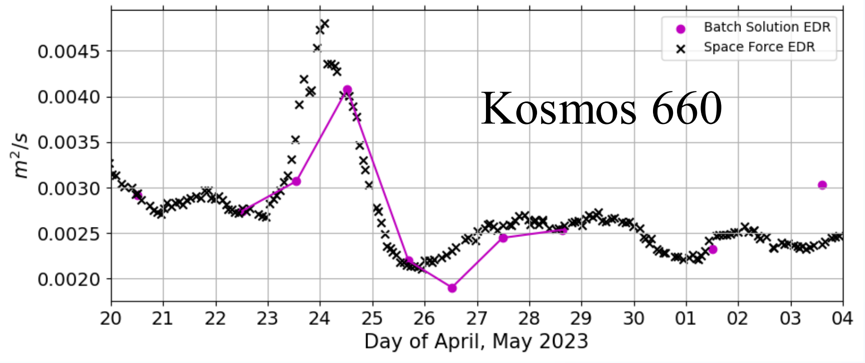
- magenta curve: EDRs computed using the Solari Batch solution
- green curve: EDRs generated by Omitron's solution using the same time-frame as the Solari Batch Solution EDR
- black 'x' markers: independently computed Space Force EDRs (have a different time range and cadence than the Solari Batch & Omitron EDRs)

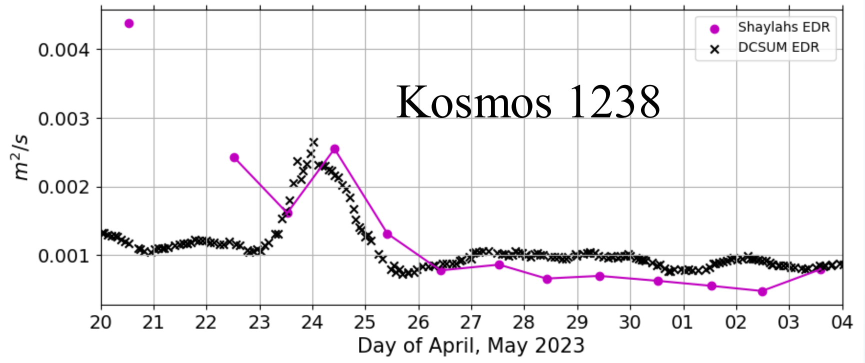


Kosmos 807 EDRs from Solari Batch solution, Omitron's solution, and the Space Force

Radar Data Feasibility Study

- However, other satellites did not have as good performance
- Possible causes of solution degradation:
  - radar passes/tracks
  - Batch satellite state initialization error (high initial state error when using TLE)
  - orbit observability/sensor location diversity (measurements collected form several vs. few sensor locations)
  - Batch fitspan/EDR time-range
  - orbit characteristics
- We plan to further investigate and automatically handle these factors when the radar tracking data processing tool is fully implemented in Phase II.





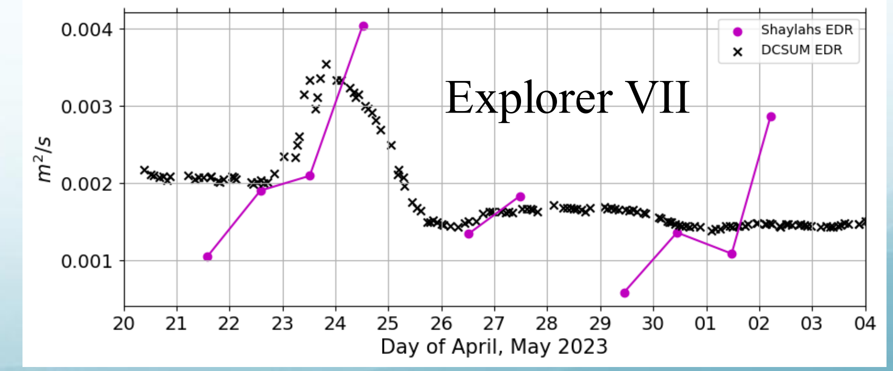


Table 1. Satellites processed in radar data processing tool

Name	Kosmos 660	Kosmos 807	Kosmos 1238	Explorer VII
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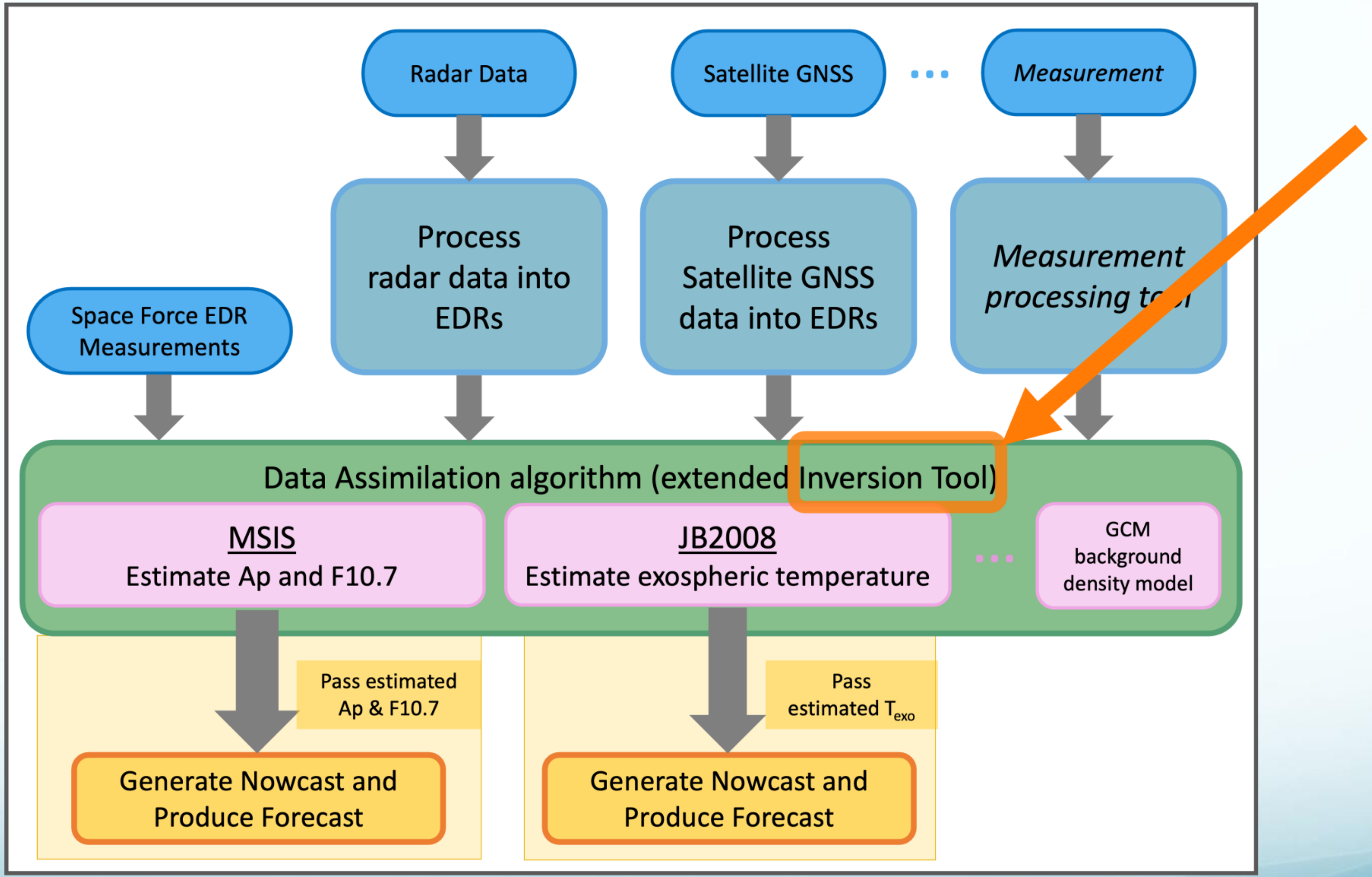
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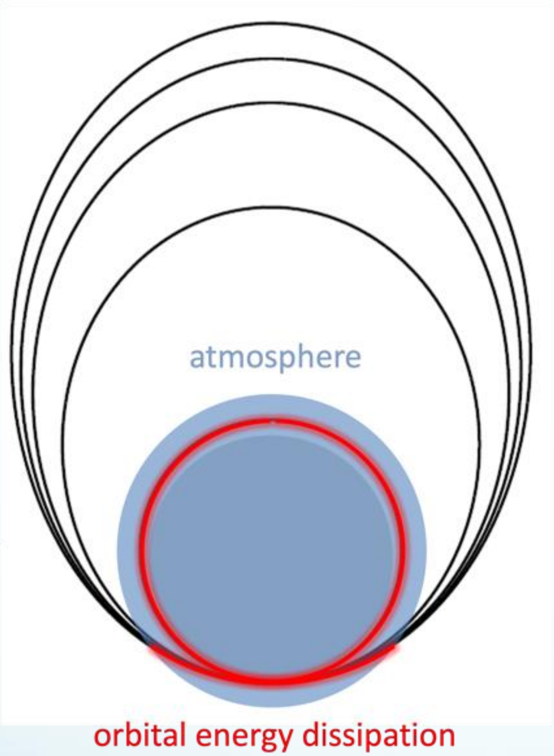
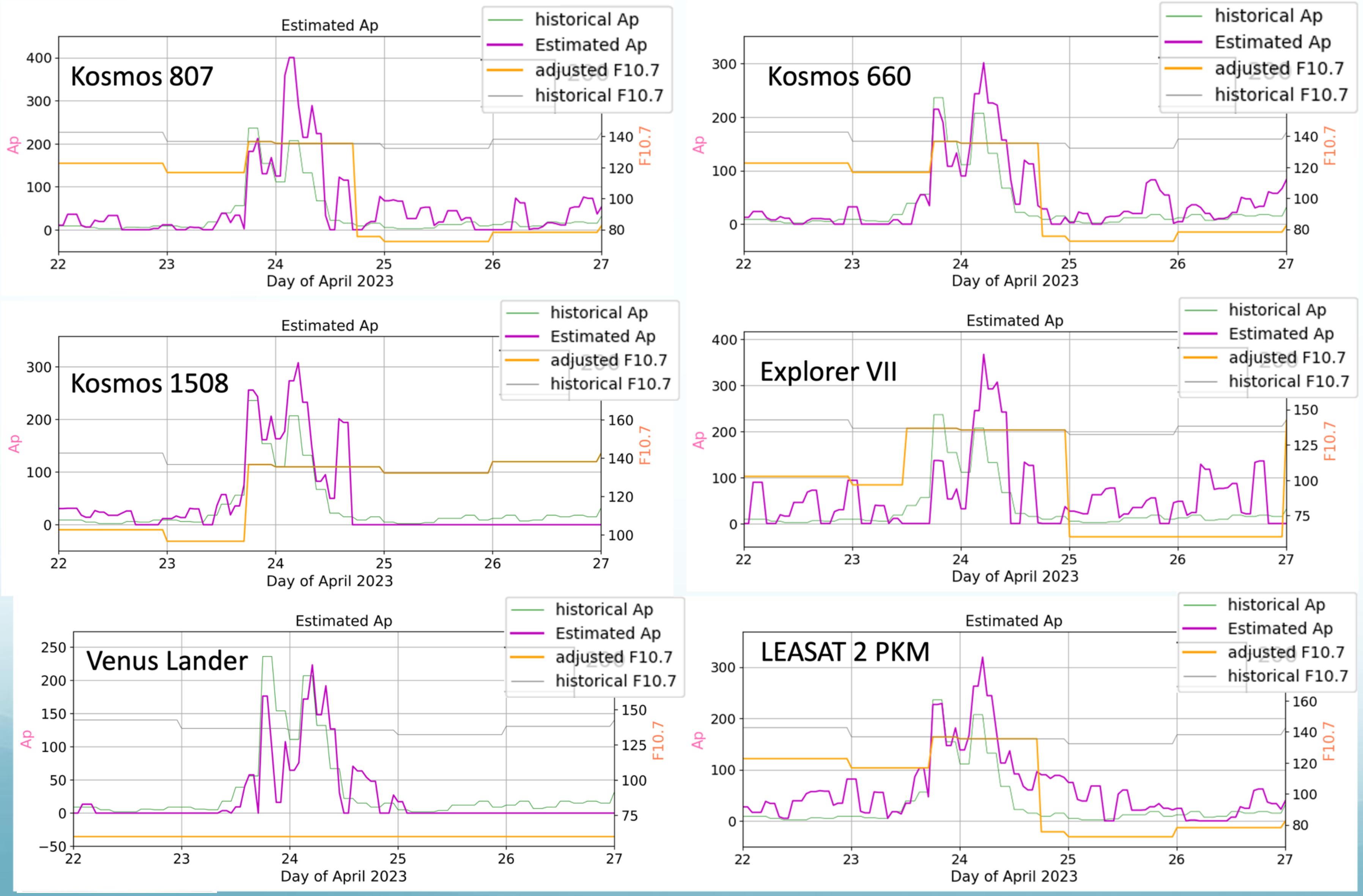
Inversion Tool



Visual representation of EDR localization for orbits of varying eccentricities

- EnKF
- Measurements: *Space Force* EDRs from a single satellite
  - Note: these results are not using the EDRs extracted from LeoLabs data (yet)
- Estimates: corrections to historical Ap using sliding estimation window architecture
- In most cases, an adjusted F10.7 is applied because it is necessary to remove energy from the thermosphere in order to estimate a physically possible Ap (Ap > 0)

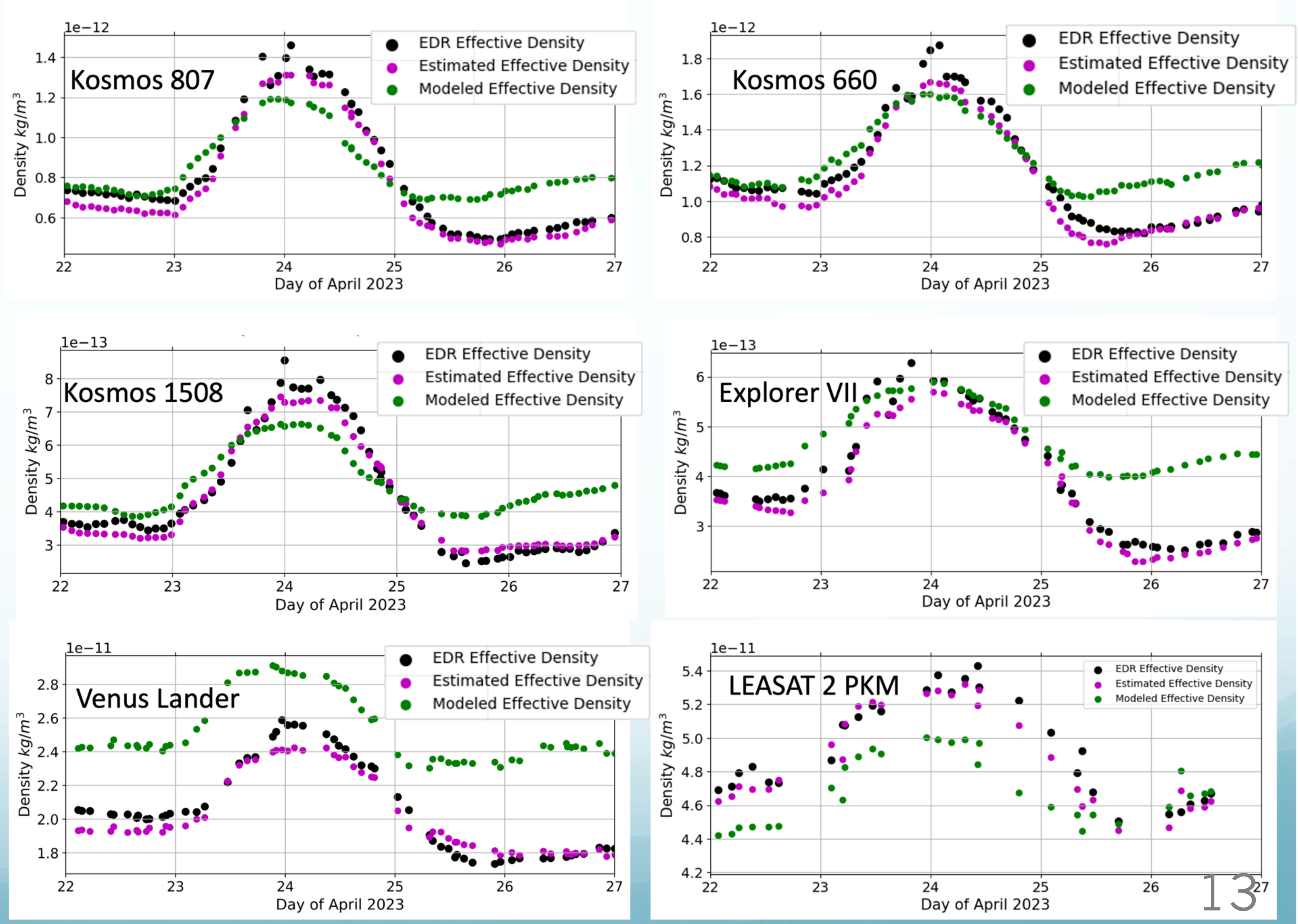
Estimated Ap



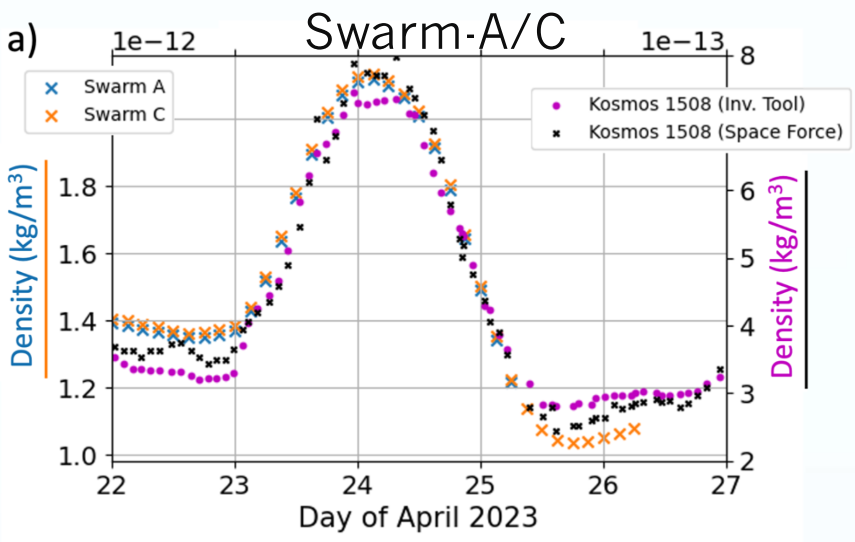
- The aim is not to estimate an Ap that matches the historical Ap, but rather an Ap that produces an effective density that matches the observed effective density (from Space Force EDRs)
- Overall, the estimated Ap from both satellites has a similar double peak structure to the historical Ap

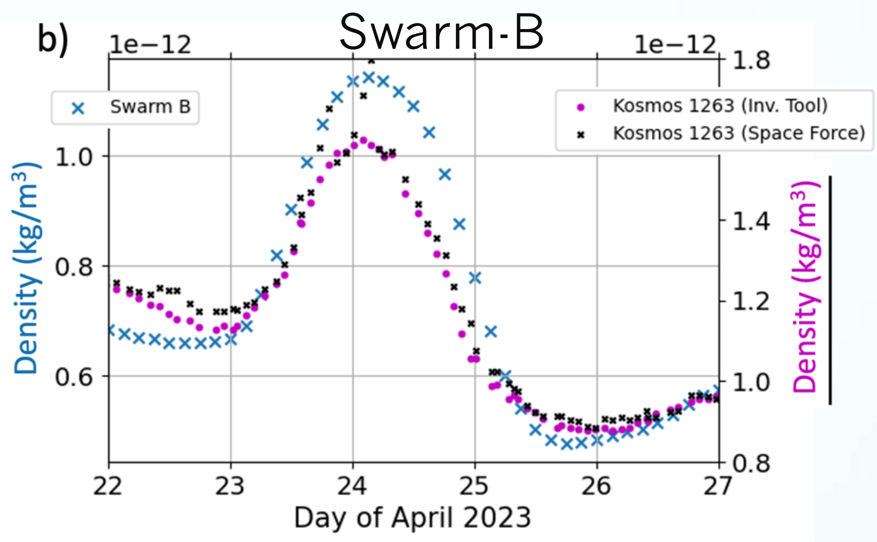
Effective Density Post-fit Residuals

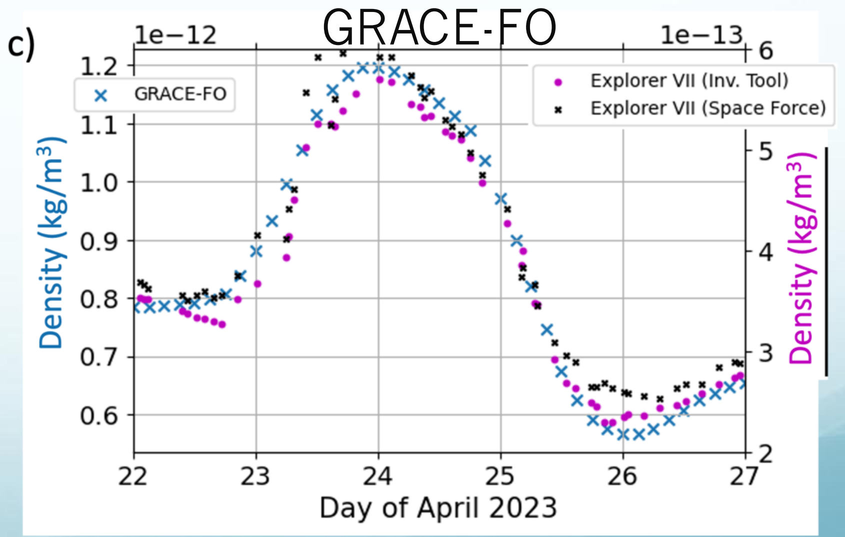
- The *estimated* effective density is computed by using the *estimated* Ap and adjusted F10.7 as input to MSIS
- The estimated effective density clearly aligns better with the Space Force EDR measurement effective density than the modeled effective density generated by assuming historical space weather indices in MSIS



Swarm & GRACE-FO Comparison







Swarm-A/C: 470 km

Swarm-B: 510 km

GRACE-FO: 500 km

- A calibration satellite with similar orbital characteristics to each of the accelerometer satellites is identified
- The overall density behavior is very well aligned
  - the Swarm/GRACE-FO and calibration satellites' effective densities are not exactly the same because they do not have the exact same orbit

Conclusion

Phase II:

- Fully construct Solari
  - Assimilate multiple measurements simultaneously
  - Utilize both MSIS and JB2008 as background models
  - Complete radar data processing tool
- Develop and implement forecast methodology (using SET operational solar & geomagnetic indices)

Solari

Inversion Tool publication (in review):
Mutschler, S., Pilinski, M., Zesta, E., Oliveira, D. M., Delano, K., Garcia-Sage, K., & Tobiska, W. K. (2025). First results of a new inversion tool for thermospheric neutral mass density computations during severe geomagnetic storms. *Journal of Earth and Space Science*, submitted September 2025.

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Discussion

Upcoming:

- Extension of HASDM density database through mid-2025 will be publicly available Spring 2026

- New forecast Dst integrated into SET's operational JBHSGI (provided to Space Force for HASDM & available on UDL) Spring/Summer 2026

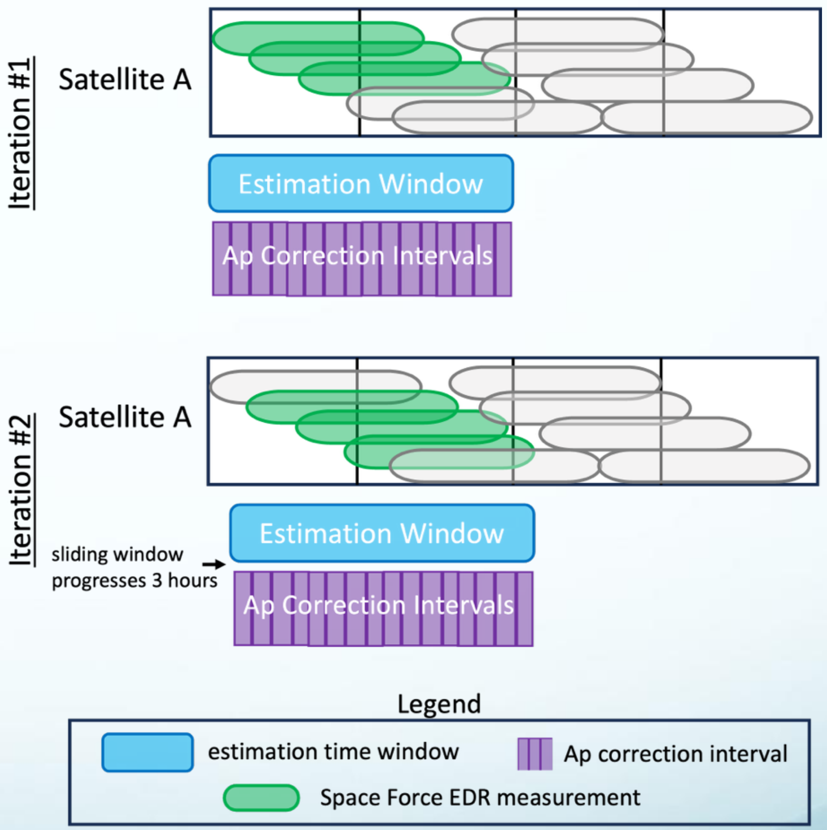
Posed Questions:

- What observations should be prioritized? NO, POD
- How can the community support research in DA for advancing SW predictions? Facilitate the availability of real-time observations

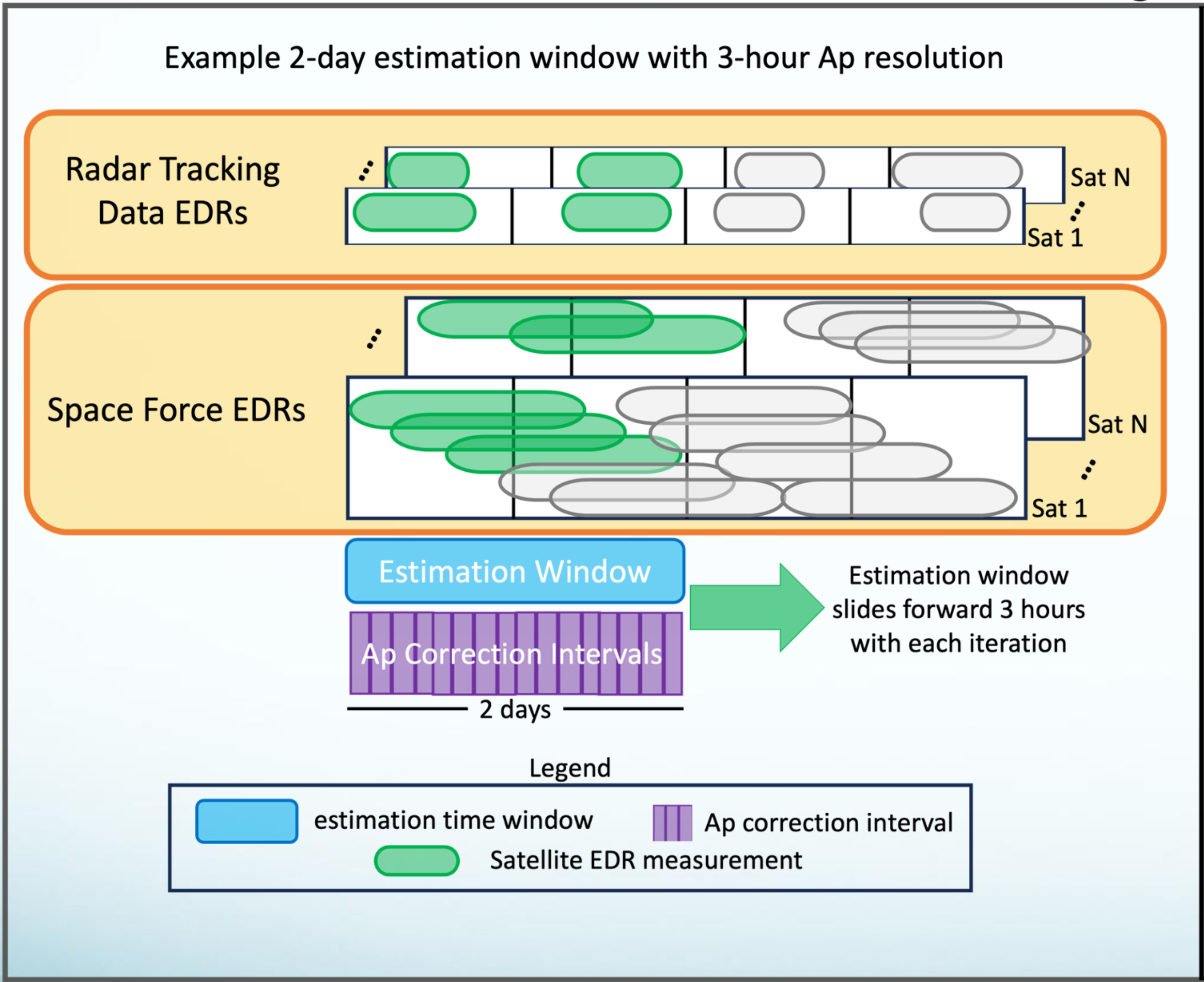
Backup Slides

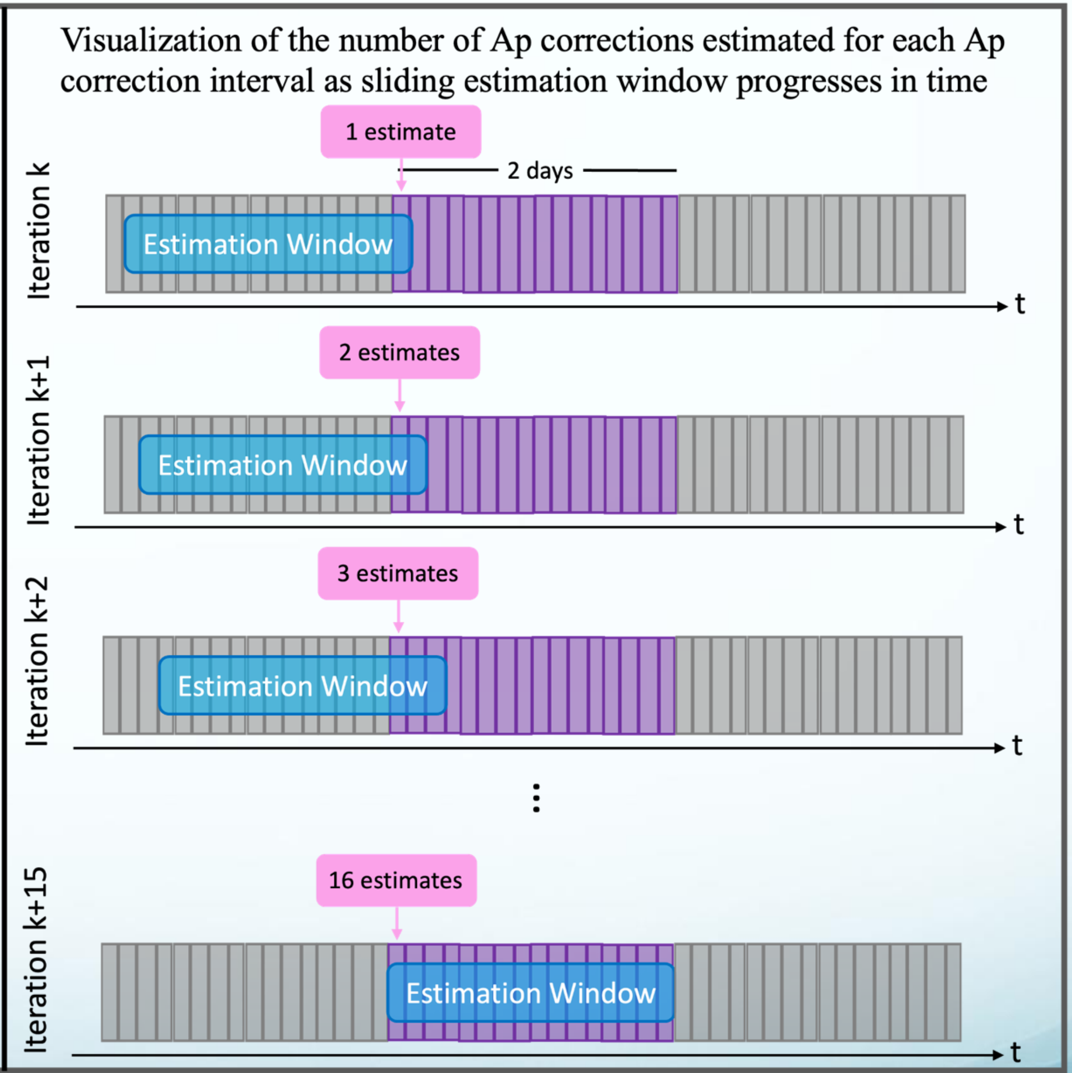
EnKF Inversion Tool Procedure

1. Determine F107 tuning for the time period of interest by examining the modeled and observed effective densities
2. For all time assimilation windows in the time period of interest
   a. Select all orbit arcs for the satellite which fall entirely within an assimilation window centered on time t_k
   b. Generate an ensemble of modeled effective densities based on randomly selected Ap values
   c. Compute covariance and Kalman gain
   d. Estimate the optimal Ap values for the assimilation window
3. Advance assimilation window by $t_{advance}$
4. Combine Ap solutions from overlapping windows by a weighted average of all solutions available for a certain time
5. Run MSIS for the tuned F10.7 from step 1 and the Ap solutions from step 3



Solari DA Algorithm





Satellites processed in Inversion Tool

Name	**Kosmos 807**	**Kosmos 660**	**Kosmos 1508**	**Explorer VII**	**Venus Lander**	**LEASAT 2 PKM**
NORAD ID	8744	07337	14483	00022	06073	15244
AMR	0.005	0.005	0.005	0.011	0.002	0.01522
Min/Max Altitude [km]	370/1139	383/1134	399/1442	490/661	209/1661	179/7698
Eccentricity	0.05	0.05	0.07	0.01	0.10	0.36
Inclination [deg]	83	83	83	50	52	27
Median EDR time-range [**days**]	1.5	1.5	1.5	2.1	1.6	1.9
Median EDR frequency [**hours**]	1.7	1.7	1.7	1.8	1.8	2.7