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Ensemble Assimilation Using First-Principles Models
A Tool for Three-Day Space Weather Forecasts

CEDAR, 2015

Thursday, June 25th, 2015

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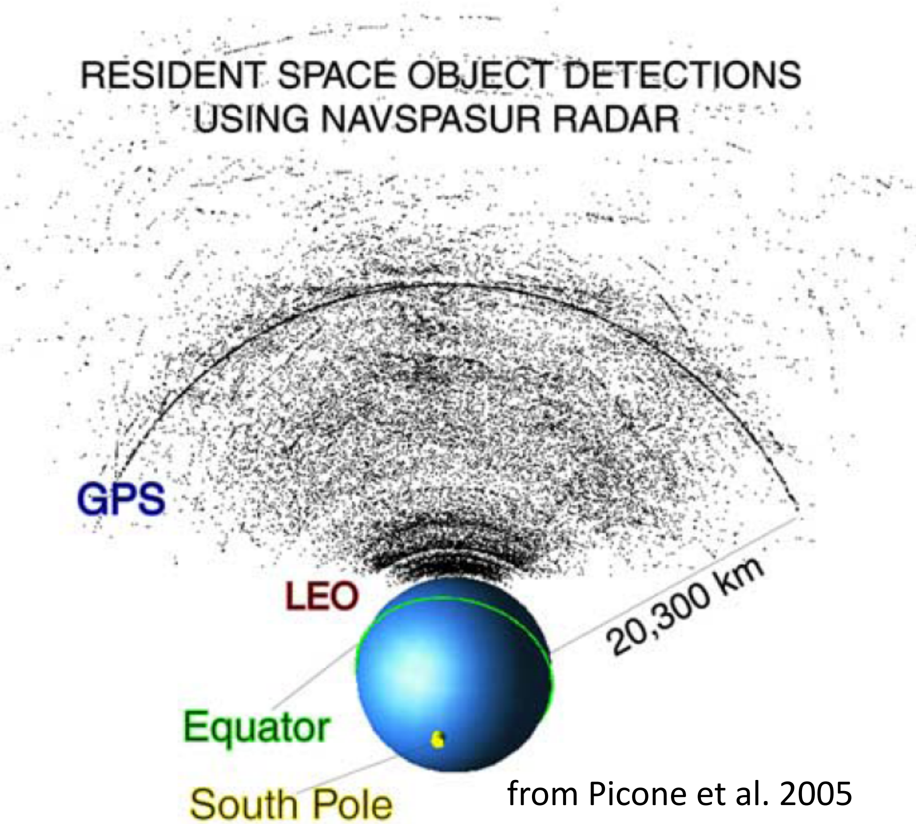
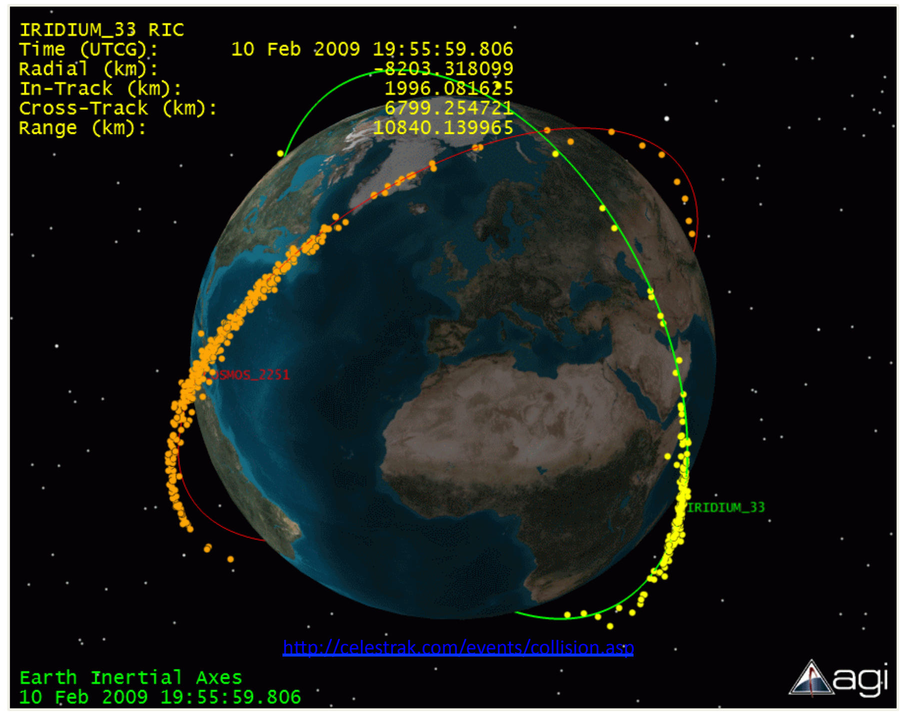
Motivation for Neutral Density and Satellite Drag Specification

Satellite drag errors degrade capability to:

- Maintain accurate catalog of all space objects
- Predict and avoid space collisions
- Predict satellite reentry time & location



from Picone et al. 2005



Altitude Regimes of Satellite Drag

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❖ Technology
❖ Applications
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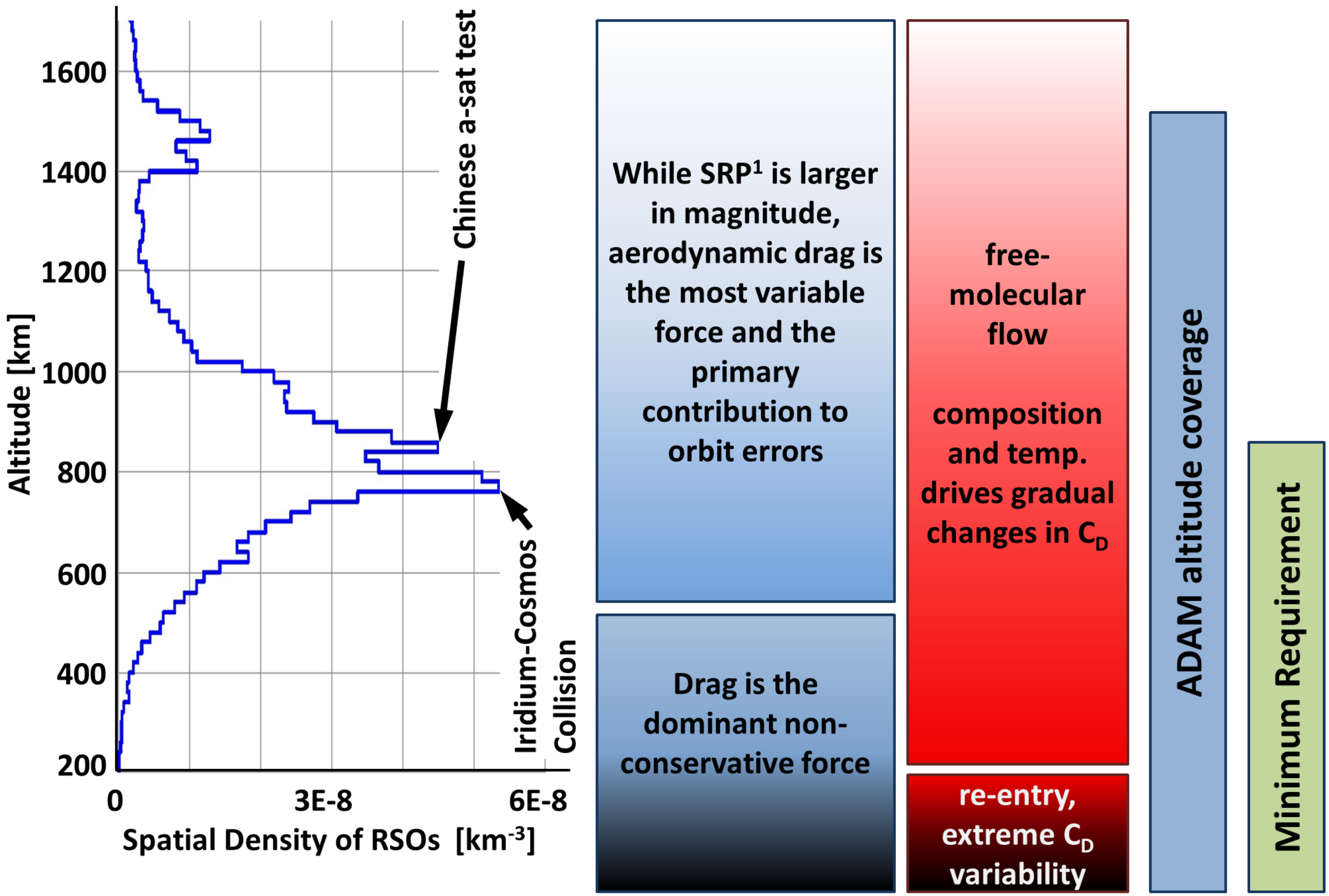
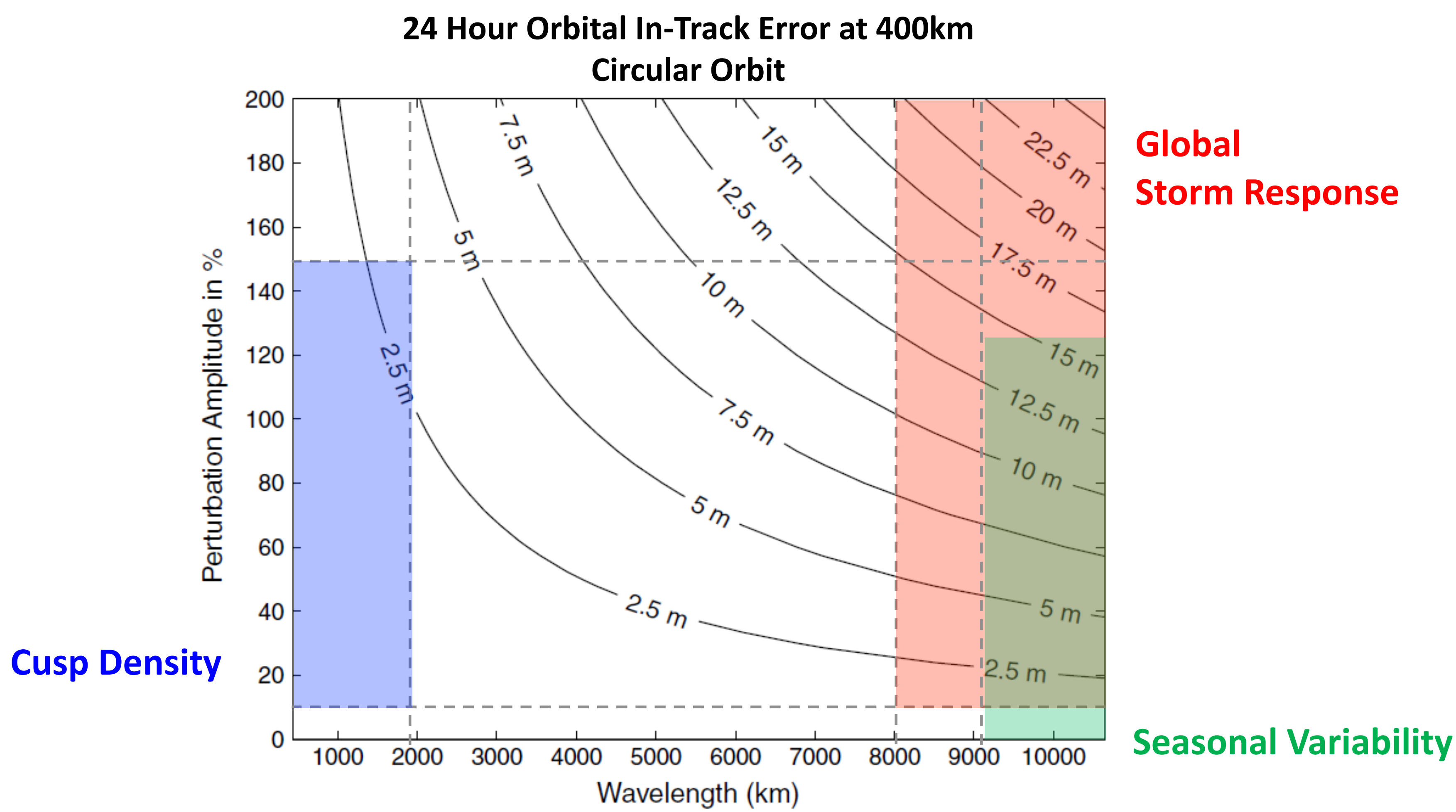


What physical processes are important?



[Anderson et al. 2009]

Summary of Goals

Develop an ensemble assimilative neutral density model

- AF requirement for better satellite drag specification and forecast: improve specification beyond JB08 and HASDM
- Provide a modeling tool that outperforms current AF capabilities
- Consists of ensemble of world-class first-principles well-validated IT models
- Assimilative

Overview

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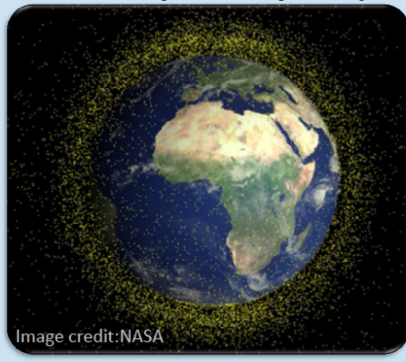
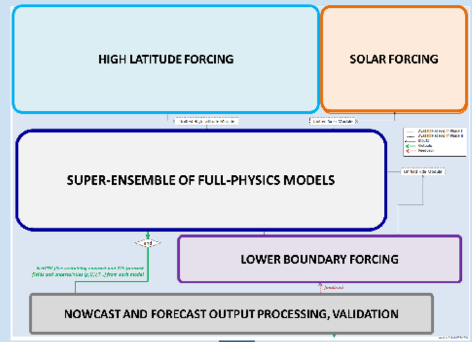
Resident Space Objects (LEO)



satellite drag and density observations

- ***Orbit observations***
- *GPS*
- *Accelerometers*
- *O/N_2*
- *Mass Spectrometer*

ADAM Architecture



orbital analysis

Atmospheric
Density
Assimilation
Model

conjunction analysis

Super-Ensemble Approach

Image credit: TerraMetrics, Google

Output information feeds into existing orbit prediction and determination tools

Results

- Improved satellite orbit nowcast and 72h forecast
  - Improvements over HASDM and JB08
  - Up to three-fold improvement during storms and solar minimum
- Densities, winds, and composition outputs
- Covers altitudes from 30 km to 1500 km
- Improved performance during geomagnetic storms

ADAM top level design

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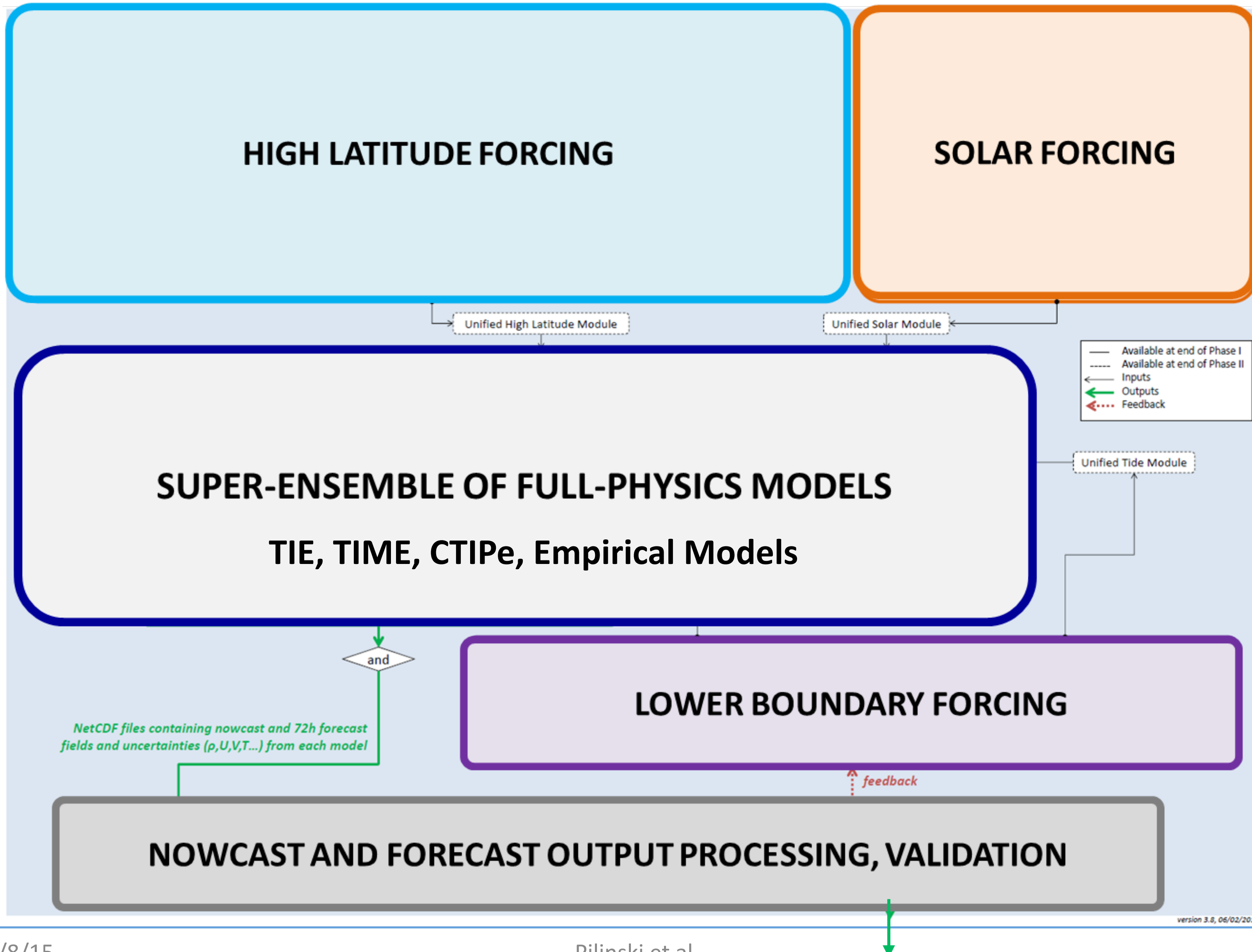

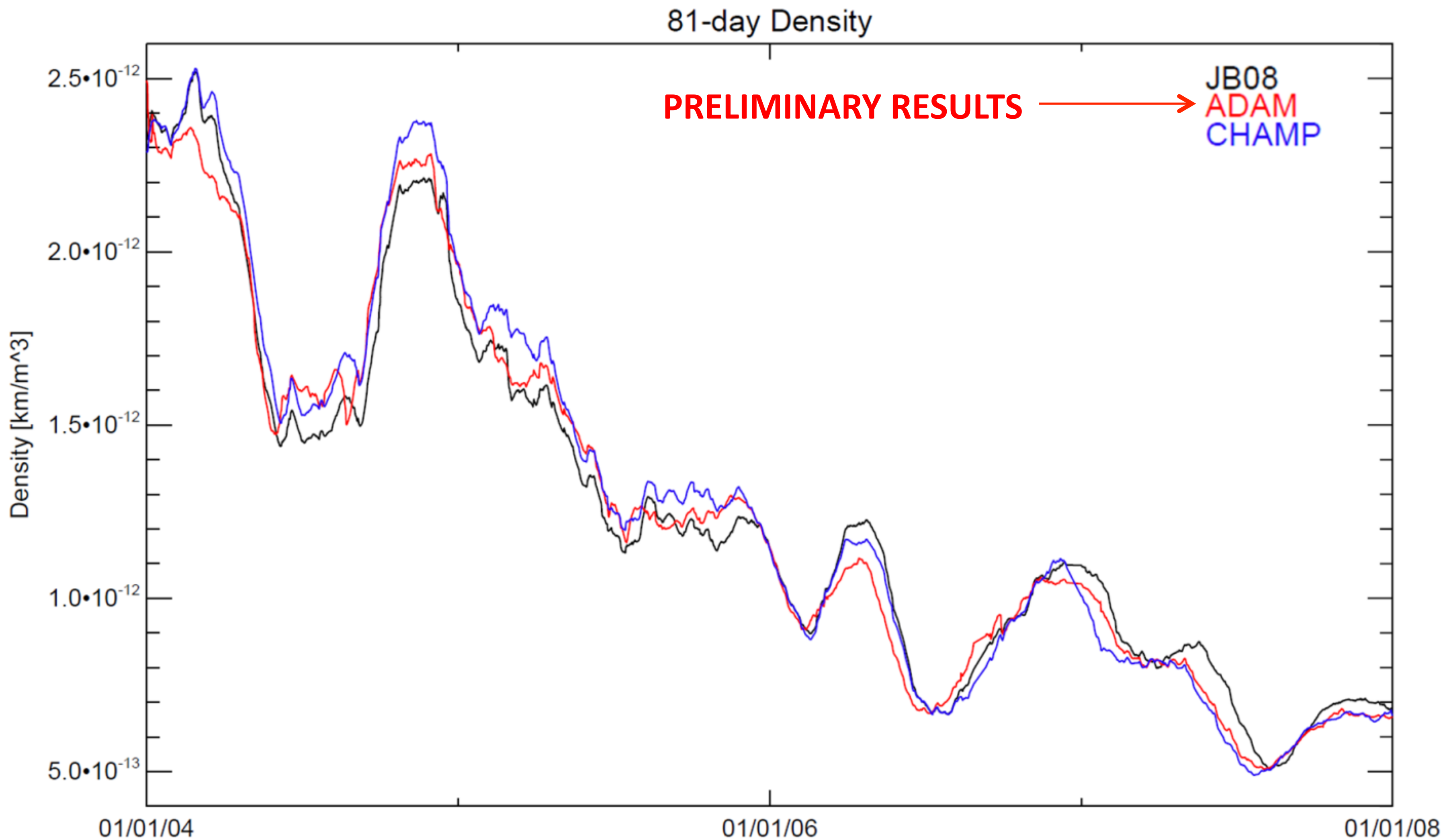

JB08 and CHAMP densities compared with best performing model in super-ensemble of full-physics members

Options for additional inputs

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Assimilated Data Types

Data Type	Assimilation Time Span	Notes
Orbit Average Drag i.e. Calspheres, DANDE, POPACS	6-72 h	Infer observed energy dissipation rate (EDR) from general perturbations (TLEs) or special perturbations (high task tracking data). Select 30-90 objects with stable ballistic coefficients.
HASDM Densities	6h	EDR is inferred from HASDM density outputs
Orbit Average Densities	24 hours	Already processed high-task tracking data
Orbit Resolved Drag: GPS	15-30 min	Observed EDR from special perturbations and GPS measurements
Orbit Resolved Drag: accelerometers (Swarm)	15 min	Observed acceleration at 10-45 sec cadence (in-track and cross-track), binned to 15 min
O/N2 (GOLD)	30 min	Dayside disk composition
Mass Spectrometer	10-30 sec	In-situ day and night composition

Test-data coverage

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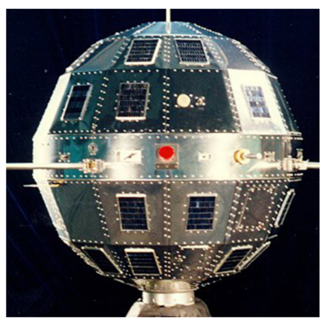
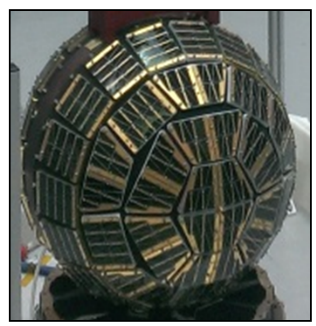
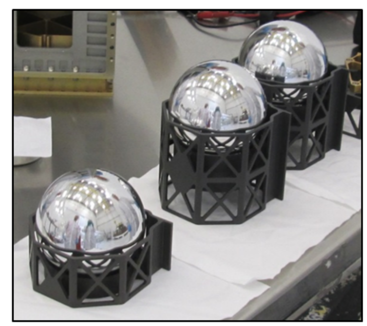
	min alt [km]:	190	250	300	400	500	600	700
	max alt [km]:	250	300	400	500	600	700	900
Inclination ranges [deg]	20-30	1		4				
	30-40	1	1	1		2		
	40-50		1					
	50-60	1			1			
	60-70				1			
	70-80			2				2
	80-100	1	1	14	2	2		1
	SUM:	4	3	21	4	4	0	3


VANGUARD II


DFH-I


DANDE


POPACS 1, 2, 3


RIGIDSPHERE 2

Assimilation

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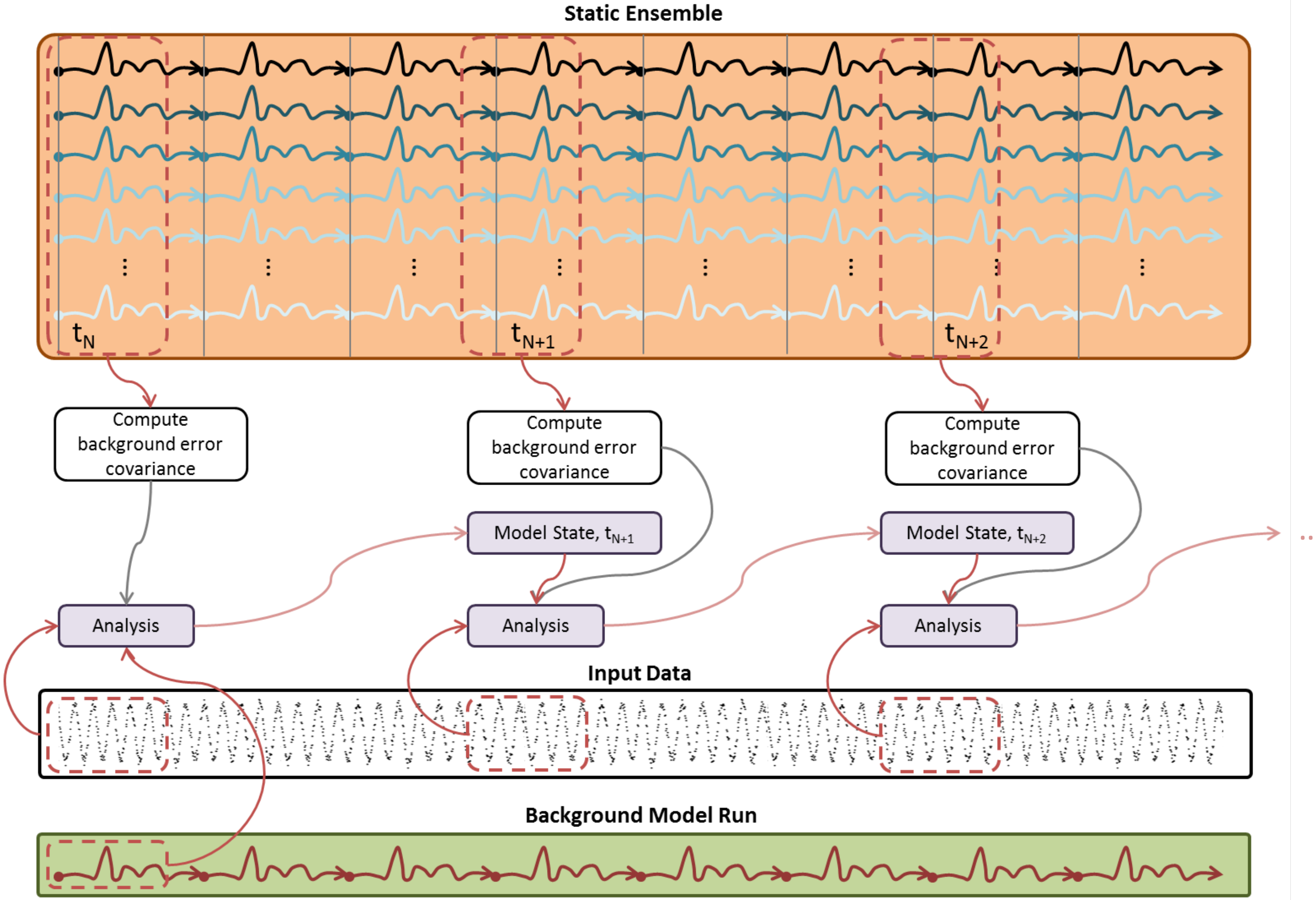

Storm response modeling 8/24/2005

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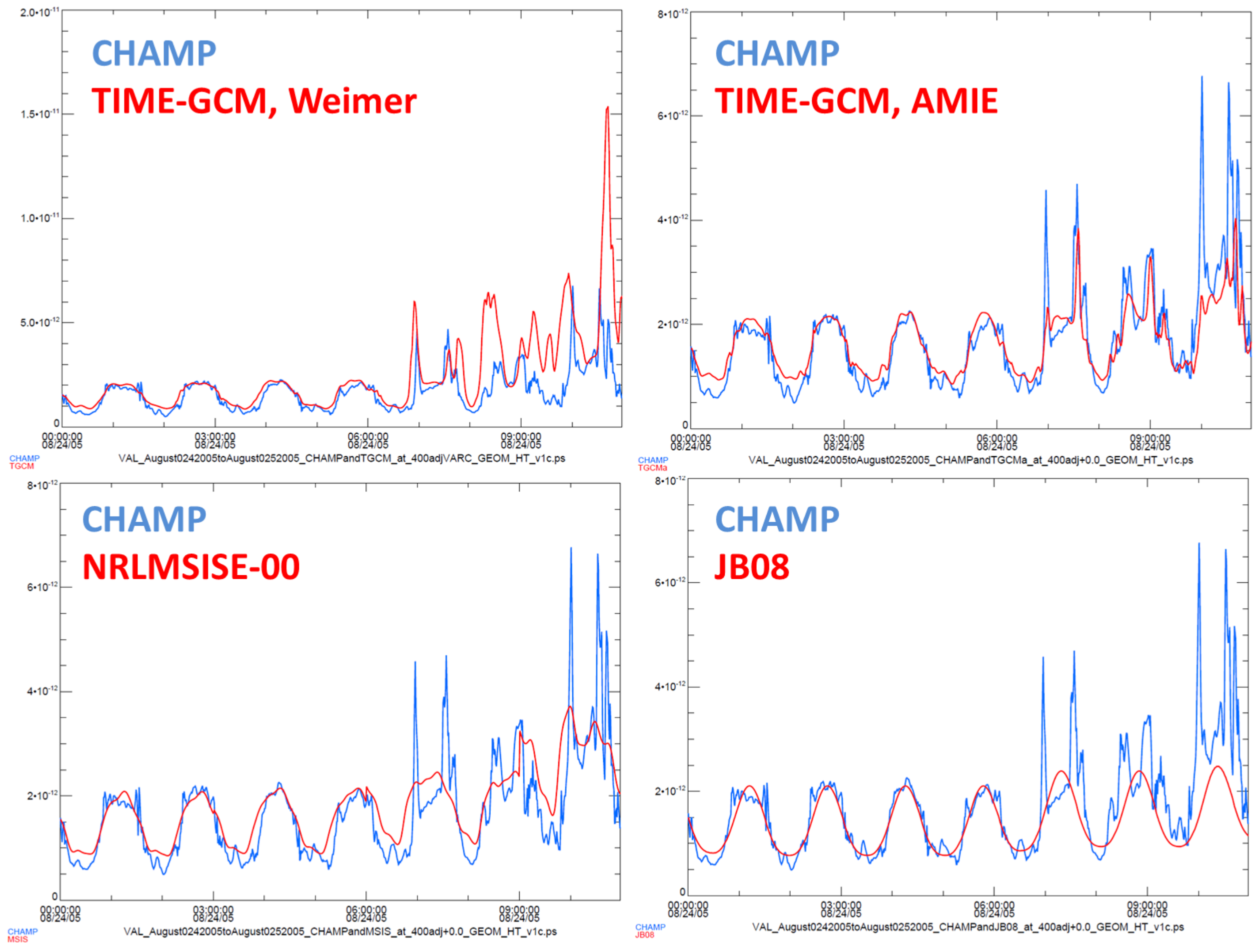
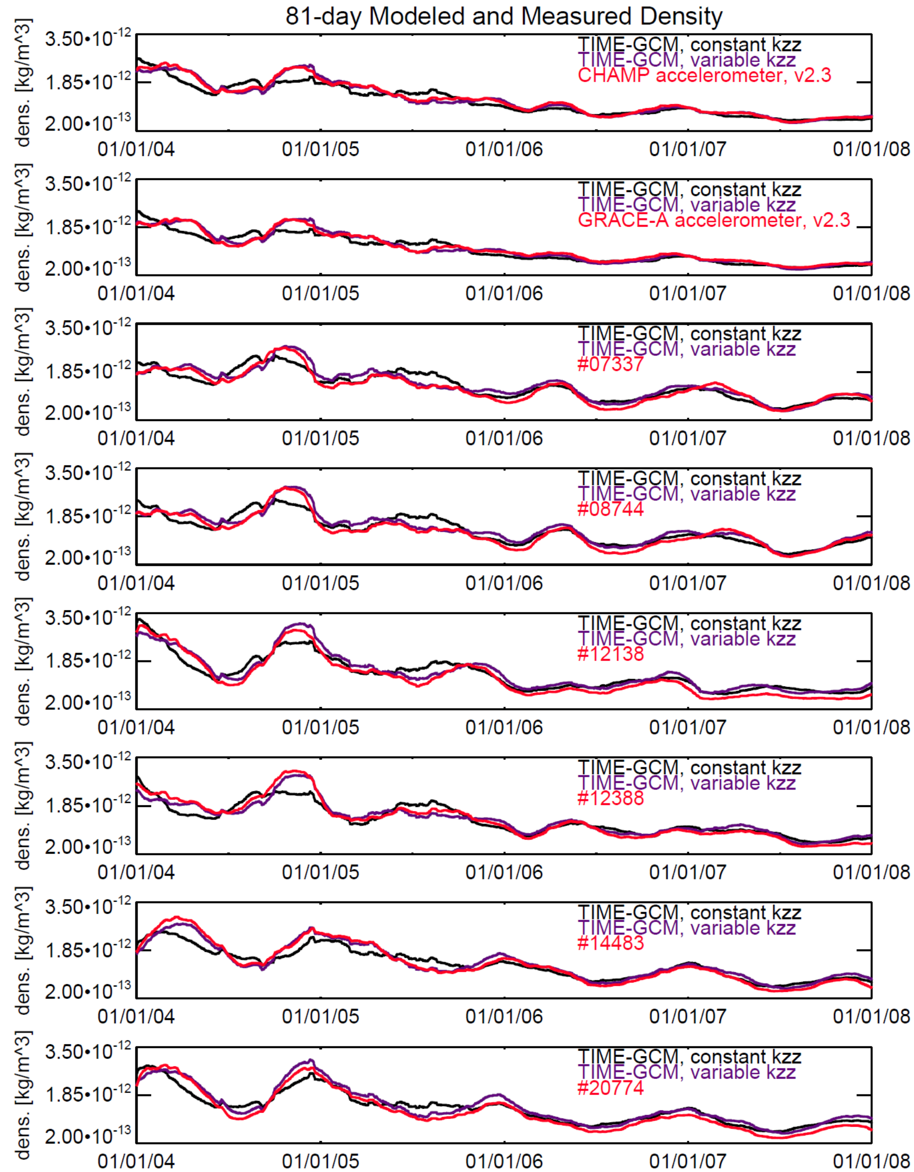


Time-series of model and measured densities along the CHAMP satellite track. Various models are represented above showing the improvement in the representation of high latitude density features when using AMIE. It is also seen that TIME-GCM with AMIE outperforms the empirical models.

Lower boundary parameter assimilation: 2004 to 2007



[Pilinski and Crowley, 2015]

March 17th 2015 Storm Results

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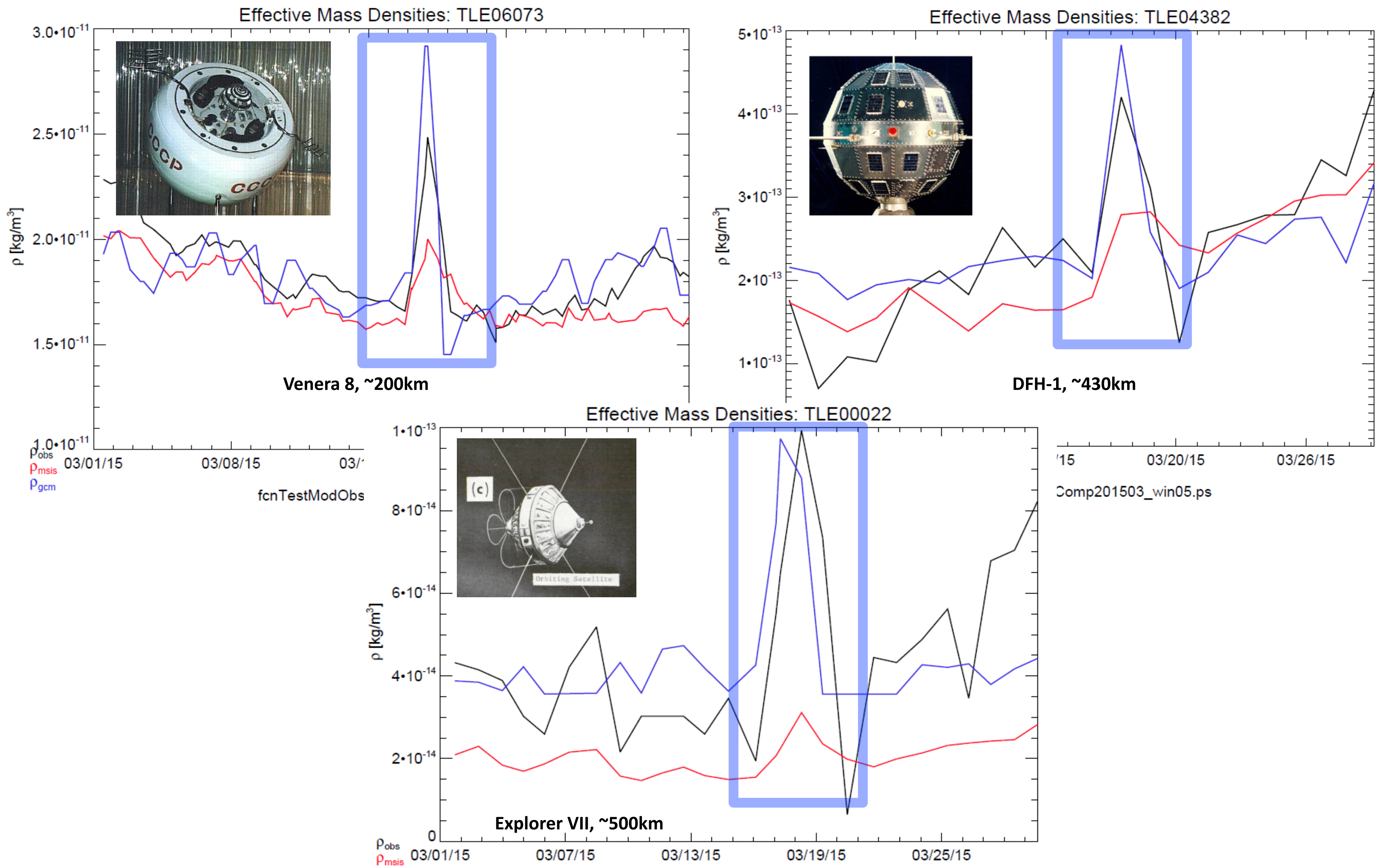


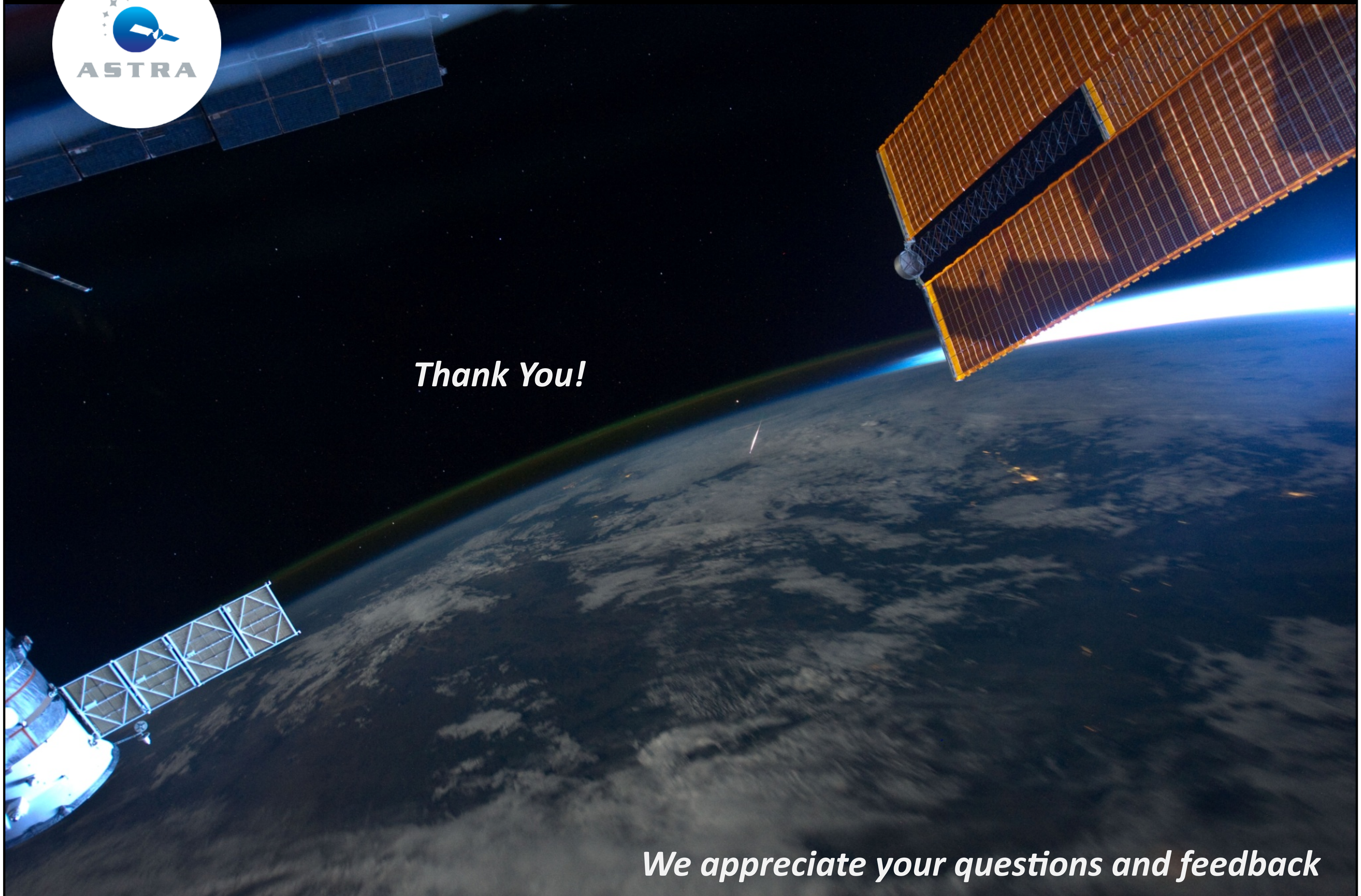
Conclusion

- New state-of-the-art assimilative model of the atmosphere is being developed to include many of the lessons learned from NADIR MURI

- Improve over operational drag-specification models

- Includes altitudes up to and above 1000km

- Future plans to make outputs commercially available to civilian customers


Thank You!
We appreciate your questions and feedback

Design Features

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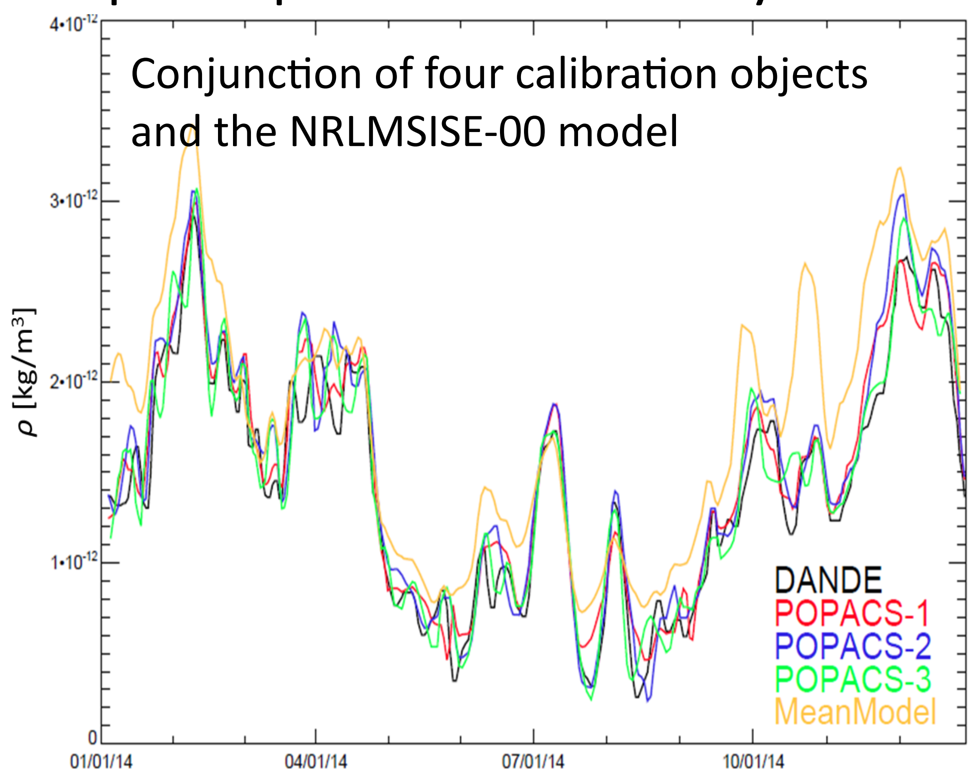
- Dynamically tuned models result in optimum background atmospheric state
- Multiple model (super-ensemble) approach allows for graceful degradation in case of input-stream or model interruption
- Inclusion of TIME-GCM allows for specification of densities in the re-entry regime, down to 30km
- Inclusion of Helium in several models allows for drag computation up to 1000km

- TLE's are being used as a stand in for orbital arcs analysis
  - Cadence and arc length is a conservative stand-in for the special-perturbations approach available operationally to the customer
  - Transition to 6-hour arcs from special perturbations analysis in Phase III
- TLE's provide some of the same sampling characteristics and measurement parameters as the special-perturbations approach
- Drawbacks
  - Lower signal-to-noise
  - Latency (~1 day)



Requirements

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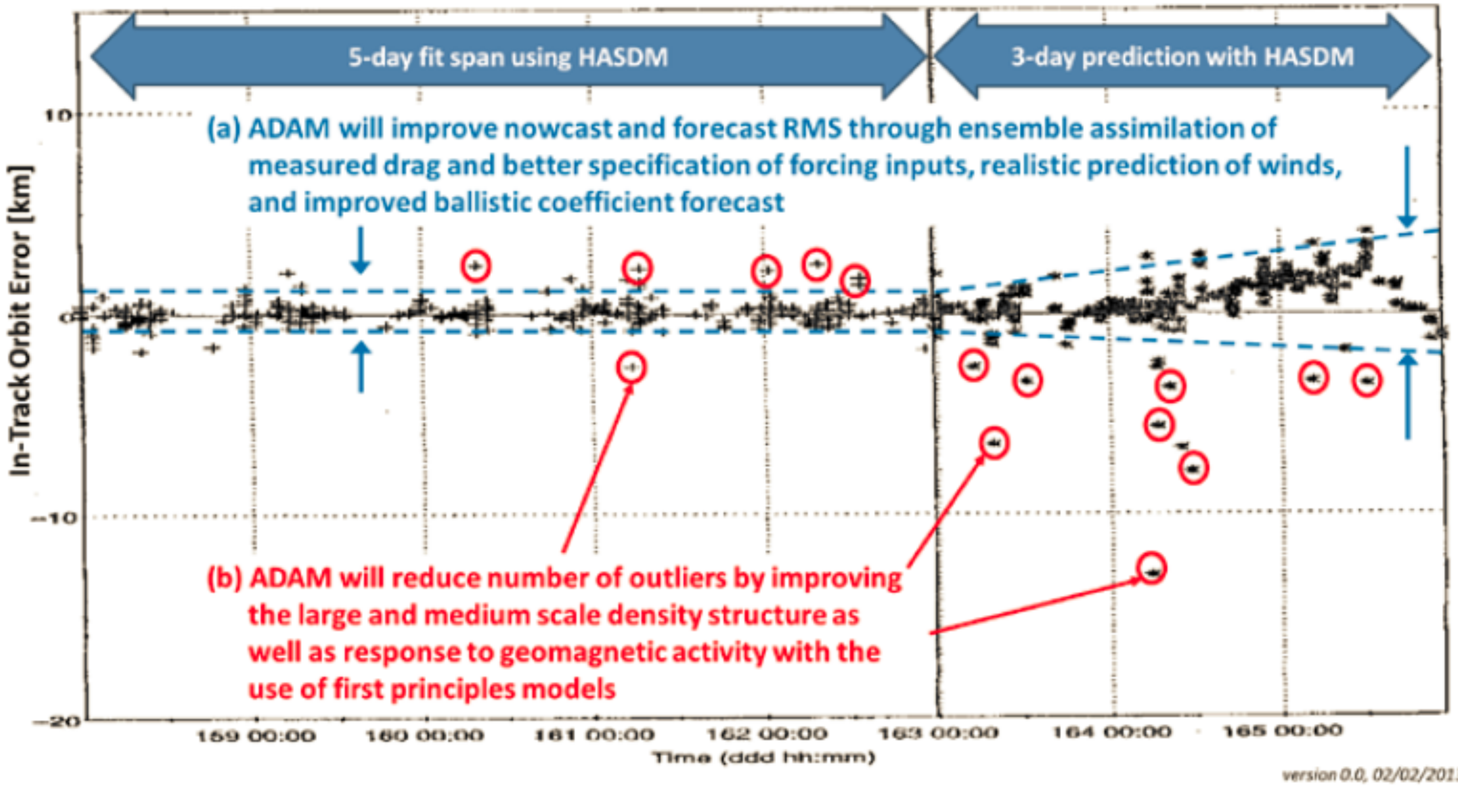

	Requirement	Goal
Nowcast	RMSE lower than JB08 more than half the time for storm time and quiet conditions 250 to 1000km. *JB08: 7-18% at 200-800km*	RMSE better than HASDM more than half the time for storm time and quiet conditions 30-1000km *HASDM: 6-10% at 200-800km*
72h Forecast	RMSE lower than JB08 in forecast mode	RMSE better than HASDM in forecast mode

Phase I Accomplishments: storm response

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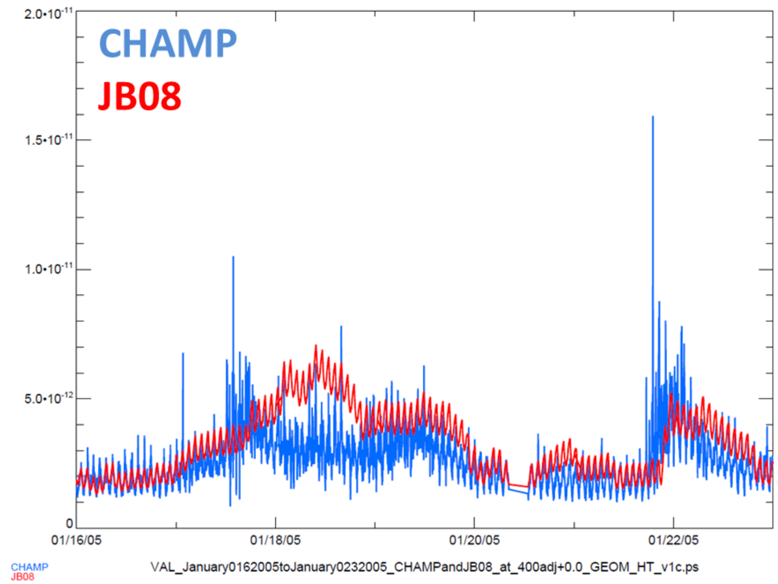
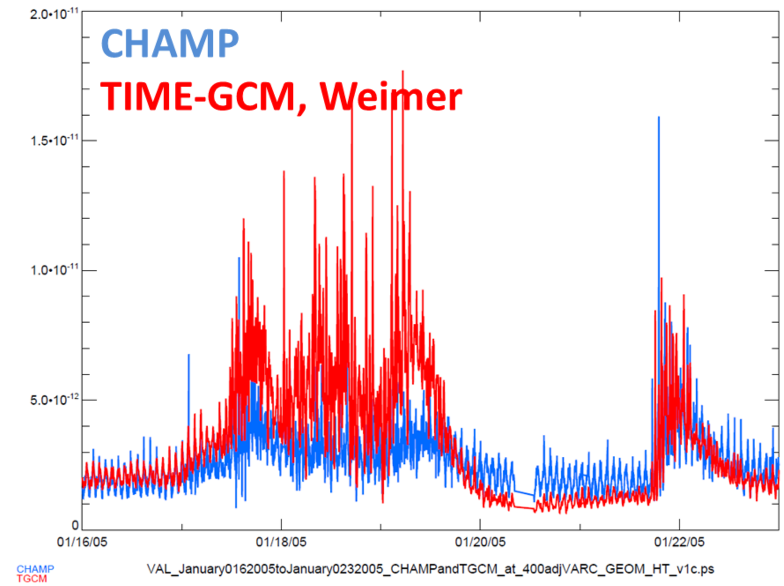
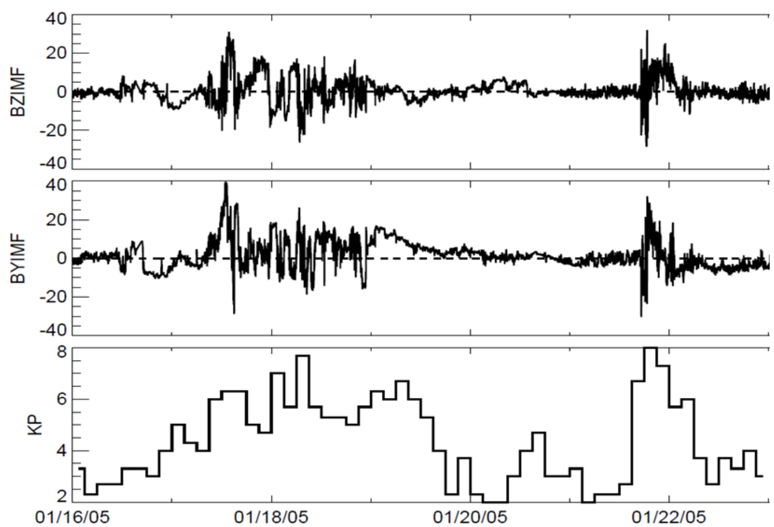
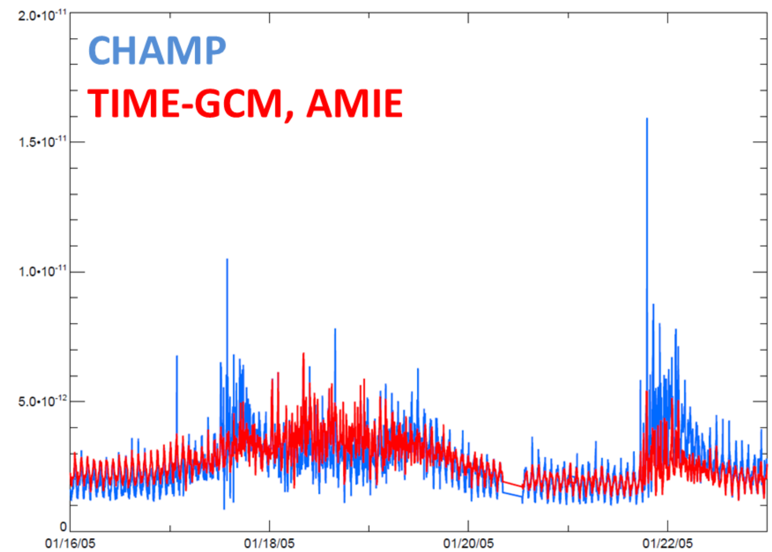
AMIE and Weimer driven TIME-GCM compared with JB08 and CHAMP densities for two storms in January 2005.









Phase I Accomplishments: seasonal effects and tuning

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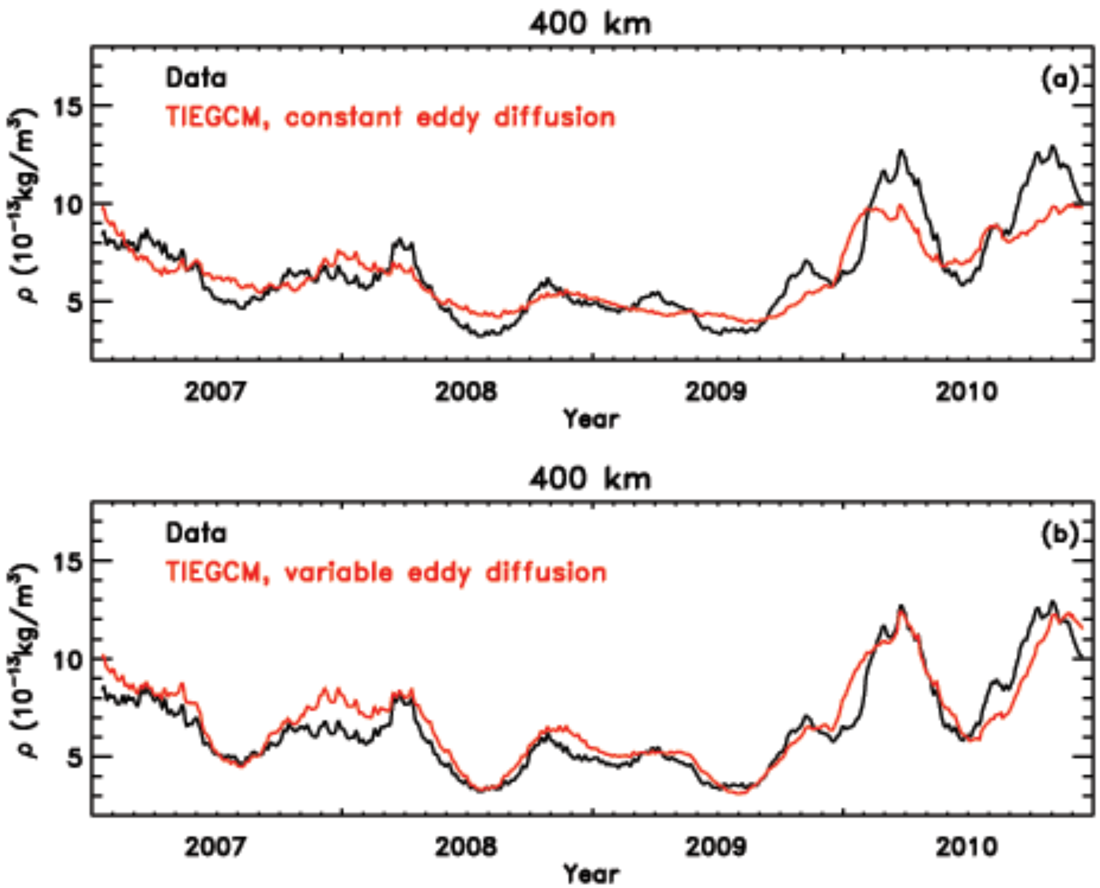

Model-data comparisons of global-mean neutral density at 400 km. Black: neutral density derived from drag data of more than 5000 orbiting objects [Emmert, 2009]; Red: TIE-GCM simulated neutral density. (a): model-data comparisons when the default constant eddy diffusion was imposed at the model lower boundary; (b): model-data comparisons when the variable eddy diffusion was imposed at the model lower boundary.

What is Satellite Drag?

Relative importance of various scales

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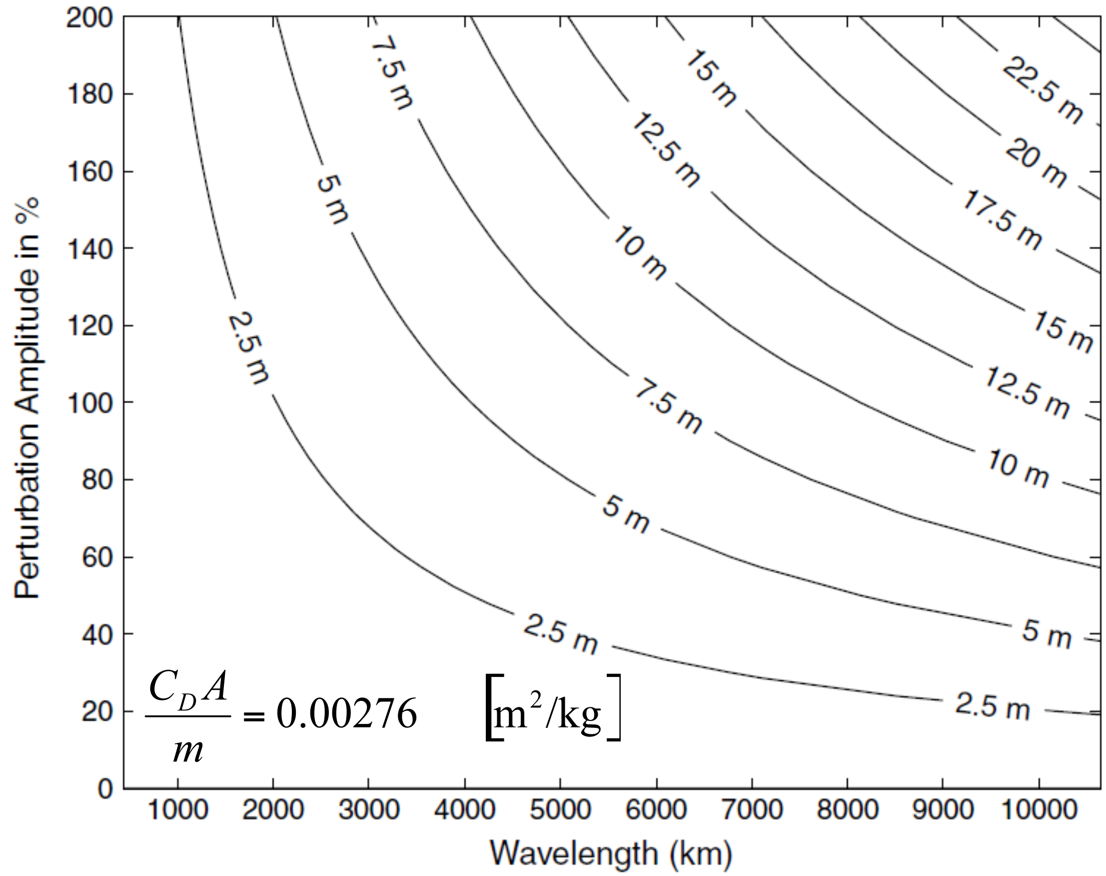
- Large scale perturbations can be misrepresented in empirical models
- It takes long-wavelength perturbations to cause significant position errors
- 3U sun-pointing CubeSat
  $$\frac{C_D A}{m} \approx 0.02 \qquad \left[\mathrm{m}^2/\mathrm{kg}\right]$$
- 100m errors are considered "significant" by USAF at 400 km altitude [Anderson et al. 2008]

24 Hour Orbital In-Track Error at 400km Circular Orbit



[Anderson et al. 2009]

Lower Boundary Forcing

(Dynamic Tuning) – to backup

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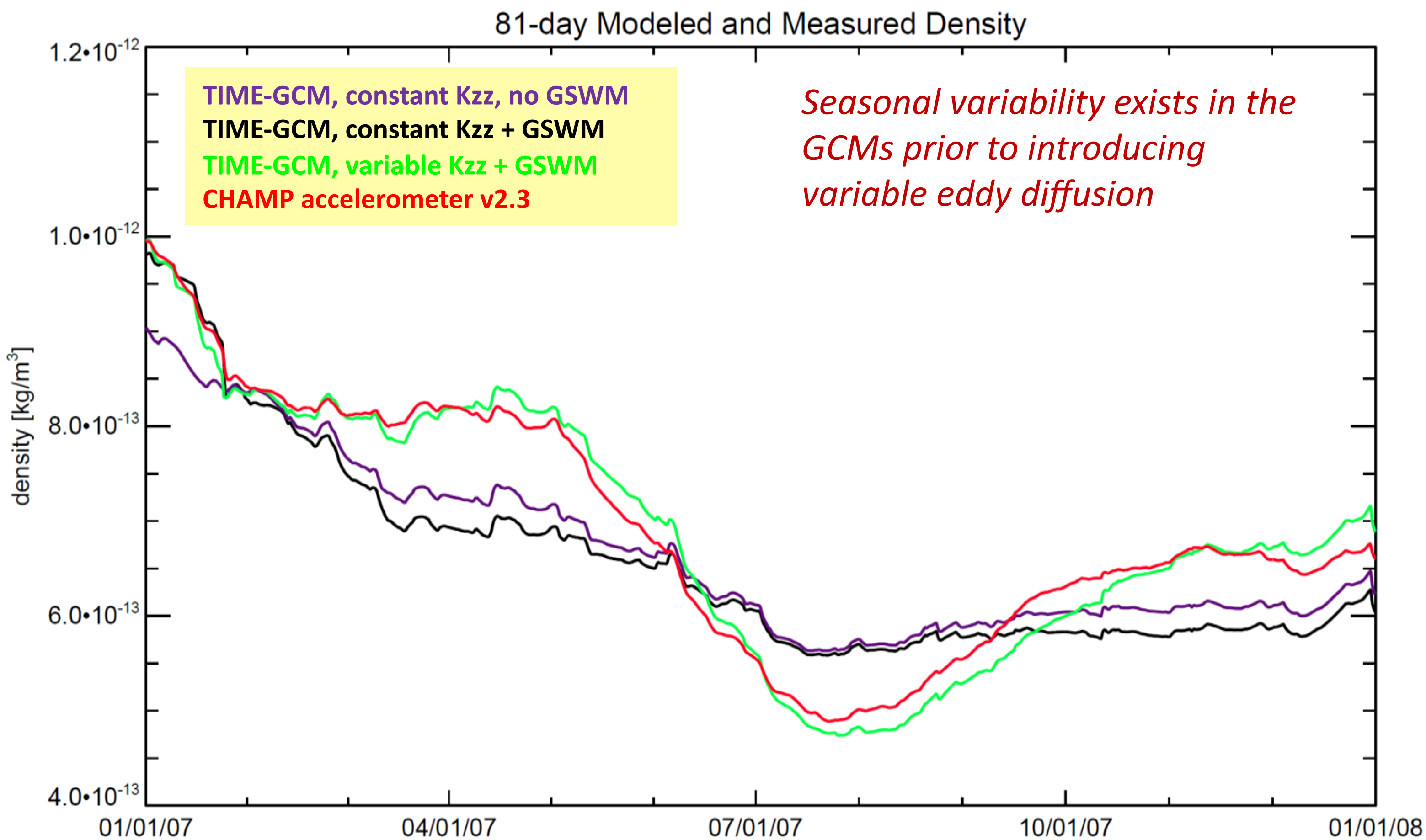
- **Example of dynamically tuned eddy diffusion coefficient**
- **Our approach combines dynamic calibration/tuning with assimilation**



Pilinski and Crowley, 2015

Ensemble-Member Real-time Architecture

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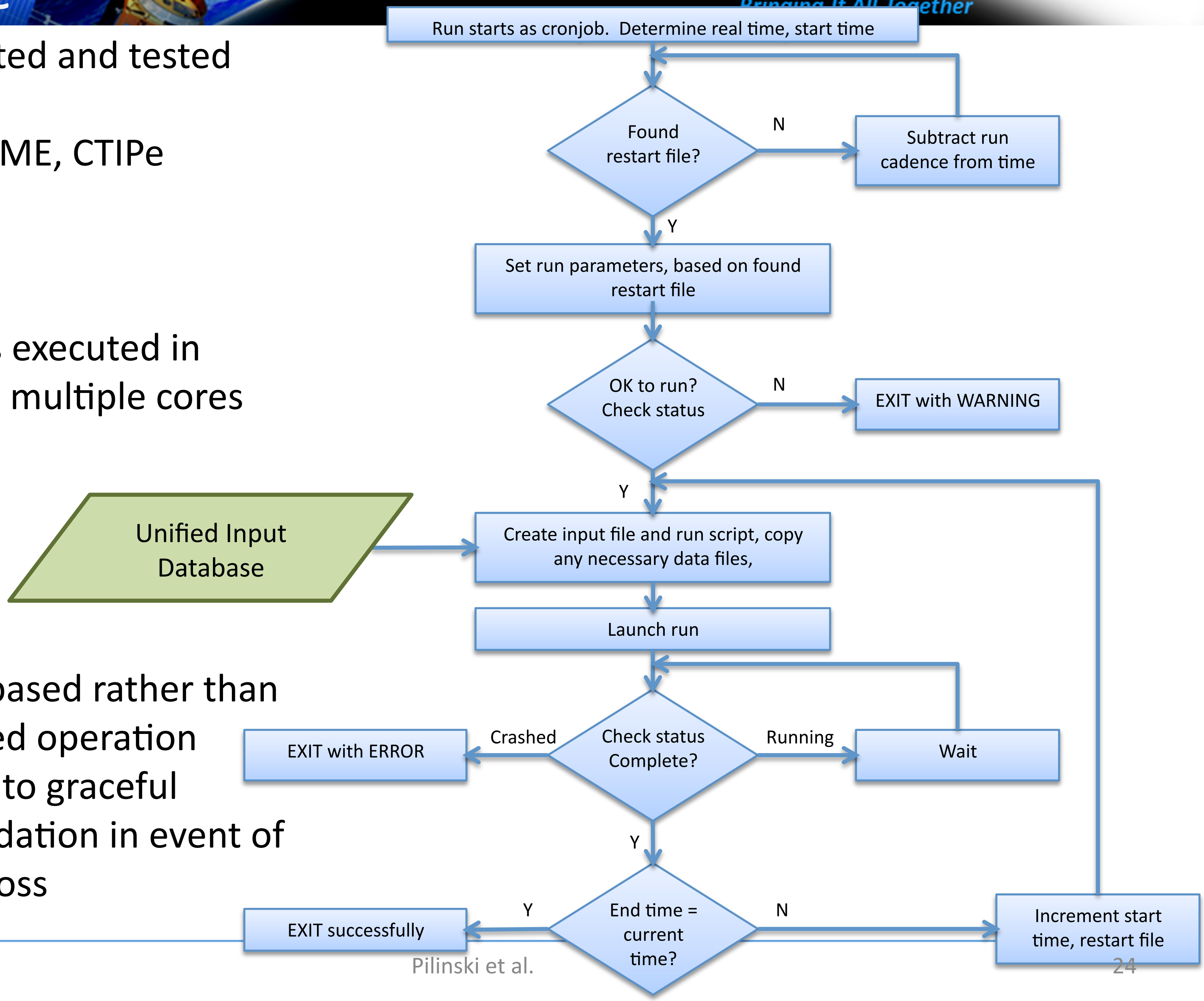
- Implemented and tested with:
  - TIE, TIME, CTIPe
- Ensembles executed in parallel on multiple cores
- Schedule based rather than event based operation
  - Leads to graceful degradation in event of data-loss



Realtime Ensemble Tests

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