Bridging High-Fidelity Modeling and Operations with Reduced-Order Thermospheric Data Assimilation

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Introduction

Motivation

- Thermospheric density uncertainty drives large errors in LEO orbit prediction
- Accurate, low-latency density estimates are essential for space operations
- See Poster 4 in this session by Nijanthan Vasudevan

Variability & Forcing

- Dominant forcing from solar EUV irradiance causes order-of-magnitude density changes over the solar cycle, additional variability occurs on diurnal, seasonal, and geomagnetic storms
- Even small density errors accumulate rapidly in low Earth orbit propagation

Modeling Gap & Deep Learning efforts

- Empirical models lack event-scale responsiveness
- Physics-based models are accurate but too expensive for real-time use[2]
- See Poster 6 in this session by Immanuel Ulinfun

Reduced-Order Modeling

- ROMs capture dominant thermospheric variability in a low-dimensional space[3]
- Enable fast propagation while retaining key physical structure **(10000x speedup)**
- See Poster 7 & 10 in this session by Nathaniel Michek & Harshitha Challa

Data-Driven Dynamics

- Linear (DMDc) and sparse nonlinear basis (SINDyc) models capture forced dynamics[1]
- Autoregressive terms incorporate memory and state–driver interactions
- See Poster 8 in this session by Daniele Sicoli

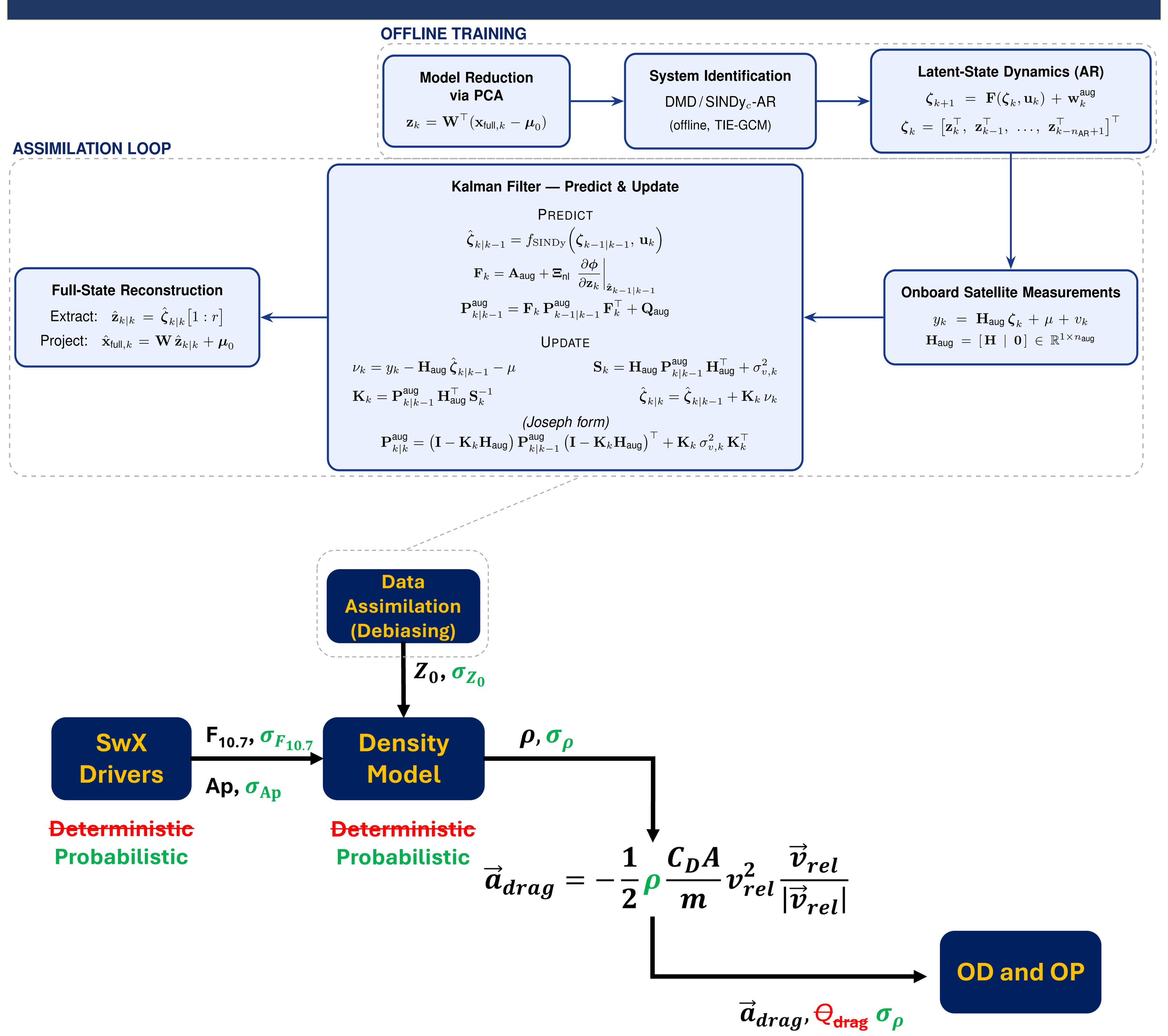
Data Assimilation

- Kalman filtering combines ROM dynamics with sparse in-situ density data[4]

This Work

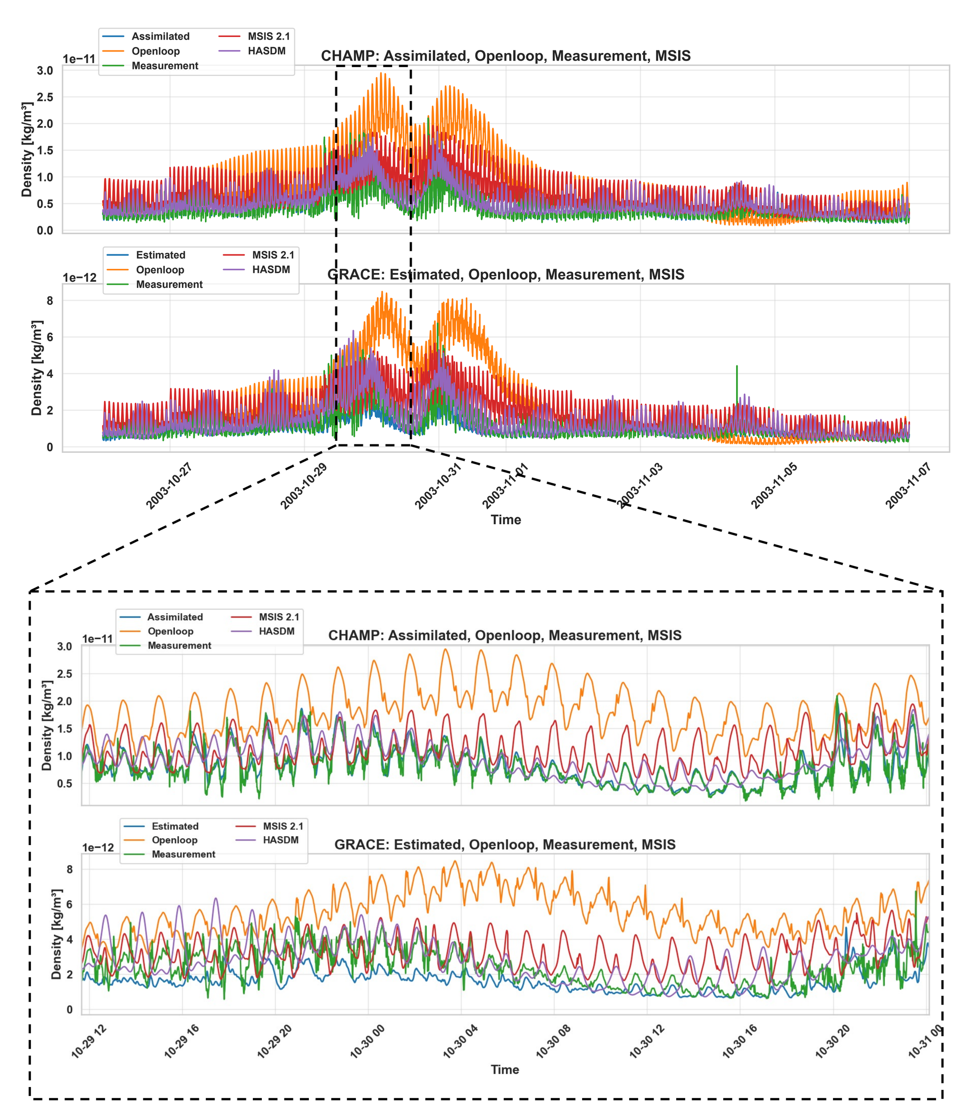
- Combines interpretable ROMs with multi-satellite density assimilation
- Validated across quiet and disturbed geomagnetic conditions
- Improved density estimates and released 2000–2025 assimilated dataset

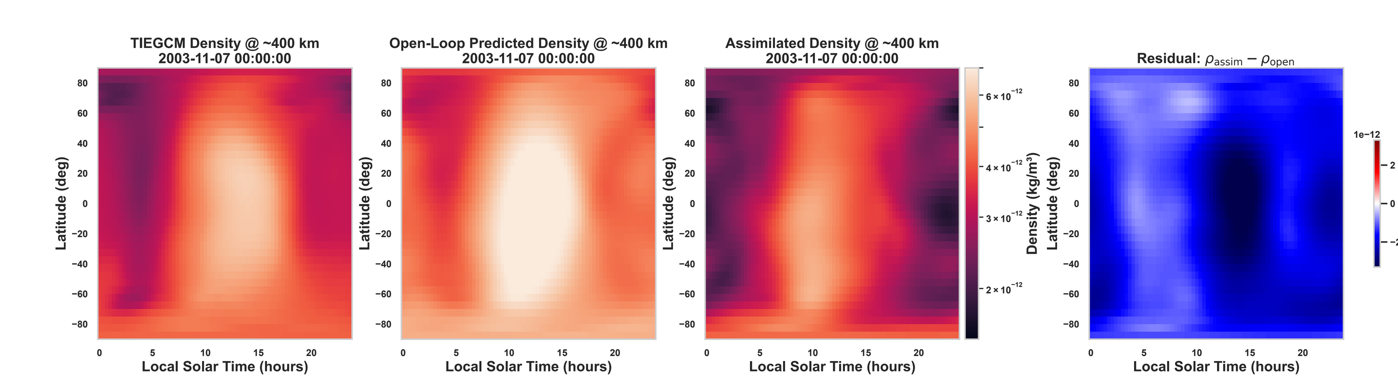
Assimilation Framework

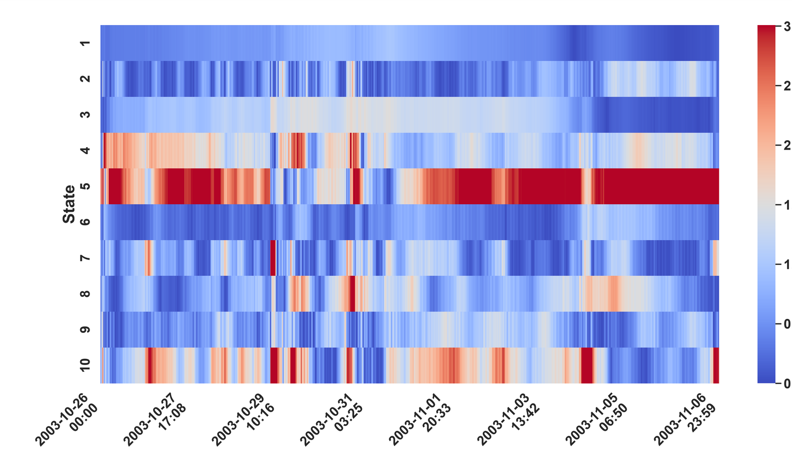


Applications

Single-Satellite Assimilation: Halloween Storm

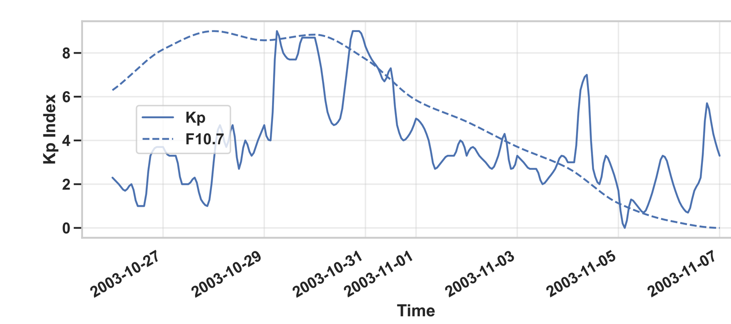






Orbital Parameters for Measurement Satellites

Mission	Operational period	Alt. range (km)	Inc. (deg)	Ecc.	Period (min)
CHAMP	2000-07 – 2010-09	456 – 250	87.18	0.004	93.6
GRACE	2002-03 – 2017-10	500 – 330	89.00	0.0025	94.5
GRACE-FO	2018-05 – present	490 – 475	89.00	0.002	94.0
GOCE	2009-03 – 2013-11	255 – 224	96.70	0.001	88.4
Swarm-A	2013-11 – present	462 – 430	87.35	0.001	93.7
Swarm-B	2013-11 – present	511 – 505	87.75	0.001	94.9
Swarm-C	2013-11 – present	462 – 430	87.35	0.001	93.7



$$\mathrm{MAPE} = \frac{100}{N}\sum_{k=1}^{N}\left|\frac{\hat\rho_k - \rho_k^{\mathrm{meas}}}{\rho_k^{\mathrm{meas}}}\right|$$

All Assimilation Scenarios Considered

Scenario	Orbit	Role	SINDy$_c$-AR	DMDc	Open-loop	MSIS	HASDM
Single-satellite — 2003 Halloween storm							
CHAMP to GRACE	CHAMP	A	9.24	6.07	85.92	49.00	36.74
	GRACE	V	22.08	40.09	98.80	58.72	51.78
Single-satellite — 2024 geomagnetic storm							
GRACE-FO to Swarm-C	GRACE-FO	A	8.73	12.44	94.79	58.46	—
	Swarm-C	V	51.65	43.71	94.04	57.37	—
November 2009 — single-satellite baseline							
CHAMP to GOCE	CHAMP	A	6.40	11.72	59.94	24.54	40.70
	GOCE	V	29.98	92.92	73.88	15.67	31.80
November 2009 — dual-satellite							
CHAMP + GRACE to GOCE	CHAMP	A	5.12	18.75	59.94	24.54	40.70
	GRACE	A	6.19	12.18	44.96	29.20	48.29
	GOCE	V	24.54	67.12	73.88	15.67	31.80
November 2009 — multi-satellite (three satellites)							
CHAMP + GRACE + GOCE	CHAMP	A	10.57	8.46	59.94	24.54	40.70
	GRACE	A	13.03	10.78	44.96	29.20	48.29
	GOCE	A	3.47	4.61	73.88	15.67	31.80

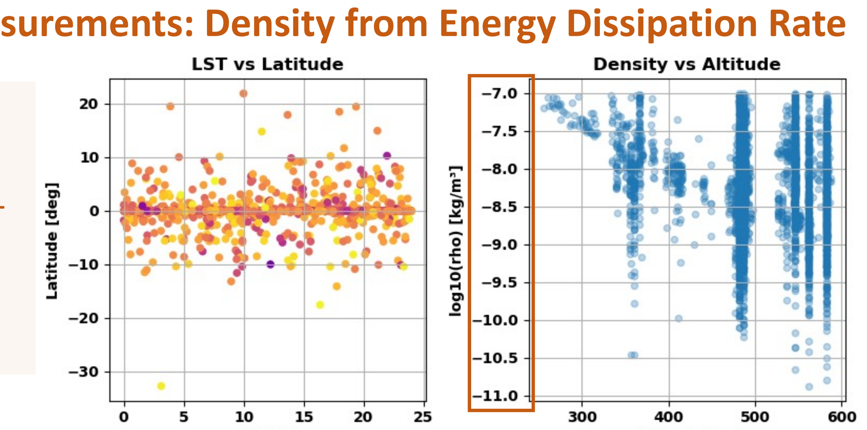
- CHAMP density measurements are assimilated during the Oct–Nov 2003 Halloween storm; GRACE is withheld for validation
- Validation against GRACE shows improved cross-orbit performance
- Outperforms open-loop ROM, NRLMSIS 2.1 and HASDM
- Better than driver estimation as this allows to correct global state
- Directly be used for optimization work, generating long-term dataset, retraining of models

Long-Term Assimilated Density Dataset

- Spanning Aug 2000–Dec 2025. Release(TBD)
- Generated in approximately 5hrs possible due to ROM speedup

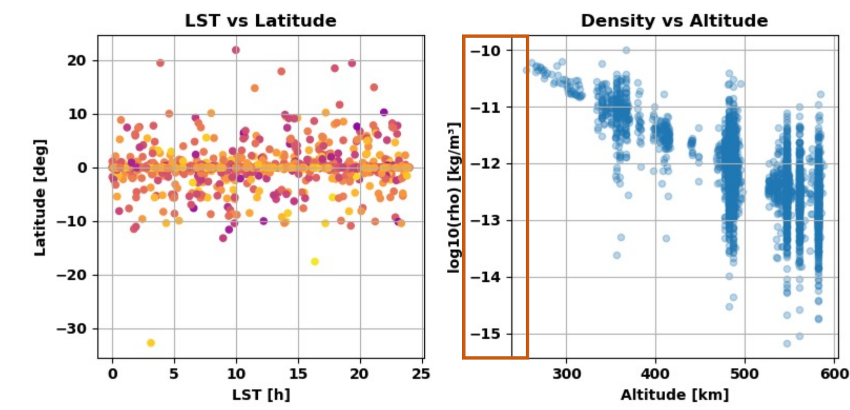
TLEs as measurements: Density from Energy Dissipation Rate

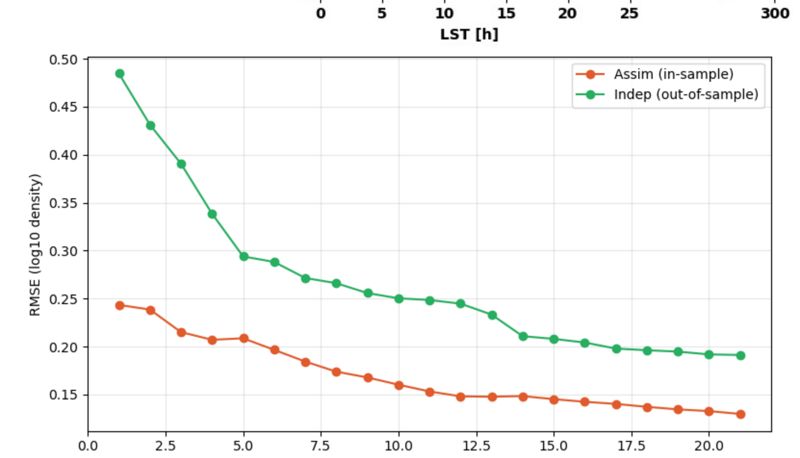
Scenario: 500 Starlink satellites, one-week propagation horizon.



Slope present but scale incorrect

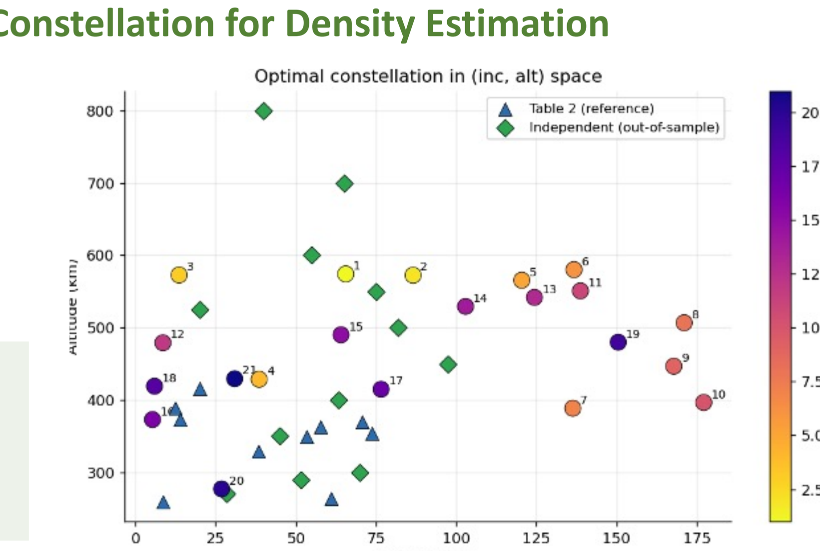
If calibrated against MSIS



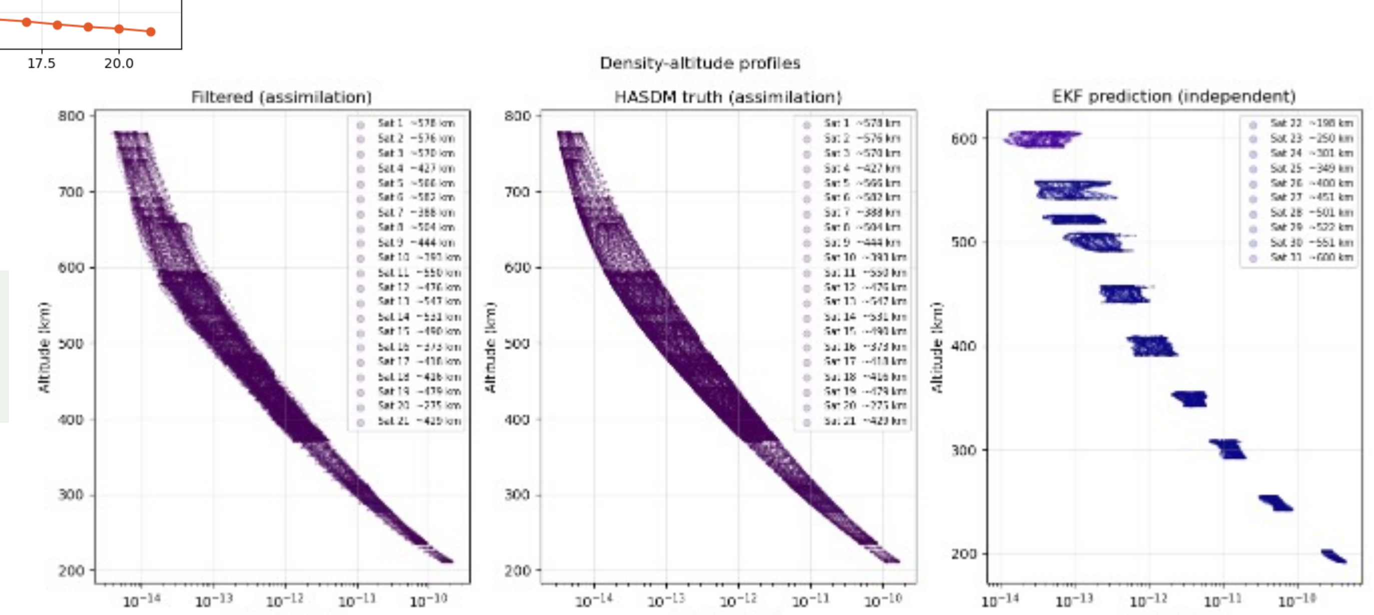


Constellation vs Table 2[5] (prior work) vs Independent set

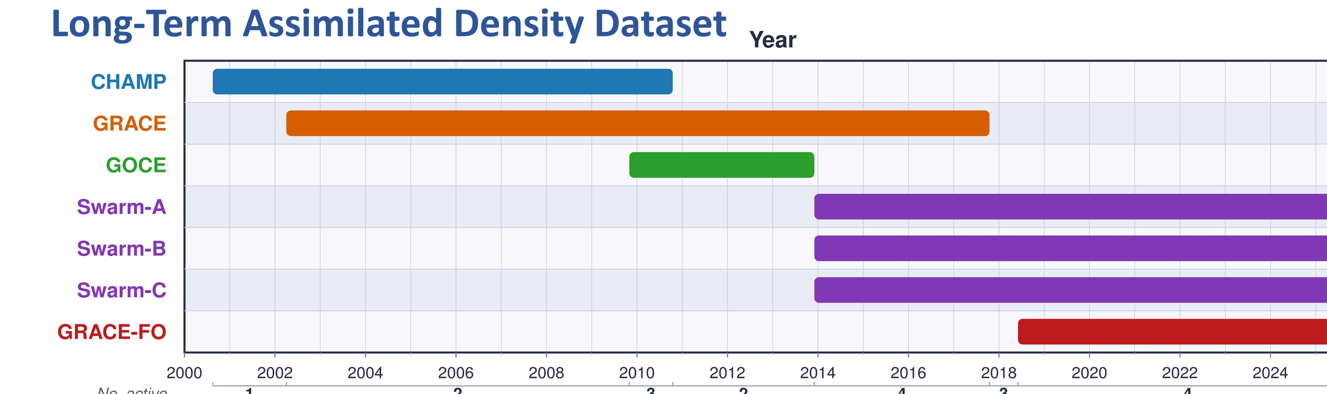
Constellation for Density Estimation



Assimilate constellation and validate against independent orbits



Long-Term Assimilated Density Dataset



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ACKNOWLEDGMENTS

This research is based upon work support in part by the Office of the Director of National Intelligence (ODNI), Intelligence Advance Research Projects Activity (IARPA), via 2023–23060200005. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing official policies, either expressed or implied, of ODNI, IARPA, or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for governmental purposes not withstanding any copyright annotation therein'. This work is also supported in part by the University of Colorado Boulder(OSC via CU CIRES).

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