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Assimilative Specification of Neutral Density in Low Earth Orbit

Stefan Codrescu • ssmmcc1@gmail.com • Vector Space LLC

INTRODUCTION

Accurate Neutral Density (ND) specification is critical for orbit prediction in Low Earth Orbit due to the impact of ND on satellite trajectory through drag. Data assimilation in a physics based model combines the predictive strength of physics based models with an anchor in reality through observational data. We assimilate different combinations of ND measurements from CHAMP and GRACE satellites during a large geomagnetic storm to demonstrate that assimilating data from even a single accelerometer results in improved global specification. During the 2003 Halloween storm, orbit maximum ND increases by a factor of 2.5x within several hours. Along track ND specification during this extreme event is better than 27% NRMSD in all experimental setups.

1/ What is Data Assimilation?

Data Assimilation (DA) is a technique to correct model results using observations of the real system. There are various forms of DA. We use the Ensemble Kalman Filter.

$$\vec{X}^f_{t+1} = f(\vec{X}^a_t)$$ model forecast step

$$\vec{X}^a_{t+1} = \vec{X}^f_{t+1} + K(y - h(\vec{X}^f_{t+1}))$$ analysis step (correct forecast)

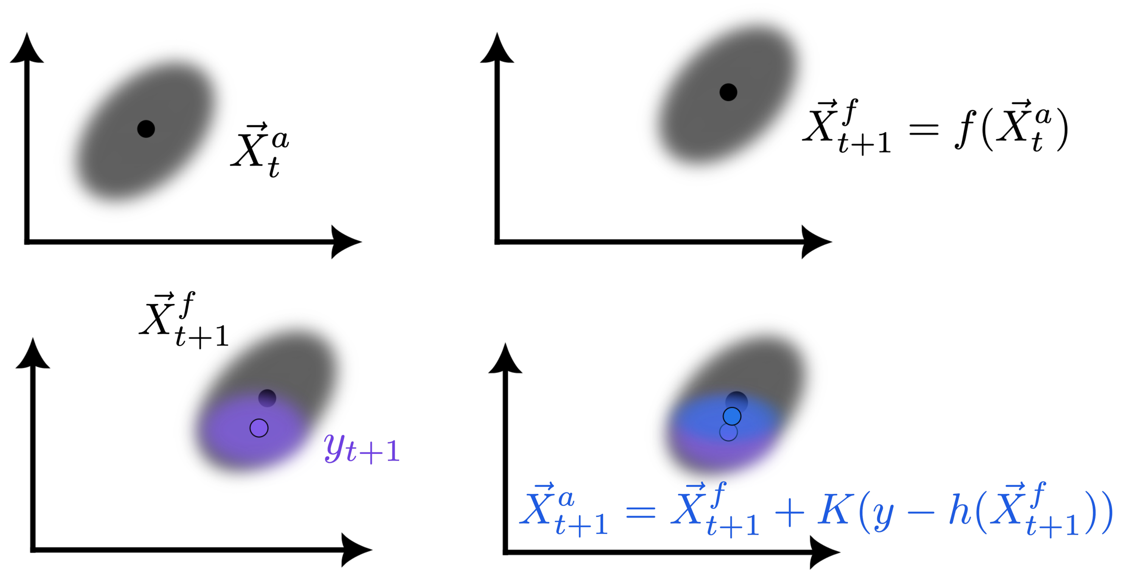
where

$\vec{X}_t$ is the model state, at time t

f is the model itself, here CTIPe.

y are measurements

h is the measurement operator, gives the measurement as specified by the model



DATA ASSIMILATION in the Thermosphere-Ionosphere

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OVERVIEW

- Data assimilation is a *technique* to correct model results using measurements.
- The model used: CTIPe -- physics based.
- Assimilation code: TIDA -- Ensemble Kalman Filter.
- Observations assimilated: Neutral Density from CHAMP and GRACE satellites in LEO.
- Results: Improved agreement between model and observed neutral density.

So What?

- Inaccurate neutral density modeling contributed to the loss of 38 SpaceX Starlink satellites in Feb 2022.
- Improved neutral density specification could improve orbit prediction -- ultimately saving resources.

5/ Results

The table below shows Normalized Root Mean Square Deviation (NRMSD) as a percentage for Reference, Forecast, and Analysis over the 2003 Halloween storm: October 26-30, 2003. The Reference performs especially poorly due to missing solar wind forcing measurements.

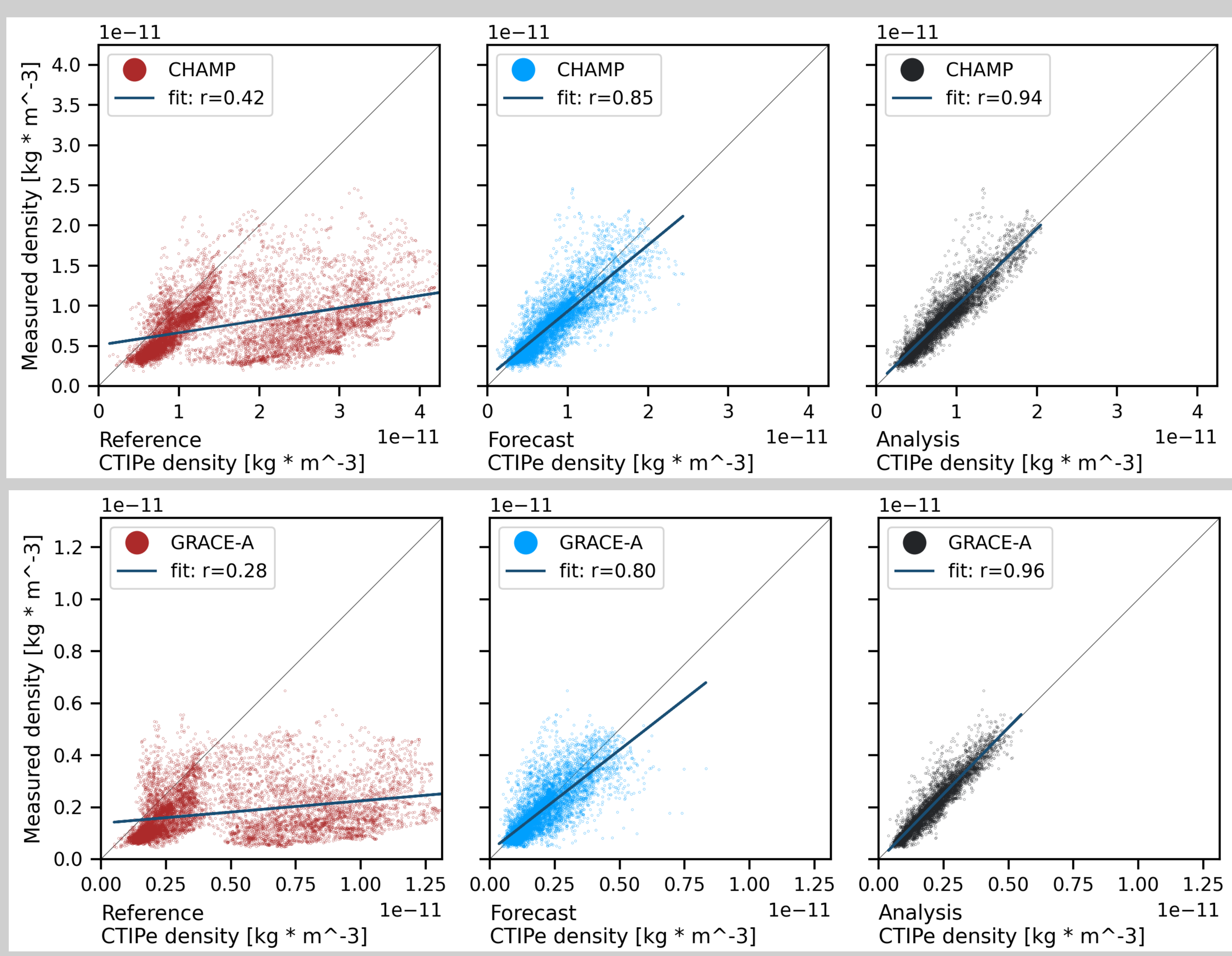
Assimilating data from one satellite and comparing specification at another non-assimilated satellite demonstrates that the correction is global.

In these results:

- **Reference**: is the model without assimilation, (note: missing forcing due to Solar Energetic Particle event)
- **Forecast**: is the model forecast from the pervious corrected state, without corrections from data in forecast period.
- **Analysis**: is the model forecast corrected using observations in the forecast period.

$$\text{NRMSD} = \frac{RMS(model - measurements)}{mean(measurements)}$$

		Datasets assimilated							
		All satellites		Only CHAMP		Only GRACE-A		Only GRACE-B	
Satellite	Reference	Forecast	Analysis	Forecast	Analysis	Forecast	Analysis	Forecast	Analysis
CHAMP	159.47	26.35	16.12	21.98	14.82	22.52	21.33	23.14	21.61
GRACE A	235.82	35.46	15.97	28.32	26.63	29.39	14.75	29.54	15.55
GRACE B	232.84	35.02	15.82	27.96	26.30	29.04	14.80	29.29	15.48



Scatter plots of measurements versus modeled values for CHAMP and GRACE-A from the "All satellites" assimilated scenario. GRACE-B looks virtually the same as GRACE-A.

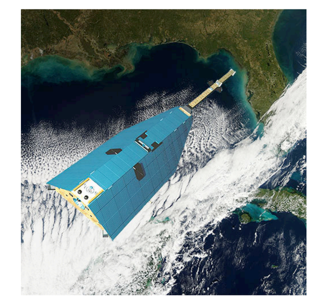
The data assimilation process results in improved agreement between the model and observed data, illustrated by the clustering of points towards the $y = x$ line in the Analysis.

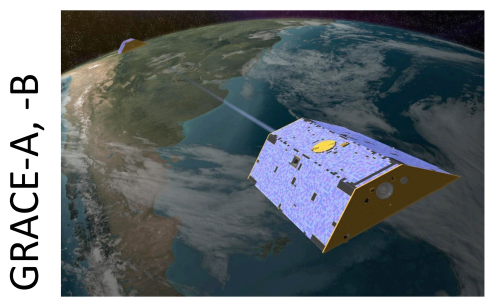
2/ CTIPe and TIDA

CTIPe: the Coupled Thermosphere Ionosphere Plasmasphere with Electrodynamics model. A physics based simulation of the region from ~ 80 to 450km altitude.

TIDA: Thermosphere Ionosphere Data Assimilation code. An opinionated implementation of an Ensemble Kalman Filter, focused currently on CTIPe.

3/ Neutral Density Observations


CHAMP


GRACE-A, -B

Neutral density measurements are derived from accelerometers flown on board CHAMP, GRACE-A, and GRACE-B satellites. In 2003, CHAMP was at ~400km altitude, and GRACE-A & B were at ~480km.

In a simplified sense, neutral density is observed by solving for the drag equation for ρ using the observed acceleration.

$$F = ma \qquad F_D = \frac{1}{2}\rho v^2 C_D A$$

4/ Experimental Setup

For these results, we assimilate various combinations of CHAMP, GRACE-A, and GRACE-B neutral density observations.

- Assimilation time step: 30 minutes
- Ensemble size: 75 members
- No localization
- Kalman State:
  - neutral temperature
  - neutral winds
  - mixing ratios
  - forcing parameters (via state augmentation)

Note: With state augmentation of the forcing parameters, we are able to perform simulation even in the absence of forcing measurements!

CHAMP and GRACE image credit: nasa.gov

Codrescu, M. V., Codrescu, S. M., & Fedrizzi, M. (2022). Storm time neutral density assimilation in the thermosphere ionosphere with TIDA. In Journal of Space Weather and Space Climate (Vol. 12, p. 16). EDP Sciences. https://doi.org/10.1051/swsc/2022011