Data Assimilation of Thermosphere Neutral Densities in WAM

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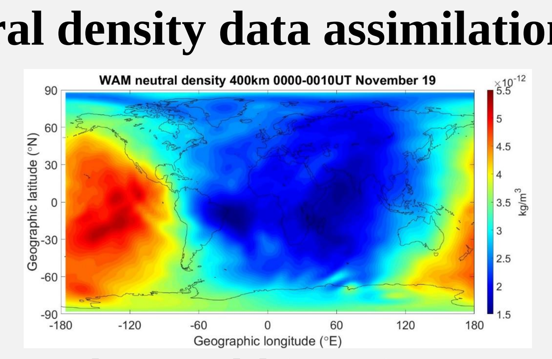
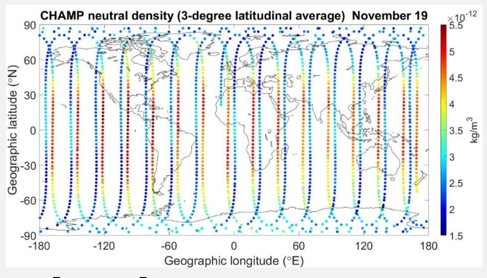
Abstract

The Iterative Driver Estimation and Assimilation (IDEA) data assimilation technique was used with the Whole Atmosphere Model (WAM) to improve neutral density specification in the upper thermosphere. Two different neutral density data sources were used to enhance the capability of simulating the global thermosphere state. The first was the accelerometer estimates of neutral density from the Challenging Mini-Satellite Payload (CHAMP). The second was the neutral density estimates from the Global Ultraviolet Imager (GUVI) limb scan airglow observations aboard the Thermosphere Ionosphere Mesosphere Energy and Dynamics (TIMED) satellite. Due to the intensity of the November 2003 storm, two changes were necessary in WAM. The first was allowing the Kp scale to exceed beyond 9 and the second was changing the relationship between Kp and the solar wind velocity used to drive the WAM model. With these changes, the results showed that IDEA effectively captures the thermospheric neutral density at the CHAMP satellite altitude (i.e. 400 km) and follows the time-dependence through the November 2003 storm period. Furthermore, a cross-compared was conducted with the limb scan measurements obtained by GUVI at various altitudes. In general, GUVI neutral density in the range of 270-320 km show the closest agreement with WAM when CHAMP data was assimilated by IDEA. We speculate on the potential for observations from GUVI at 300 km during the daytime to be used as a data source in the IDEA-WAM simulations. These simulations demonstrate the utility of the IDEA data assimilation technique and that using either accelerometer observations (e.g., CHAMP) or UV airglow limb measurement (e.g., GUVI) during extreme storm periods can equally well be used. The study also demonstrates that physical models with data assimilation can contribute to neutral density specification for enhanced orbit determination and prediction of the low Earth orbit satellites.

Research Objectives

- **Improve the nowcasting capability of physical models (e.g. WAM) in the global thermosphere state in the IDEA data assimilation scheme.**
- **Explore and evaluate potential neutral density data sources for future applications of neutral density data assimilation in WAM**





Whole Atmosphere Model (WAM)

- Extended Global Forecast System (GFS) upper boundary from 64 km to 600 km
- Resolution 2°×2° in latitude-longitude, H/4 in altitude
- Free or forecast runs
- Horizontal & vertical mixing
- Radiative heating (EUV & UV) and cooling
- Ion drag & Joule heating
- Major species composition

CHAMP satellite and accelerometer

- Launch (decay) date: 15 July 2000 (19 September 2010)
- Local time: 12 (descend) / 24 (ascend) LT
- Altitude: 400 km
- Period: 93.55 minutes
- Inclination: 87.18°
- The atmospheric density, ρ, can be obtained from corrected drag acceleration, a_D:

$$a_D = -\frac{1}{2}\rho C_D A_{ref} |\bar{v}|^2$$

where C_D is the coefficient of drag, A_{ref} is the reference area of the satellite, and $\bar{v}$ is the direction of the satellite velocity with respect to the atmosphere

1. WAM neutral density and CHAMP accelerometer

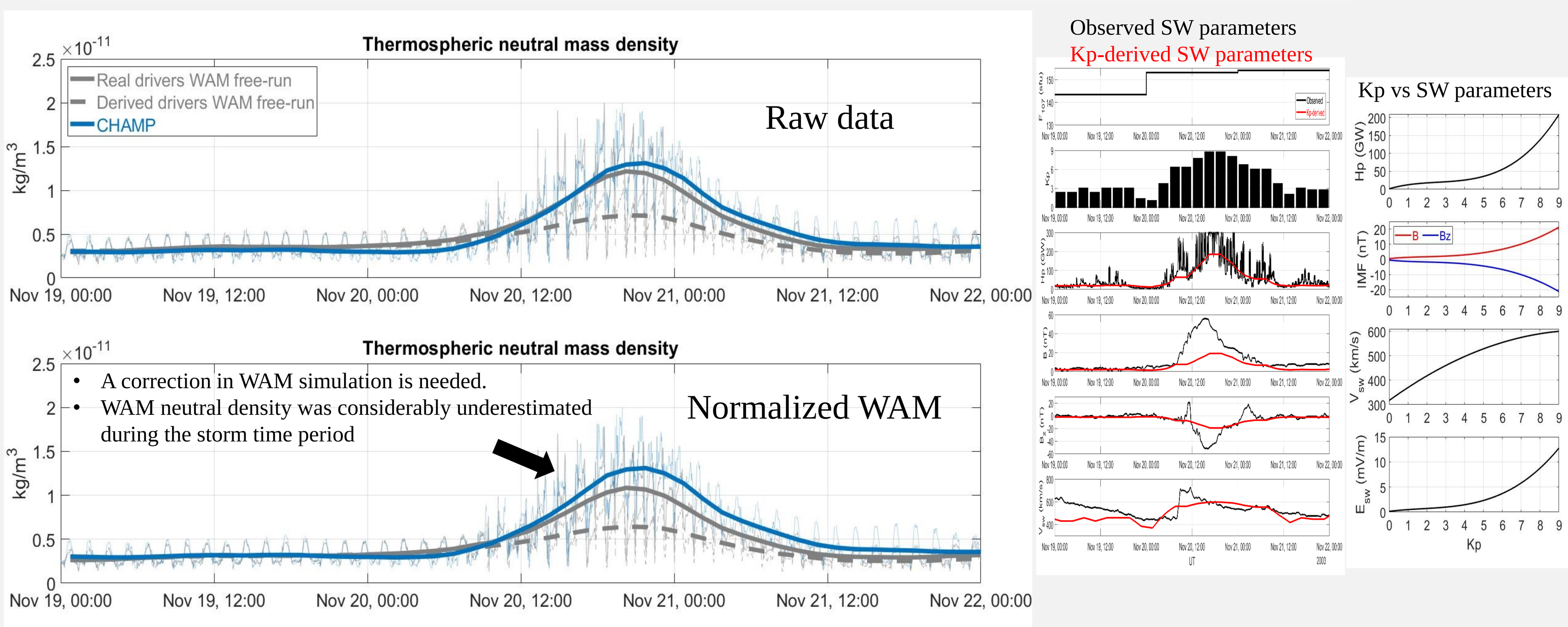
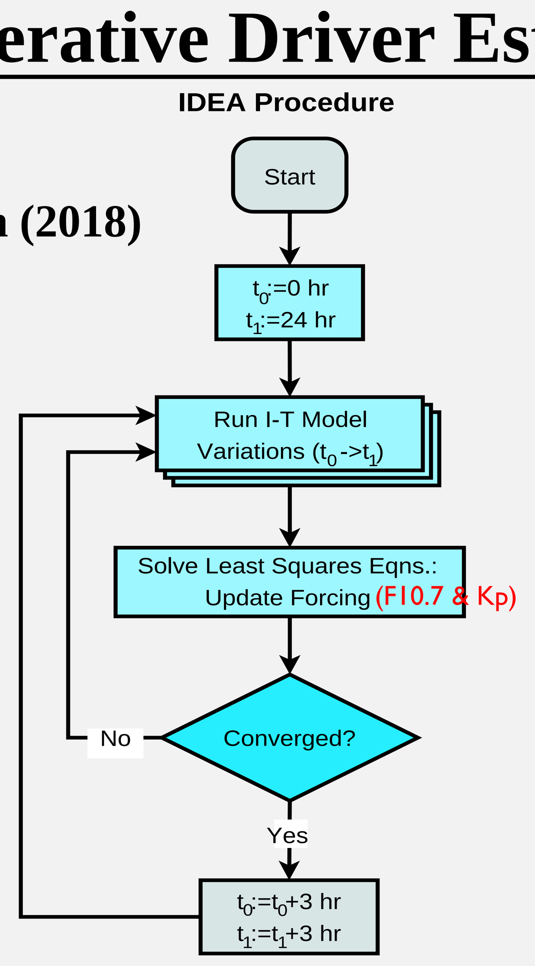


Figure 1. (left column) CHAMP accelerometer neutral densities and WAM free runs with or without normalizing to the quiet day of Nov. 19 during major storm in November 2003. Gray solid and dashed lines stand for the free-run WAM density sampled along the CHAMP satellite orbit. Blue solid line represents CHAMP accelerometer estimates of neutral density. Lighter and thinner lines are raw data mentioned above, while thicker lines are their moving averages. (middle column) Solar wind parameters ingested to drive WAM. In the free-run mode, WAM can be operated with observed or Kp-derived solar wind parameters. (right column) Relationship between Kp and solar wind parameters used in WAM. The relationships come from empirical formulas.

2. Iterative Driver Estimation & Assimilation (IDEA)

Sutton (2018)



- The IDEA runs separate instances of the I-T model forward in time under conditions (i.e., $F_{10.7}$ and Kp) slightly perturbed from the a priori. Using the perturbed model simulations to assess the sensitivity of the model to the external drivers, a linearized least squares minimization is then performed in the presence of thermospheric data.
- IDEA reinitializes the model for 24 hr into the past, and during this interval, the external drivers estimated in the previous iteration are applied to the model, and the model responds accordingly. After the iterative procedure converges, the data assimilation window can move forward to ingest newly available data

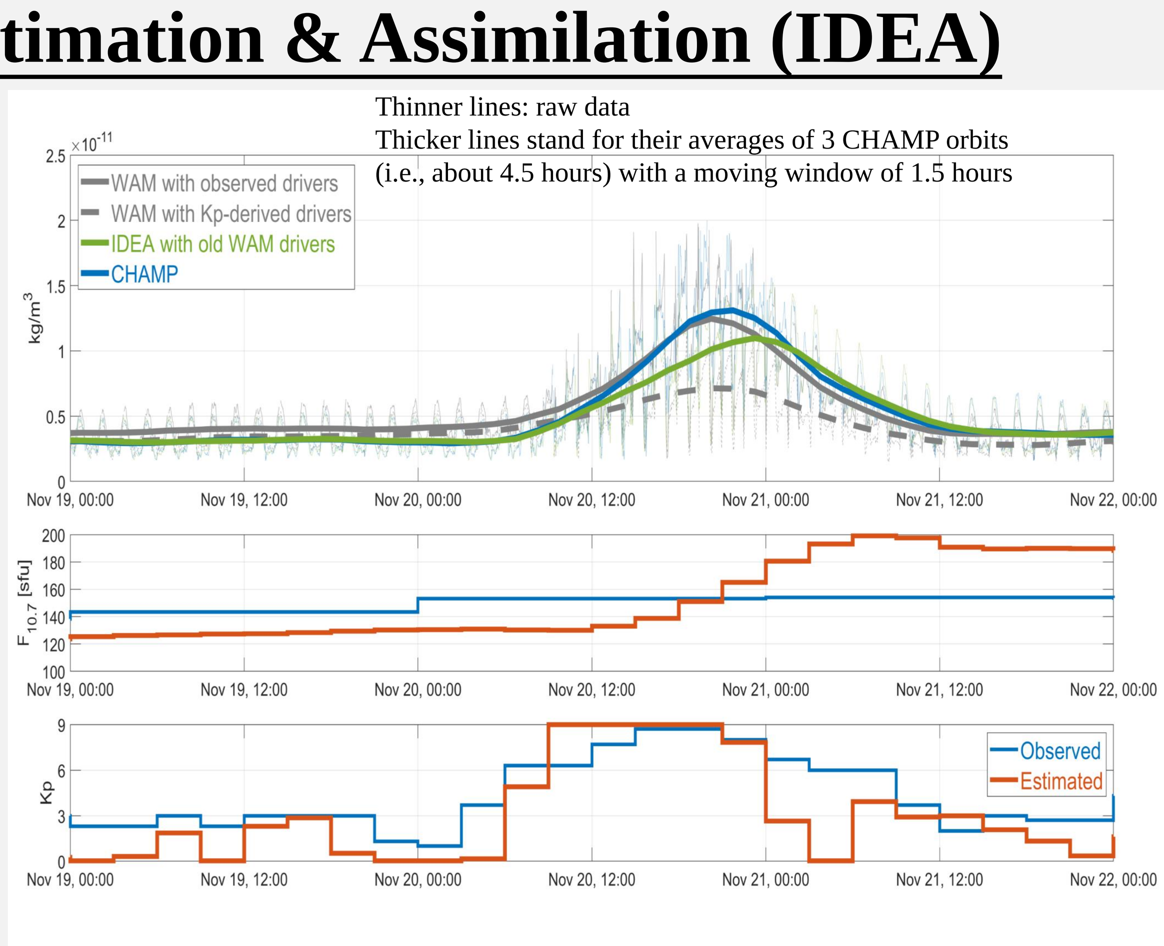


Figure 2. Time evolution of the neutral mass density obtained from CHAMP observations (blue solid line), WAM free run with observed SW drivers (grey solid line), WAM free run with Kp-derived SW drivers (grey dashed line), and IDEA data assimilation with old WAM drivers (light green solid line). Thinner lines represent raw data of the dataset mentioned above along the CHAMP satellite orbit. Thicker lines stand for their averages of 3 CHAMP orbits (i.e., about 4.5 hours) with a moving window of 1.5 hours. Bottom panels are observed $F_{10.7}$ and Kp (blue lines) and $F_{10.7}$ and Kp estimates for IDEA. Note that the $F_{10.7}$ and Kp estimates are constant for 3 hours at a time.

- IDEA was not able to effectively capture the CHAMP densities since the Kp estimates was maxed out at 9 during 1000-1900UT on the 20th, but the model was still not able to reach the high levels of the observed density, since the original empirical relationship of Kp with solar wind/IMF delivers insufficient energy and heating to the thermospheric system. To make up for the density discrepancy, IDEA enhanced the F10.7 value; however, the response of the modeled neutral density to the enhanced F10.7 value was not strong enough to capture the observed increase in CHAMP density. As a result, the WAM density was not capable of capturing the CHAMP density until approximately 0200UT on the 21st, after the recovery phase had begun.

3. Assimilate CHAMP for November 2003 Storm

Due to the intensity of the November 2003 storm, two changes have been applied in the IDEA technique:

- Allowing Kp to exceed beyond 9 (Kp>9 is allowed in the WAM simulation)
- Changing the relationship between Kp and the solar wind velocity to make the solar wind velocity increase when Kp>9 (Figure 5)

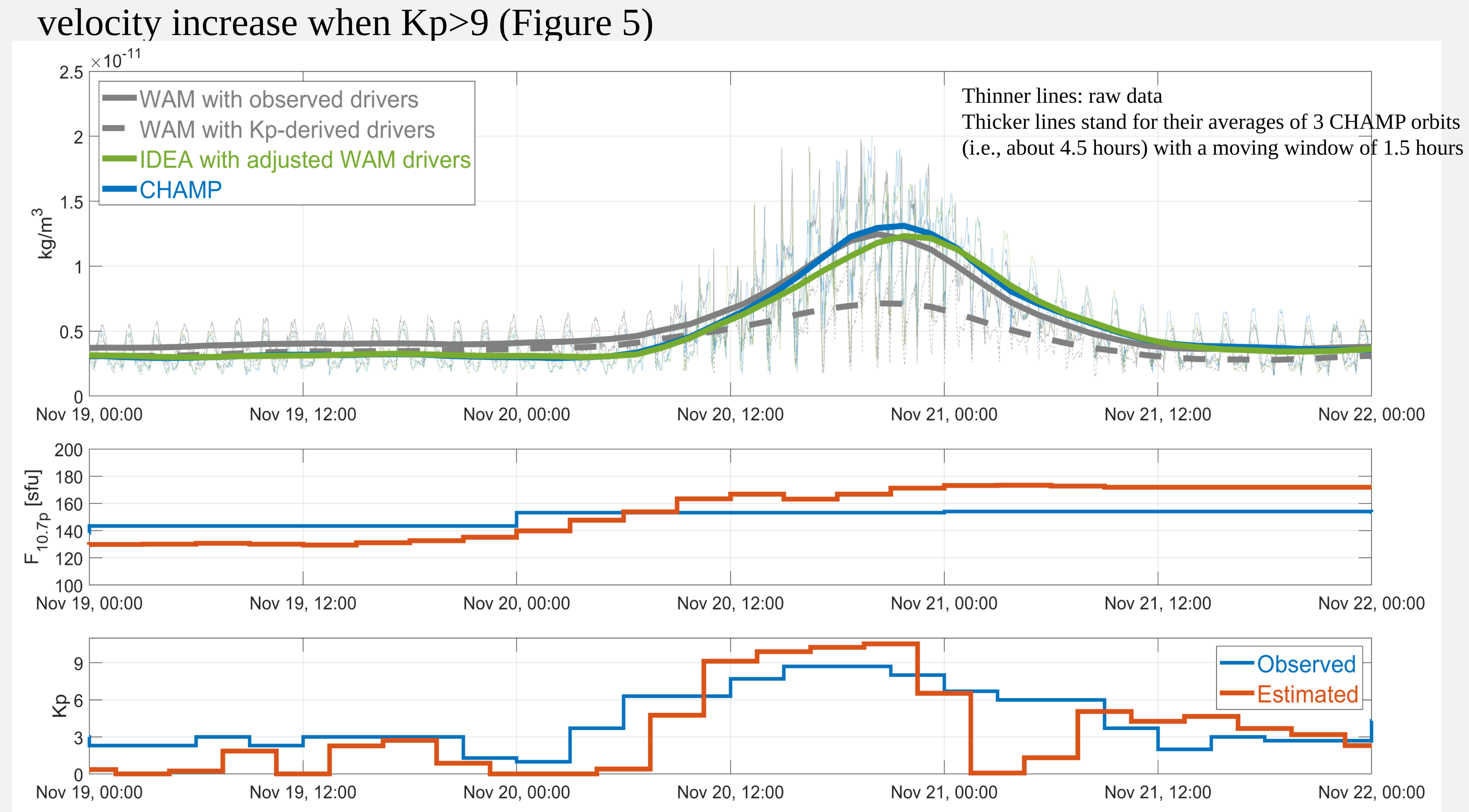


Figure 3. Upper panel is the comparison of IDEA with adjusted WAM drivers, WAM free runs, and CHAMP observation. Green lines stand for IDEA neutral density, blue lines represent CHAMP neutral density, and gray lines are WAM free runs Thinner lines represent raw data of the dataset mentioned above along the CHAMP satellite orbit. Thicker lines stand for their averages of 3 CHAMP orbits (i.e., about 4.5 hours) with a moving window of 1.5 hours. Bottom panels are the observed (blue) and IDEA-estimated (orange) F10.7 and Kp.

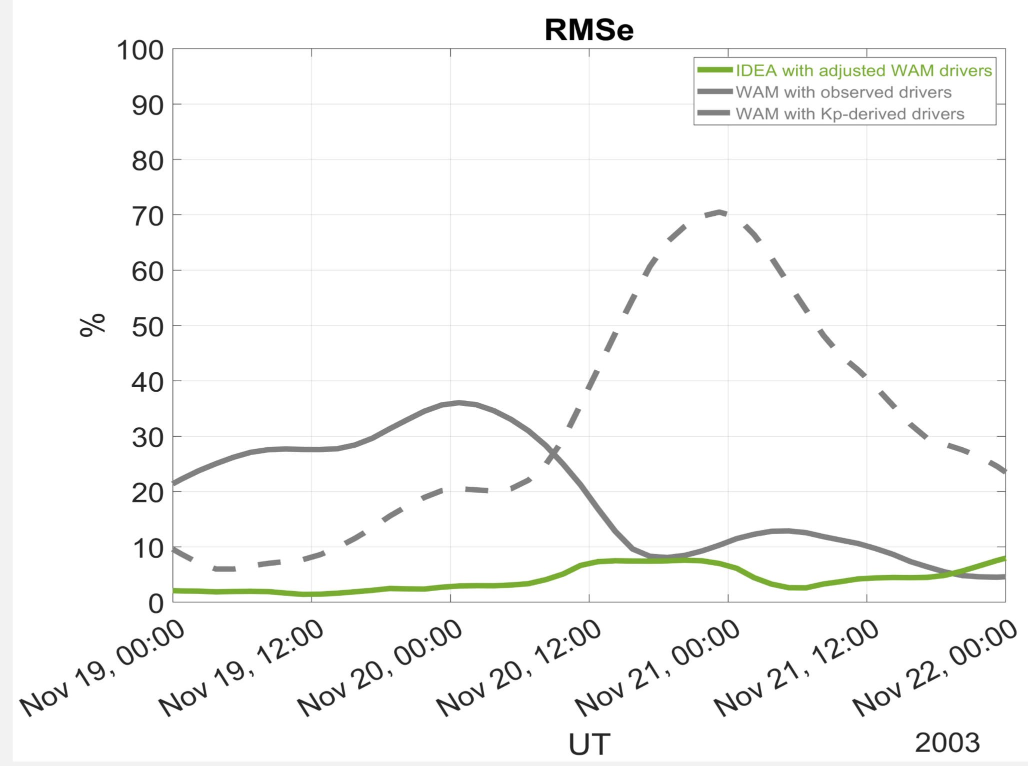


Figure 4. RMSe of observed/Kp-derived drivers WAM free runs and IDEA neutral density with respect to 3-orbital-averaged CHAMP observations.

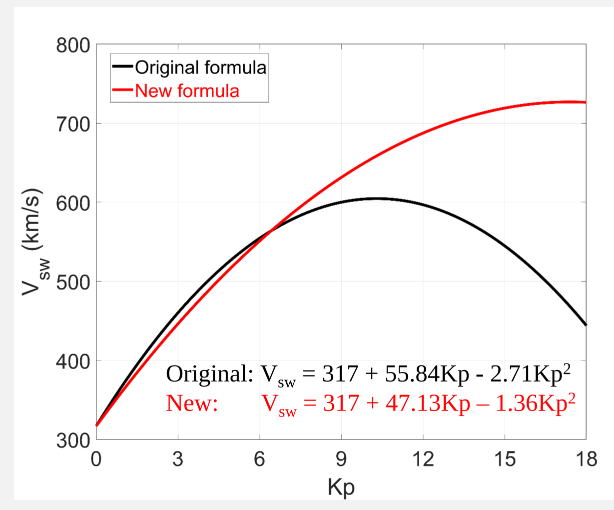


Figure 5. The 2nd and 3rd coefficients in the solar wind velocity formula have been adjusted to remain the relationship between Kp and the velocity similar and allow the velocity increase when Kp>9

Table 1. Performance metrics of WAM neutral density relative to CHAMP measurements during November 20-21

	Bias		RMSe		STD	
	Along-orbit	3-orbit-average	Along-orbit	3-orbit-average	Along-orbit	3-orbit-average
WAM (observed drivers)	4.5%	3.4%	32.9%	18.2%	32.4%	17.8%
WAM (Kp-derived drivers)	-21.4%	-22.4%	53.9%	44.5%	42.9%	30.5%
IDEA	-4.1%	-2.3%	23.5%	5.2%	23.0%	4.6%

- Given that the IDEA system minimizes the RMSe in the log densities, the bias, RMSe, and STD are calculated in log space (Sutton 2018), and the quantities are expressed as percentages, e.g., % = 100 × (exp(RMSe) − 1). Note that for bias, % = 100 × (bias − 1)
- From the 3-orbit-averaged perspective, IDEA with adjusted WAM drivers clearly outperforms free-running WAMs and IDEA with old WAM drivers. On the other hand, along CHAMP orbits, IDEA with adjusted WAM drivers exhibits better performance compared to free-running WAMs and slightly outperforms IDEA with old WAM drivers.

(Bias)
$$\mu(m/o) = \exp\left(\frac{1}{N}\sum_{i=1}^{N}\ln\frac{\rho_{m,i}}{\rho_{o,i}}\right)$$

m: model output
o: observations
N: number of data points

$$\mathrm{RMSe} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\ln\frac{\rho_{m,i}}{\rho_{o,i}}\right)^2}$$

(STD)
$$\sigma(m/o) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\ln\frac{\rho_{m,i}}{\rho_{o,i}} - \ln\mu(m/o)\right)^2}$$

4. IDEA-CHAMP vs TIMED-GUVI Neutral Density

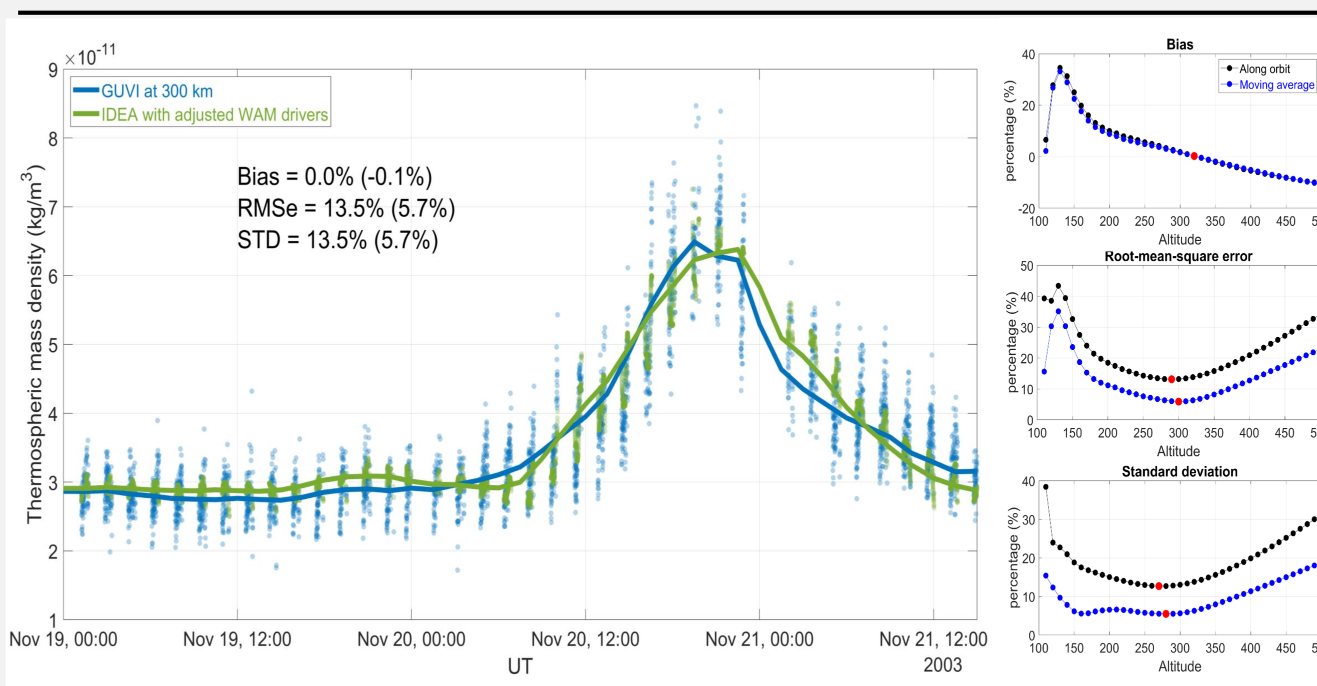
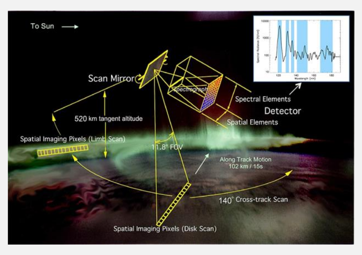


Figure 6. (left) Comparison of IDEA-WAM and GUVI neutral density at 300 km altitude. IDEA-WAM was adjusted by assimilating CHAMP. GUVI densities at around 00UT on November 21 are determined as outliers and discarded. (right) Bias, RMSe, and standard deviation between IDEA-WAM and GUVI density in various altitudes. Red dots denoted in the figure highlight when the bias is closest to 0 and when minimum values of root-mean-square error and standard deviation are reached. In general, GUVI limb scan measurements are the most consistent with CHAMP and IDEA-WAM at altitudes ranging from 270 to 320 km.



TIMED-GUVI

- Thermosphere Ionosphere Mesosphere Energetics and Dynamics Global Ultraviolet Imager
- Satellite altitude: 625 km (388 mi)
- Inclination: 74.1°
- Period: 97.3 minutes
- GUVI observes thermospheric temperature, densities, auroral energy, solar EUV, and airglows.
- The 14 spatial imaging pixels across the entrance slit each generate a spectrum on the detector focal plane in 15 seconds. The scan mirror sweeps the slit across the limb and disk.
- The limb scan provides far ultraviolet (FUV) emission of all the major thermospheric species O, N_2, and O_2 in the dayside.

- GUVI data exhibit more fluctuations compared to model output, possibly due to systematic biases and inversion algorithm assumptions degrading at high latitudes and/or regions of large solar zenith angle.
- In general, this shows that GUVI limb scan measurements are the most consistent with CHAMP and IDEA at altitudes ranging from 270 to 320 km. A bias of 0.02%, RMSe of 13.5%, and STD of 13.5% between GUVI and IDEA along the GUVI orbits are lower than the corresponding values of -4.1%, 23.5%, and 23.0% between CHAMP and IDEA (Table 1). In addition, the 3-orbit-averaged values also show strong agreement, with bias, RMSe, and STD of -0.1%, 5.7%, and 5.7%, respectively, which are comparable to the corresponding values of -2.3%, 5.2%, and 4.6% between CHAMP and IDEA (Table 1). These show the potential utility of using GUVI limb scan measurements as the data source in the IDEA data assimilation system.

Summary and Future Work

This study has been submitted to Space Weather and is currently under review.

- Good agreement between IDEA vs CHAMP and IDEA vs GUVI demonstrates the utility of the IDEA data assimilation technique and that using either accelerometer observations or UV airglow limb measurement during extreme storm periods could be used.
- This study shows that physical models with data assimilation can contribute to neutral density specification for enhanced orbit determination and prediction of the low Earth orbit satellites.

Acknowledgements

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Reference

Sutton, E. K. (2018). A new method of physics-based data assimilation for the quiet and disturbed thermosphere. *Space Weather*, *16*, 736–753. https://doi.org/10.1002/2017SW001785