Data Assimilation Techniques for Physics-Based Models of the Thermosphere and Ionosphere

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Operating in LEO

Leveraging the Benefits:
LEO is the only truly sustainable environment for mega constellations

Avoiding the Risks:
The interaction with the atmosphere makes it difficult to predict conjunctions

Objects that reentered in 2018

IRIDIUM/Cosmos Collision + 3 hr
Toward Better Nowcasting and Forecasting of the LEO Environment

Validate new approach, IRIDEA, with real-world scenario

- Simulate the I-T without data assimilation
- Simulate the I-T with IRIDEA data assimilation

Variability of the I-T System

Quiet Time

**Quiet-time orbits preceding the 2015 St. Patrick’s Day Geomagnetic Storm:**

- Neutral and Plasma Densities, normalized by their average quiet-time values
- ±50–100% observed even during quiet-time
- Densities can be enhanced by a factor of ~8 during disturbed periods

**Neutral Densities (GRACE satellite, 410 km, 5:30 LT)**

**Plasma Densities (Swarm satellite, 450 km, 7:45 LT)**
Variability of the I-T System

Geomagnetic Storm

Quiet-time and Geomagnetically Disturbed orbits during the 2015 St. Patrick’s Day Geomagnetic Storm:

- Neutral and Plasma Densities, normalized by their average quiet-time values
- Densities can be enhanced by a factor of ~8 during disturbed periods
- ±50–100% observed even during quiet times
Q: Why do we need a Different data assimilation scheme?
A: Because the Ionosphere-Thermosphere (I-T) system is:

- Highly driven
- Sparsely observed

[Image adopted from Codrescu et al., 2018]
Drivers of the I-T System

The Sun-Earth System

- Sun
- Solar Wind
- Irradiance
- Magnetosphere
- Electric Fields
- Joule & Particle Heating
- Heating/Photochemistry
- Upper Atmosphere
- Upward Propagating Waves and Tides

Adapted from Prölls, 2011
Drivers of the I-T System

The Sun-Earth System

Adapted from Prölss, 2011
Data Driver Assimilation
New Approach

- Calculate what the driver *should* be for I-T model output to match observations
- Apply new estimated driver retrospectively to allow model to equilibrate

Free Run vs. IRIDEA
Day 80-365, 2003

Validate new approach, IRIDEA, with real-world scenario

- Simulate the I-T without data assimilation
- Compare output of I-T model with observations of neutral density from CHAMP

IRIDEA: Iterative Re-Initialization, Driver Estimation, and Assimilation

Without Data Assimilation

RMSE = 22.3%
Validate new approach, IRIDEA, with real-world scenario

- Simulate the I-T with IRIDEA data assimilation
  - Ingest CHAMP/STAR accelerometer observations at ~400 km
  - Estimate corrections to both solar flux and geomagnetic activity drivers
- Compare output of I-T model with observations of neutral density from CHAMP

**Free Run vs. IRIDEA**

**Day 80-365, 2003**

**With IRIDEA Data Assimilation**

- RMS error = 3.6%

**Comparing to Ingested Data**
Free Run vs. IRIDEA
Day 80-365, 2003

Validate new approach, IRIDEA, with real-world scenario

- Simulate the I-T with IRIDEA data assimilation
  - Ingest CHAMP/STAR accelerometer observations at ~400 km
  - Estimate corrections to both solar flux and geomagnetic activity drivers
- Compare output of I-T model with observations of neutral density from GRACE at ~500 km and separated in local time from CHAMP

IRIDEA: Iterative Re-Initialization, Driver Estimation, and Assimilation
Persistent Model Features
Day 80-365, 2003

Method allows us to:
- Isolate internal model features from external drivers
- …while still comparing to observations

Investigate model’s internal biases:
- Viscous and ion drag forces (e.g., Hsu et al., 2016)
- Tidal and GW influences (e.g., Jones et al., 2014)
- Cooling discrepancies
- Imposed lower boundary vs Whole Atmosphere model
Observational Response  
Sensitivity to Heating Sources

Response to Increasing Solar Irradiance

- Density Increase (%)
- $F_{10.7}$
- Days
- Local Time (hours)
- Latitude (deg)
- Longitude (deg)

Response to Increasing Geomagnetic Activity

- Kp
- Days
- Local Time (hours)
- Latitude (deg)
- Density Increase (%)
Observational Response
Sensitivity to Heating Sources

Response to Increasing Solar Irradiance

Days

Latitude (deg)

Local Time (hours)

O/N₂ Difference

Response to Increasing Geomagnetic Activity

Days

Kp

Latitude (deg)

Local Time (hours)

O/N₂ Difference
Thank you!

Summary:
- LEO can be a sustainable destination for mega constellations
- Driven I-T requires a different type of data assimilation:
  Data Assimilation -> **Driver** Assimilation
- Simulation residuals are powerful tools for diagnosing internal model physics, in (approximate) isolation of external drivers
- Observations of composition complement mass densities

This work was made possible with support from AFOSR and the University of Colorado Grand Challenge Space Weather Center
External Drivers
Observed vs. Estimated

The estimated $F_{10.7}$ time series resembles the actual

- Solar rotational modulation is evident
- But, the spikes are probably not representative of EUV variations

The estimated Kp time series somewhat resembles the actual

- Better correlation when a daily running-maximum filter is applied
- Does TIE-GCM have a problem cooling down or is correlation of the estimated drivers causing this?

How do we better disentangle solar vs. geomagnetic influences?

- Improve data coverage?
- Incorporate data types with better information content?
- Incorporate actual drivers into the mix?
Ingested Data

Independent Validation Data

Metrics

RMSe can be partitioned between model bias/offset ($\mu$) and variance ($\sigma$):

$$\text{RMSe}^2 = \ln(\mu(m/o))^2 + \sigma(m/o)^2$$