# Retrospective Cost Model Refinement and State and Input Estimation for Space Weather Modeling and Prediction

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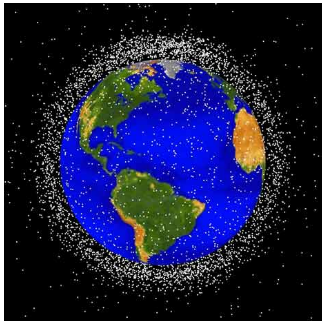


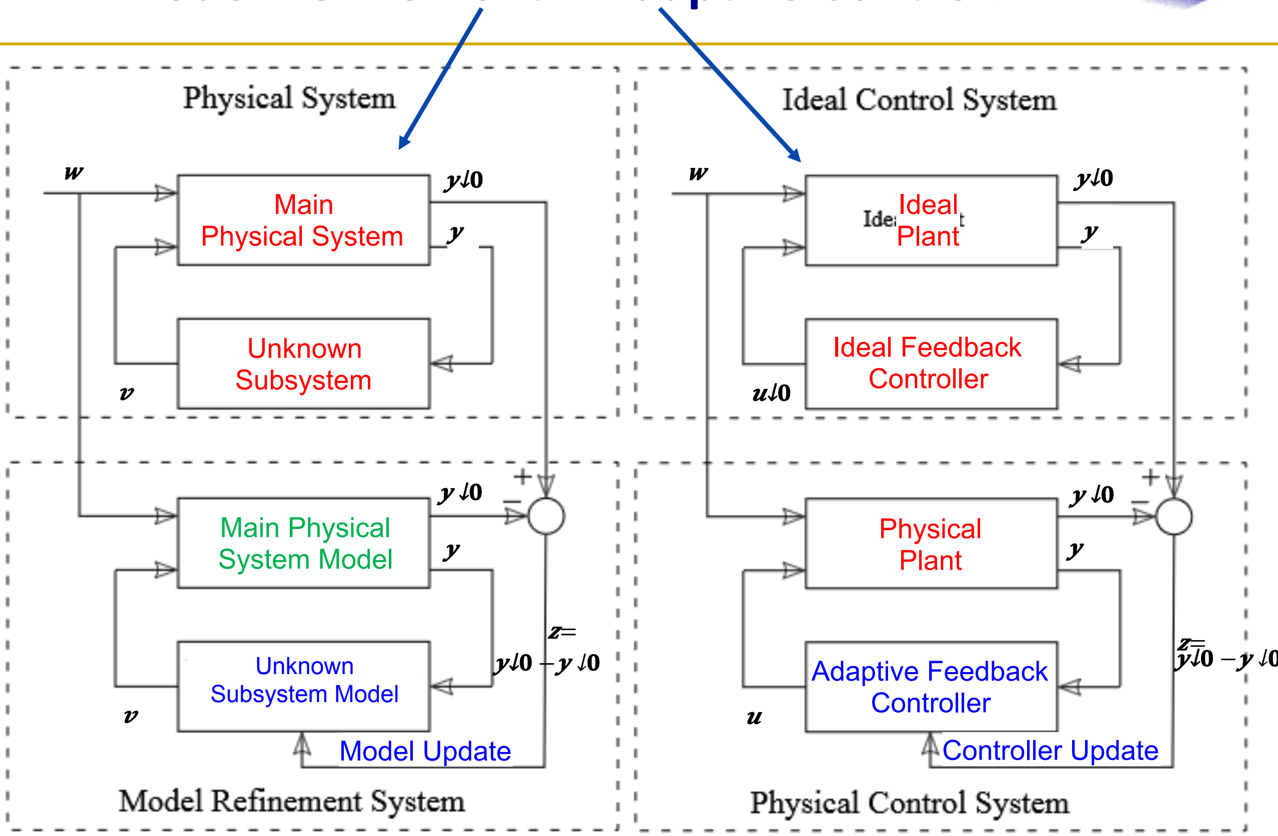
Thanks to: Ankit Goel

Supported by Frederica Darema,
AFOSR DDDAS Program

# Modeling for DDAS

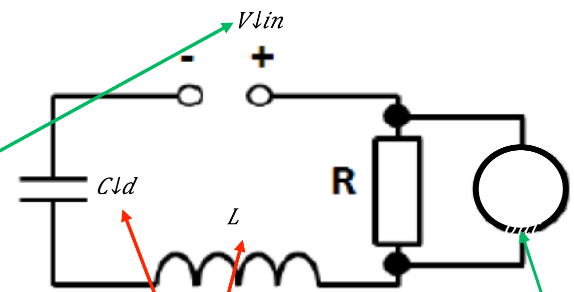
- ❑ model ≠ reality
- ❑ All models are wrong ☹
- ❑ Types of model errors
  - ❑ Parameter errors
  - ❑ Errors in dynamics----wrong or missing
  - ❑ Everything is uncertain to some extent
- ❑ But some models are useful! ☺
  - ❑ Some are more useful than others
- ❑ The "accuracy" of a model is meaningful only relative to its intended purpose
- ❑ Model refinement
  - ❑ Model + data = better model

# Model Refinement = Adaptive Control!



# Retrospective Cost Model Refinement
# Circuit Experiment

Current and voltage drops are NOT measured




This signal IS measured

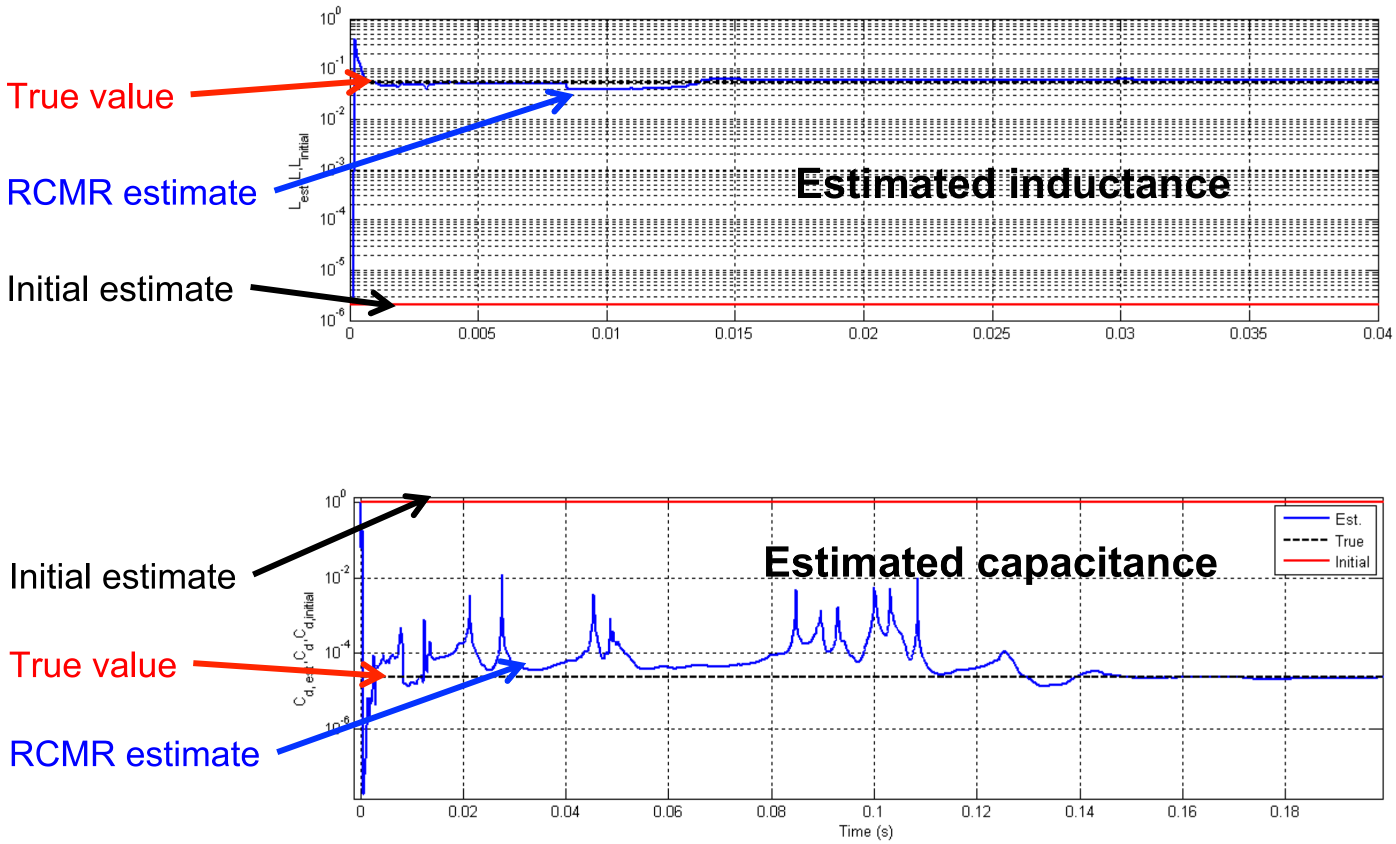
These parameters are unknown and inaccessible

- Series RLC circuit
- Driving signal is circuit voltage
- The only measurement is the voltage drop across the resistor
- The inductance and capacitance are assumed to be unknown

$$Lx + Rx + x/C_d = V_{in}$$

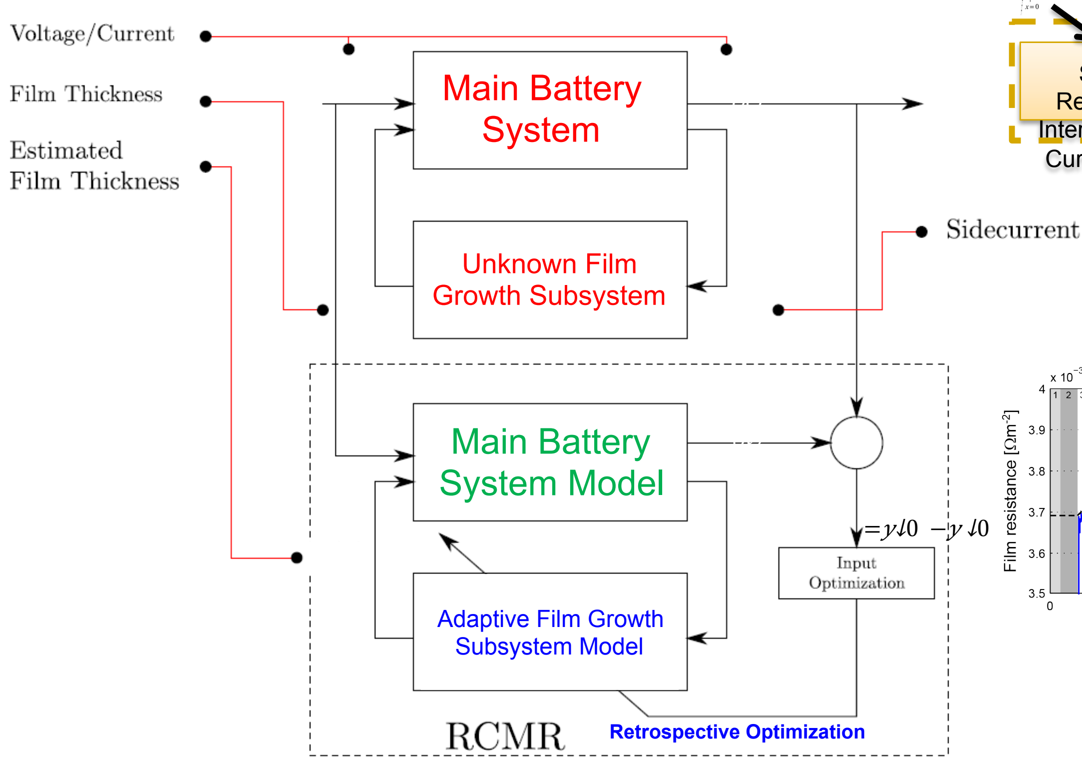
$$V_{out} = Rx$$

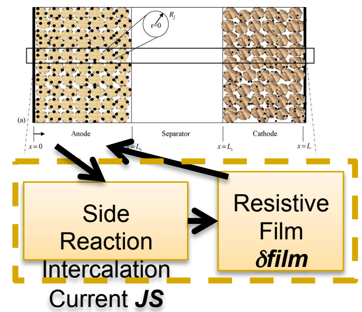
# Retrospective Cost Model Refinement
# Estimates of L and C

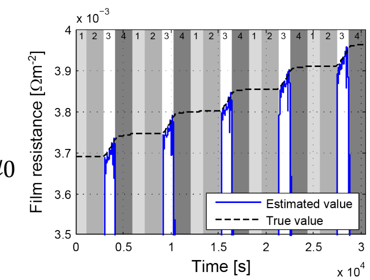


# Retrospective Cost Model Refinement
# Battery Health Monitoring

- **Objective:** Monitor battery health by estimating film growth at the negative electrode using charging measurements

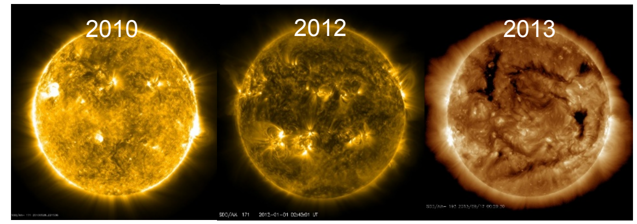


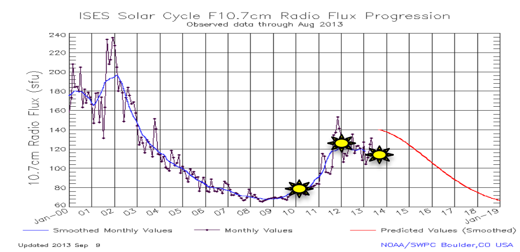



# Space Weather Modeling

- Problem
  - Unknown changes to the atmospheric density degrade the accuracy of GPS and impede the ability to track space objects
- Goals
  - Use input reconstruction to estimate atmospheric drivers that determine the evolution of the ionosphere-thermosphere
  - Use model refinement to improve the accuracy of atmospheric models
    - Achieve more accurate data assimilation




## Effects on Earth

- Space weather affects the terrestrial environment
- Space weather disturbances interfere with satellite and radio communications and operations
- Extreme space weather events can knock out the power grid, melt electronics, damage satellites, and disrupt polar air routes

Space Debris

## Orbit Determination

- Orbital prediction error is principally caused by problems in estimating atmospheric drag
- Predicting atmospheric drag requires prediction of the atmospheric density and understanding ion-neutral interactions
- Measurements in the upper atmosphere are primarily space-based

# Monitoring Space Weather

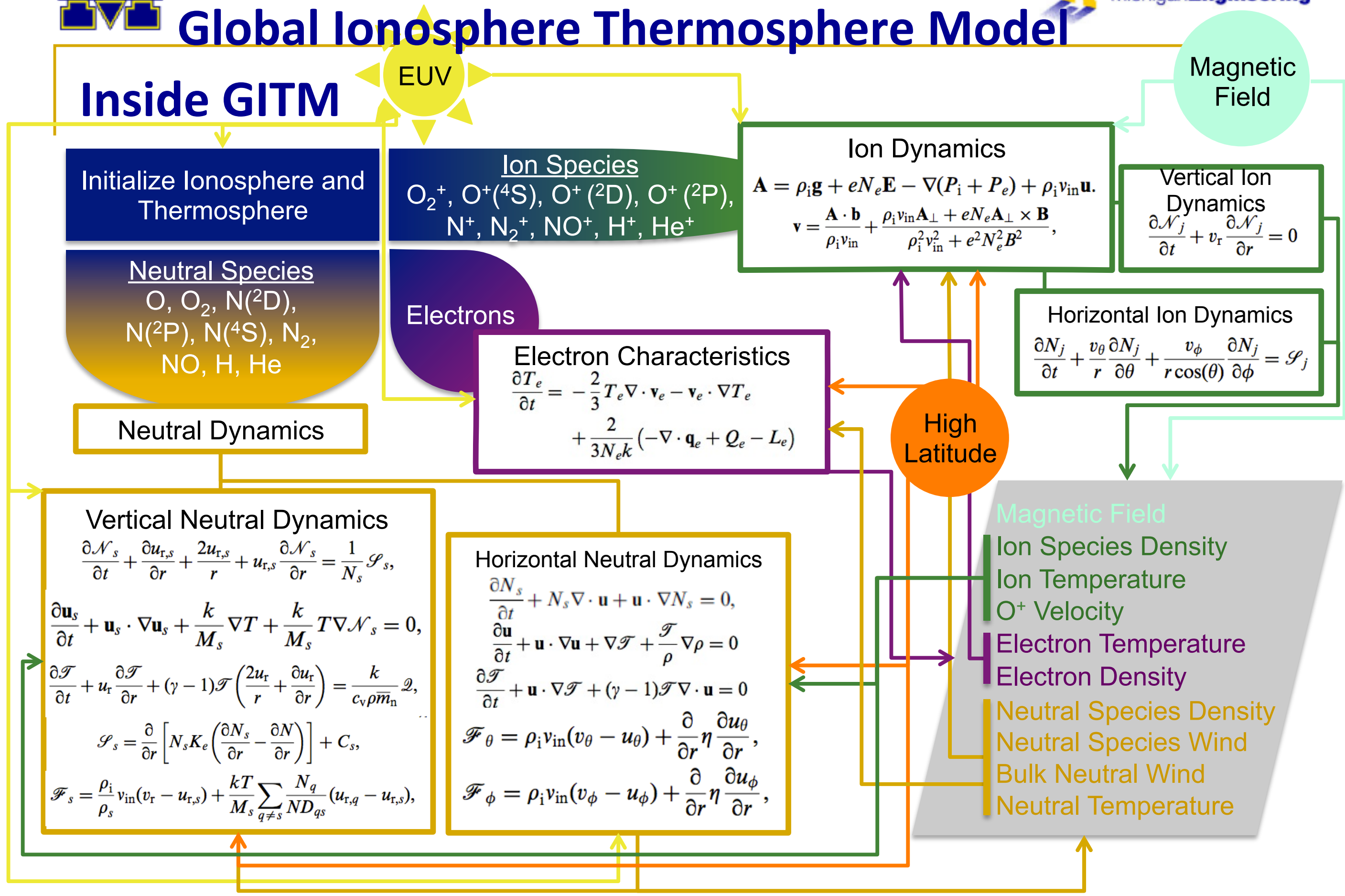
- Satellites
  - Solar Missions
  - Magnetospheric Missions
  - Atmospheric Missions
- Ground-Based Observatories
  - Ionospheric characteristics and disturbances
  - Atmospheric winds
  - Solar, magnetic, and current indices
- Monitoring and Data Centers
  - NOAA Space Weather Prediction Center
  - Heliophysics Events Knowledge base
  - Dominion Observatory in Penticton, British Columbia, Canada

NASA


# GITM

# Global Ionosphere Thermosphere Model

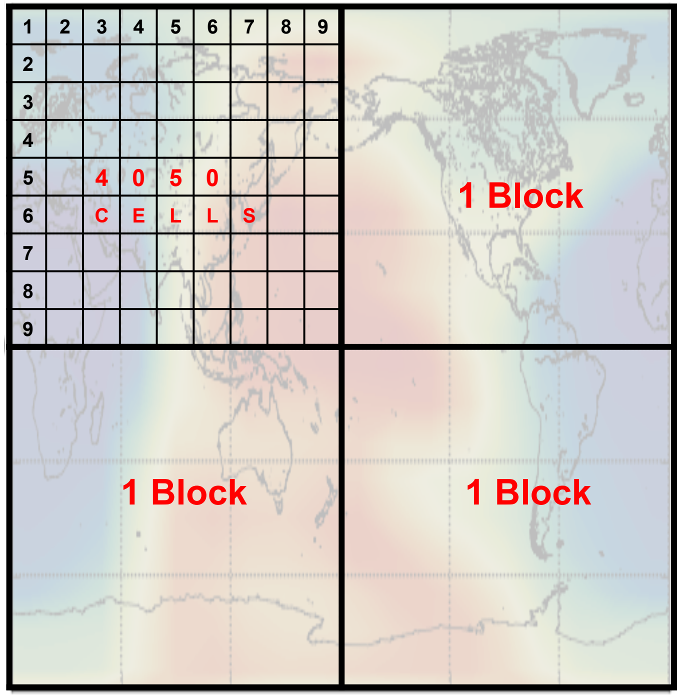
## Inside GITM



# GITM Is Fully Parallelized

- Resolution is specified by the number of blocks covering the Earth
- Each block has 4050 cells
  9 longs X 9 lats X 50 alts
- Each cell as 28 states
  - 7 neutrals, 8 ions, 3 temperatures, 7 neutral velocities, 3 ion velocities
  - Each block has 113,400 states
- Typical grids are (longitude blocks)x(latitude blocks):
  - 2x2 (4 processors)
    Testing purposes, $10° \times 20°$
    **453,600 states**
  - 8x8 (64 processors)
    Low resolution physical runs, $5° \times 2.5°$
    **7,257,600 states**
  - 8x12 (96 processors)
    High resolution physical runs, $5° \times 1.67°$
    **10,886,400 states**

2x2 Grid of the Earth (4 blocks)



# Estimate Photoelectron Heating Efficiency

**Vertical Neutral Dynamics**

$$\frac{\partial \mathcal{N}_s}{\partial t} + \frac{\partial u_{r,s}}{\partial r} + \frac{2u_{r,s}}{r} + u_{r,s}\frac{\partial \mathcal{N}_s}{\partial r} = \frac{1}{N_s}\mathcal{S}_s,$$

$$\frac{\partial \mathbf{u}_s}{\partial t} + \mathbf{u}_s \cdot \nabla \mathbf{u}_s + \frac{k}{M_s}\nabla T + \frac{k}{M_s} T \nabla \mathcal{N}_s = 0,$$

$$\frac{\partial \mathcal{T}}{\partial t} + u_r \frac{\partial \mathcal{T}}{\partial r} + (\gamma - 1)\mathcal{T}\left(\frac{2u_r}{r} + \frac{\partial u_r}{\partial r}\right) = \frac{k}{c_v \rho \overline{m}_n}\mathcal{Q}$$

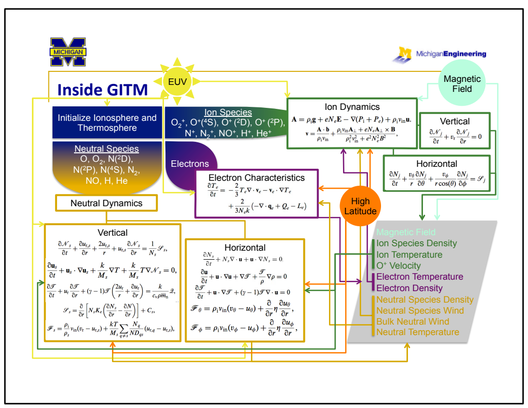
$$\mathcal{S}_s = \frac{\partial}{\partial r}\left[N_s K_e \left(\frac{\partial N_s}{\partial r} - \frac{\partial N}{\partial r}\right)\right] + C_s,$$

$$\mathcal{F}_s = \frac{\rho_i}{\rho_s}\nu_{in}(v_r - u_{r,s}) + \frac{kT}{M_s}\sum_{q \neq s}\frac{N_q}{N D_{qs}}(u_{r,q} - u_{r,s}),$$

$$\mathcal{Q} = Q_{EUV} + Q_{NO} + Q_O + \frac{\partial}{\partial r}\left((\kappa_c + \kappa_{eddy})\frac{\partial T}{\partial r}\right) + N_e \frac{\overline{m}_i \overline{m}_n}{\overline{m}_i + \overline{m}_n}\nu_{in}(\mathbf{v} - \mathbf{u})^2,$$

$$Q_{EUV} = \epsilon_{EUV}\, q_{EUV} + \epsilon_{PHE}\, q_{PHE}$$

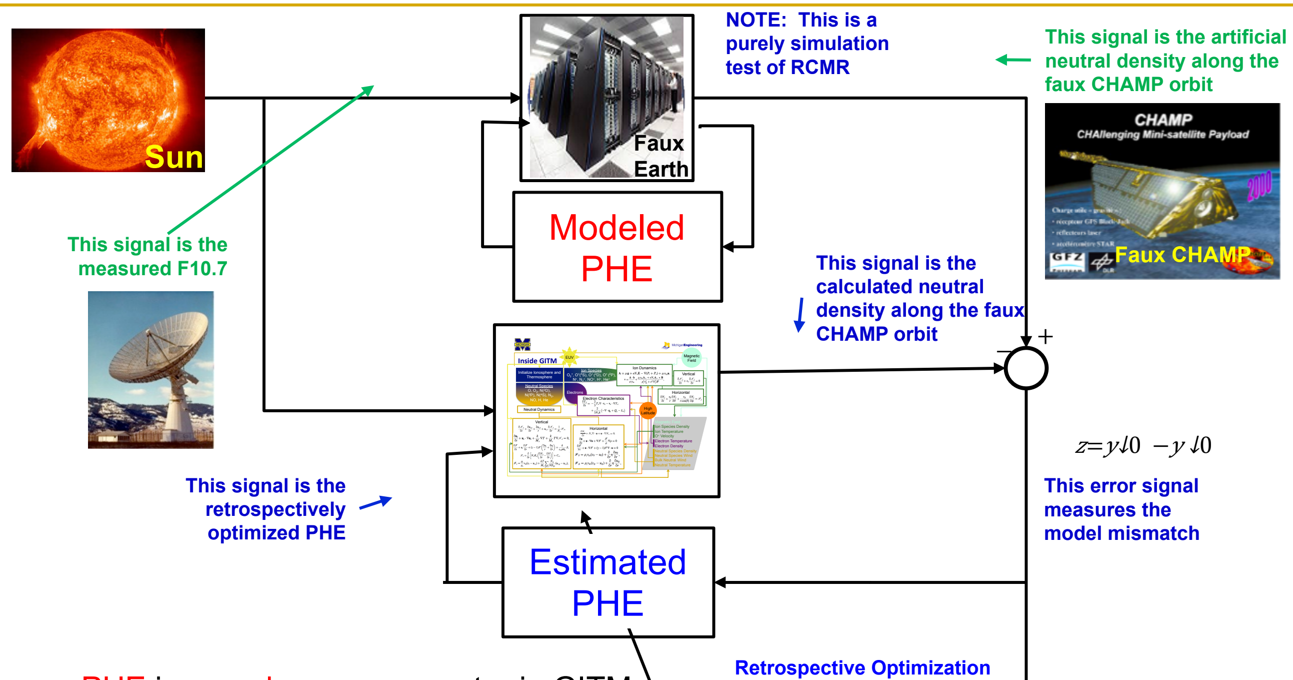
Photoelectron Heating Efficiency




  is the solar extreme ultraviolet (EUV) heating

  is the photoelectron heating---the heat released by secondary photoelectrons

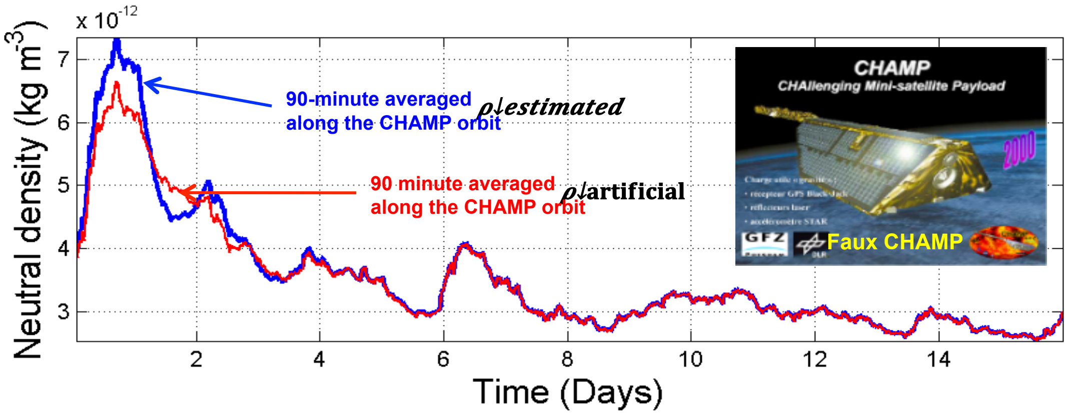
# Estimate Photoelectron Heating Efficiency Using Artificial Data



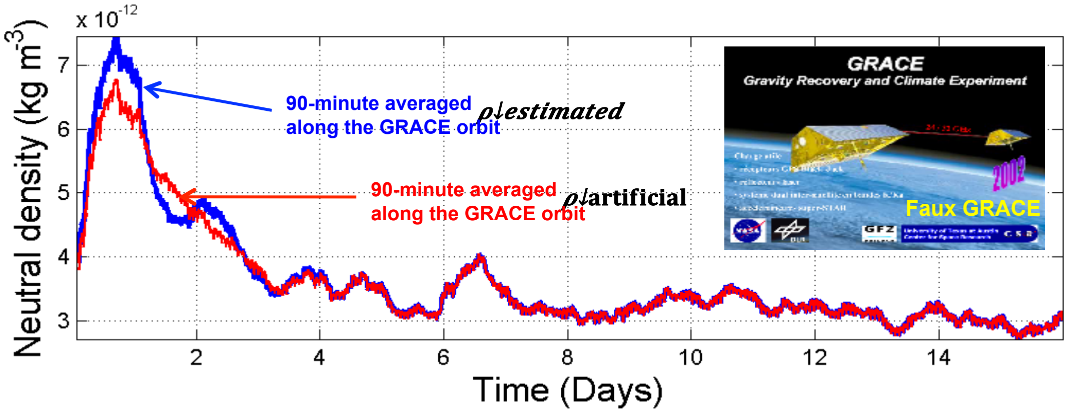

- PHE is an unknown parameter in GITM
- To estimate PHE, we compute neutral density along **CHAMP**'s orbit at the fixed altitude of 400 km, and RCMR uses this artificial data
- As a quality metric for the state estimates, we compare estimates of the neutral density along **GRACE**'s orbit at a constant altitude of 400 km

# Estimate Photoelectron Heating Efficiency Using Artificial Data

- The 90-minute average of the estimated neutral density converges to the artificial neutral density along the CHAMP and GRACE orbits at 400 km altitude




Faux CHAMP neutral density **IS** assimilated

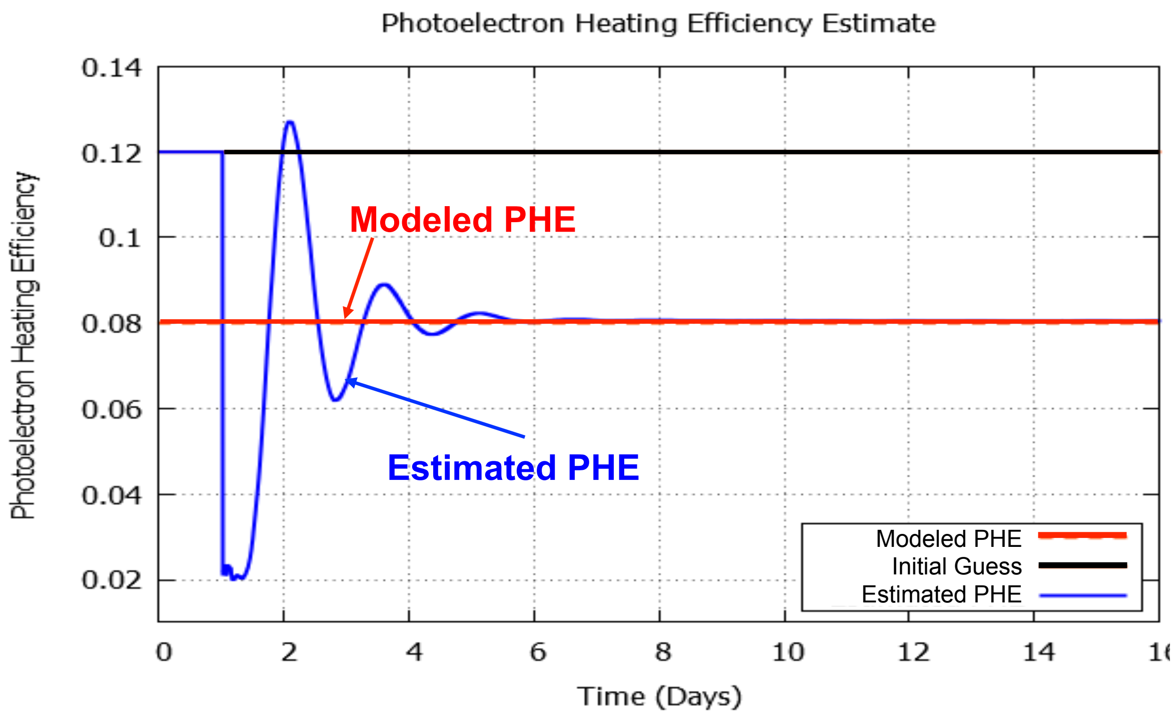



Faux GRACE neutral density is **NOT** assimilated

Faux GRACE neutral density is a performance metric

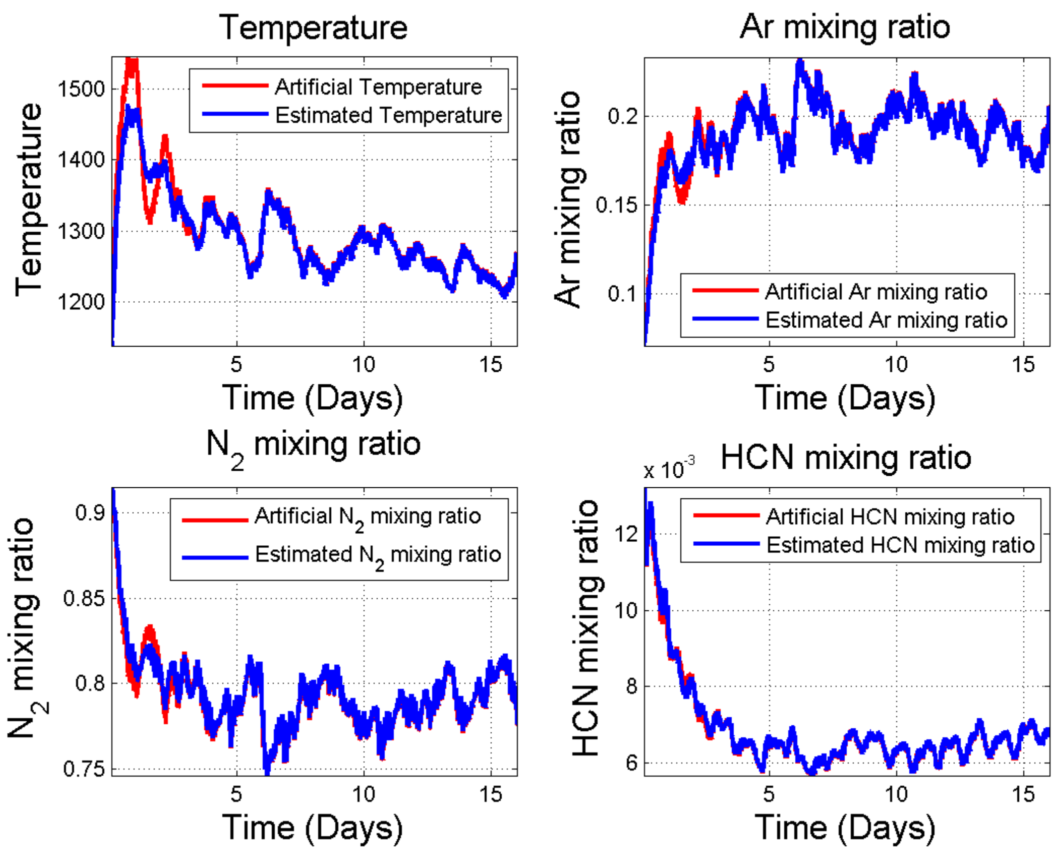
# Estimate Photoelectron Heating Efficiency Using Artificial Data

- The RCMR estimate of PHE converges to the artificial (modeled) value of PHE



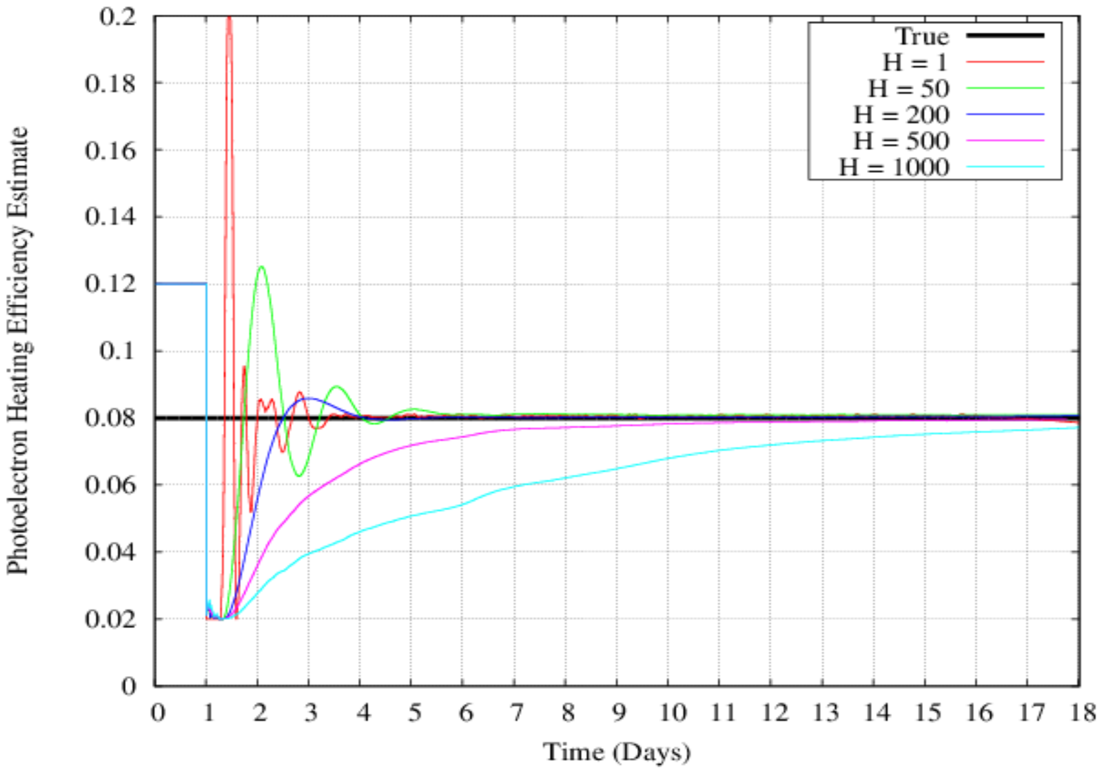
# Estimate Photoelectron Heating Efficiency Using Artificial Data

PHE convergence yields convergent state estimates

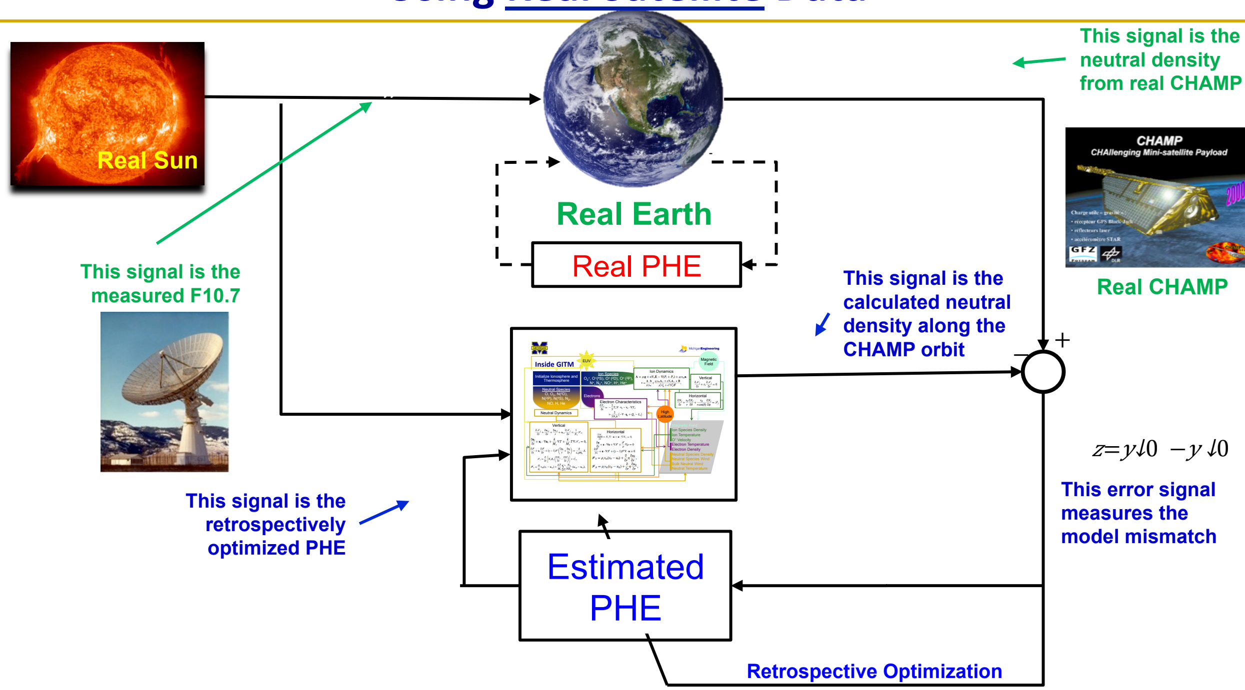


# Estimate Photoelectron Heating Efficiency Using Artificial Data

- We study the robustness of RCMR to the choice of H
- The estimate converges to the true value of PHE for a wide range of H



# Estimate Photoelectron Heating Efficiency Using Real Satellite Data

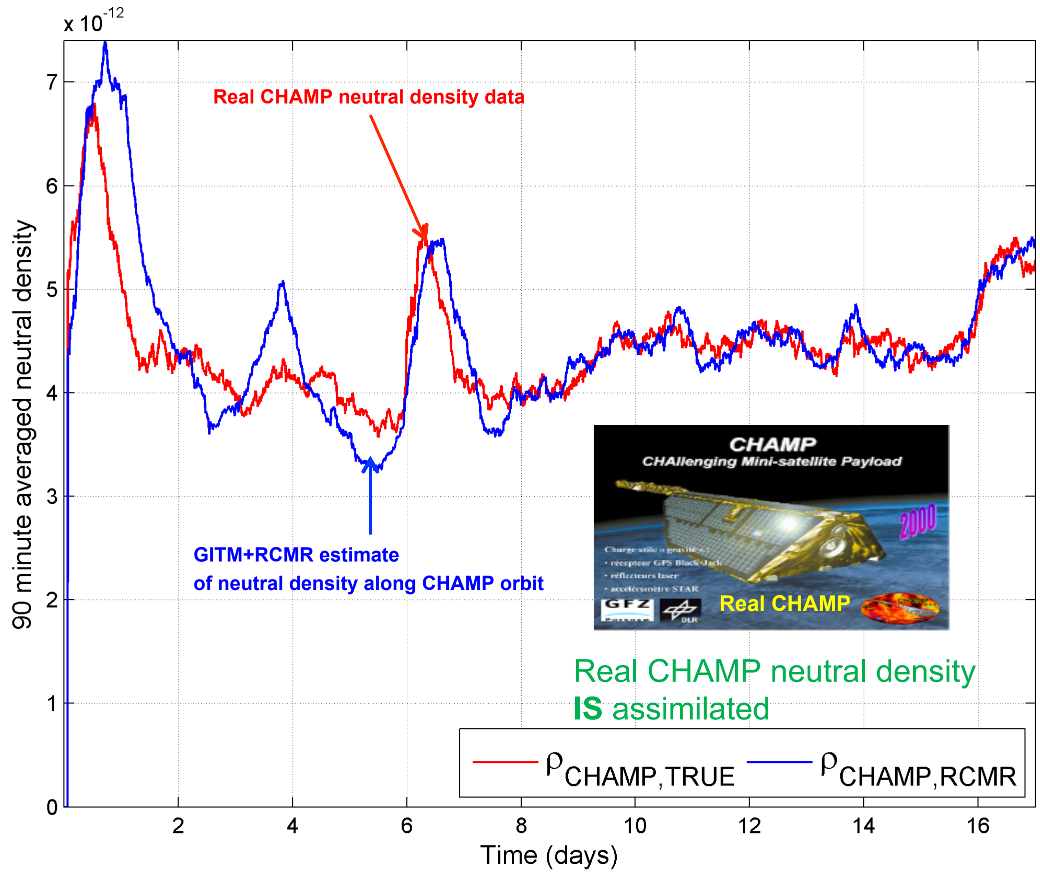



- We estimate PHE using neutral density measurements from the **real CHAMP** satellite
  - We assimilate real **CHAMP** satellite data from <u>2002-11-24 to 2002-12-06</u>
- Neutral density measurements from **GRACE** are used as a <u>quality metric</u>
  - But these data are NOT assimilated


Real GRACE

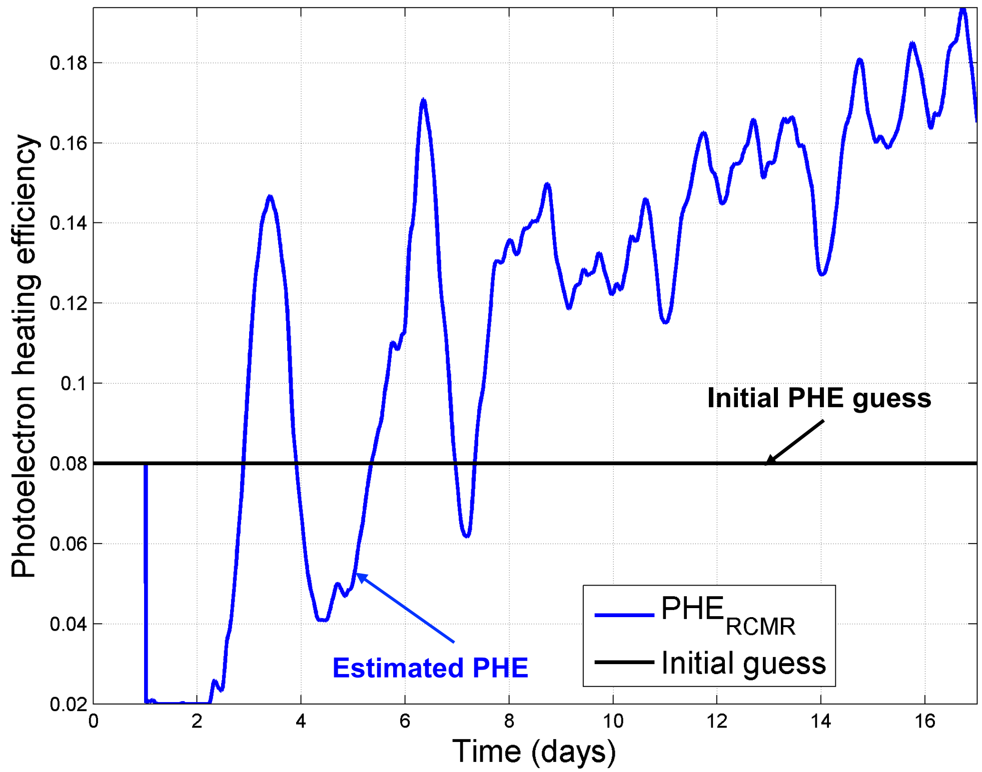
# Estimate Photoelectron Heating Efficiency Using Real Satellite Data

## RCMR minimizes the error z in the CHAMP neutral density



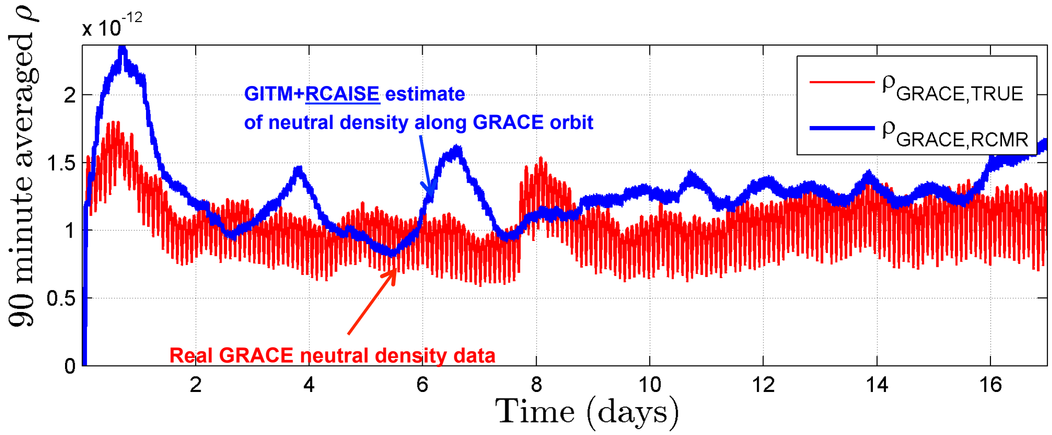
## Estimate Photoelectron Heating Efficiency Using Real Satellite Data

- RCMR determines the value of PHE that minimizes the error z in the neutral density estimate



# Estimate Photoelectron Heating Efficiency Using **Real Satellite** Data

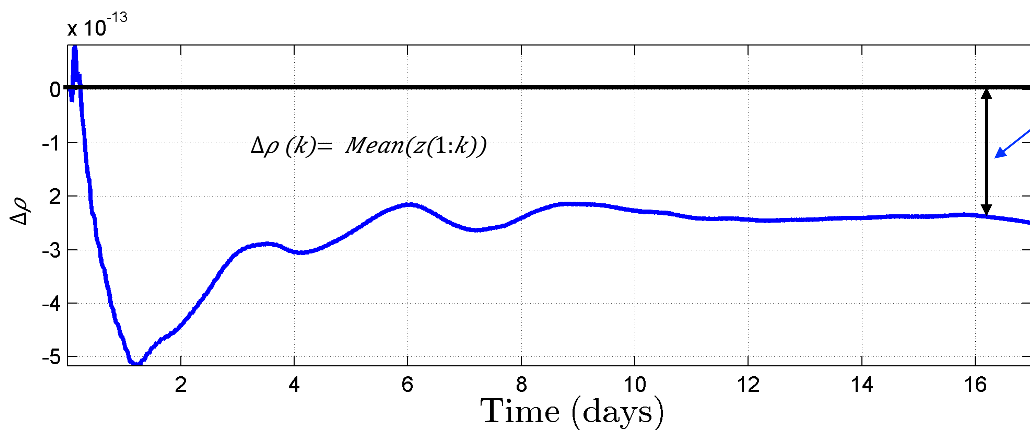
## RCAISE also corrects the neutral density at GRACE's location





GRACE neutral density data is **NOT** assimilated

This data is used only as a quality metric

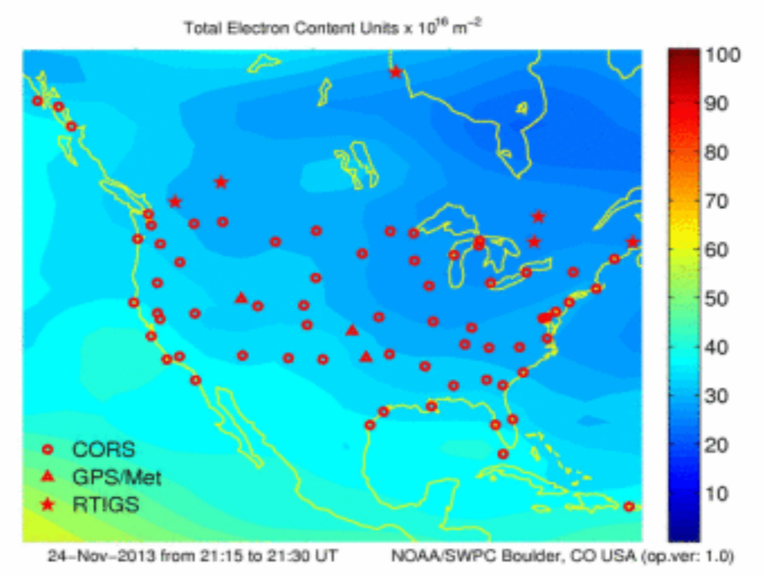



**This error may be due to what scientists believe is a calibration error in the GRACE data**

# Estimate Eddy Diffusion Coefficient in GITM using Total Electron Content

- Total electron content (or TEC) is an important descriptive quantity for the ionosphere.

- TEC is the **total number of electrons** integrated **between two points**, along a tube of one meter squared cross section. Units are **1 TECU=**$\mathbf{10^{16}\ m^{-2}}$




TEC plot for the continental USA, made on 11/24/2013

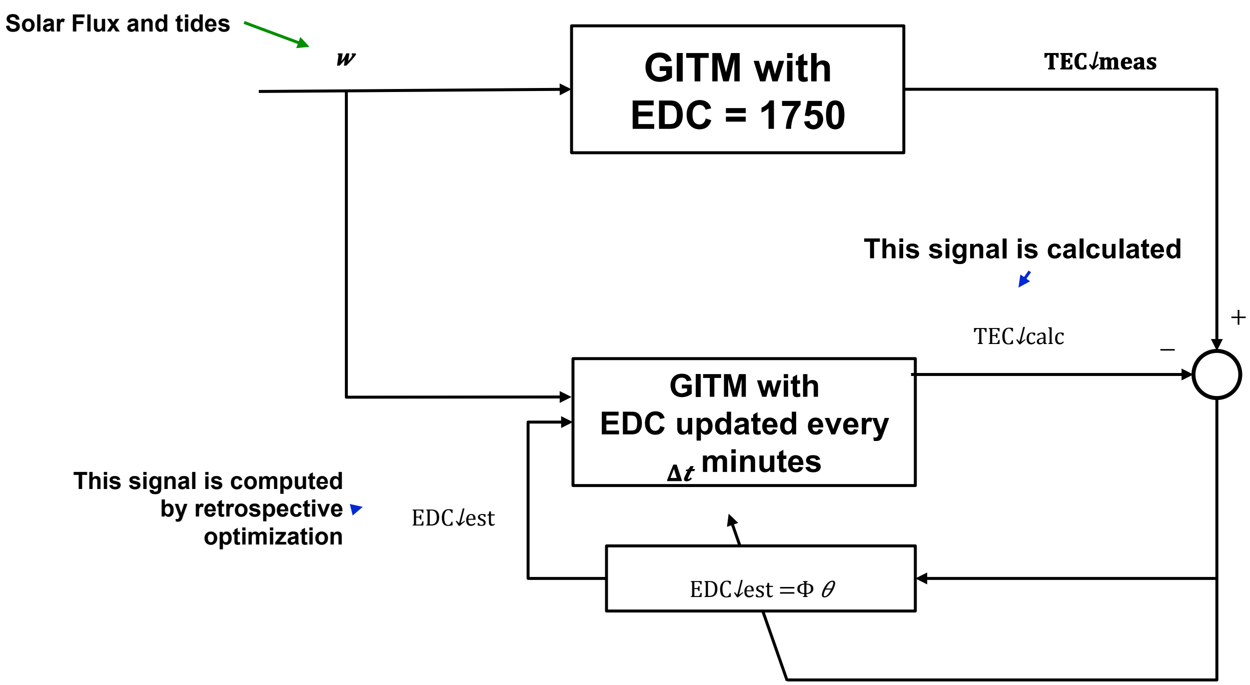
CORS = Continuously Operating Reference Stations.

GPS/Met = Ground-Based GPS Meteorology.

RTIGS = Real Time International GNSS Service.

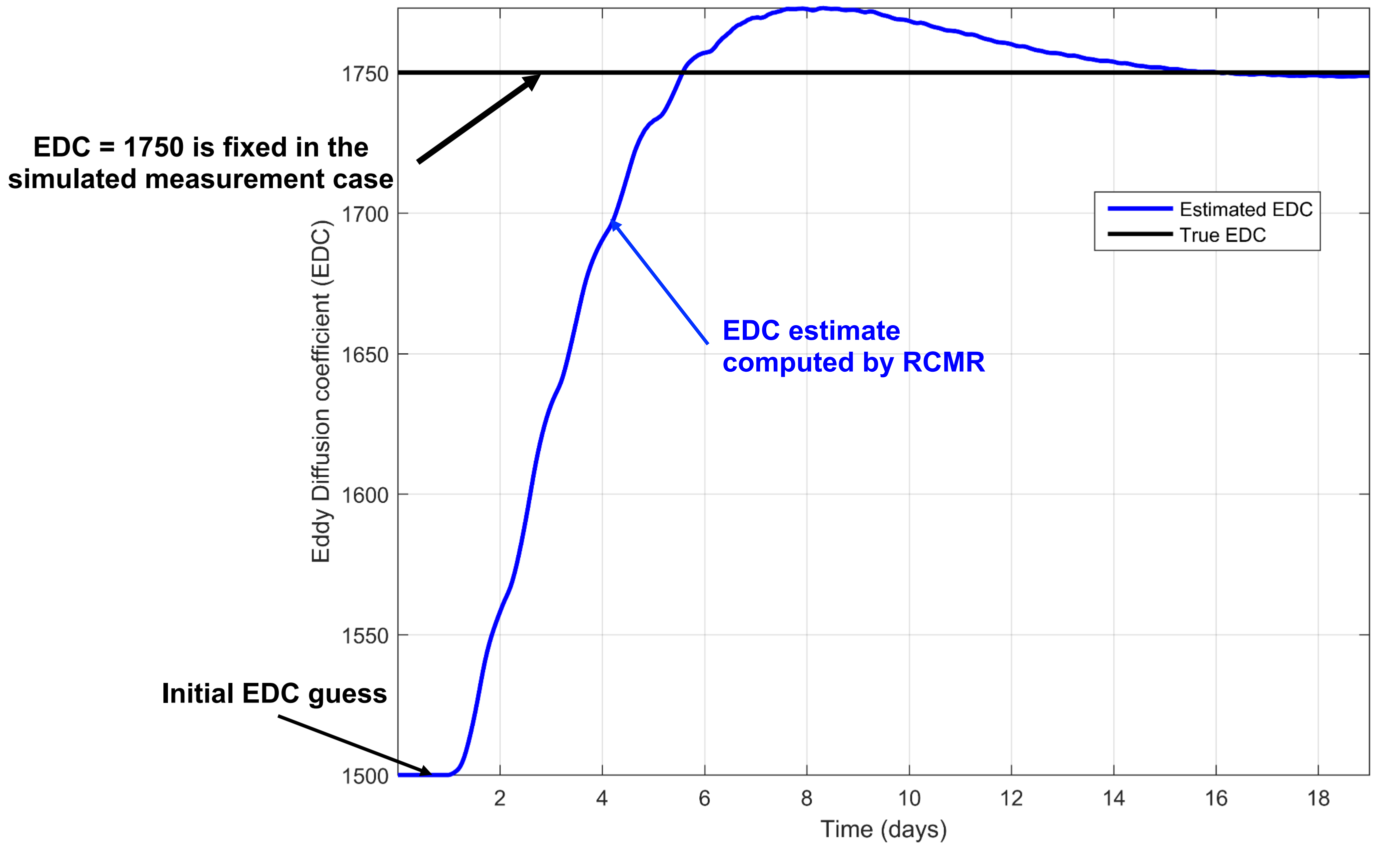
GNSS = Global Navigation Satellite Systems.

# Estimate Eddy Diffusion Coefficient in GITM using Total Electron Content

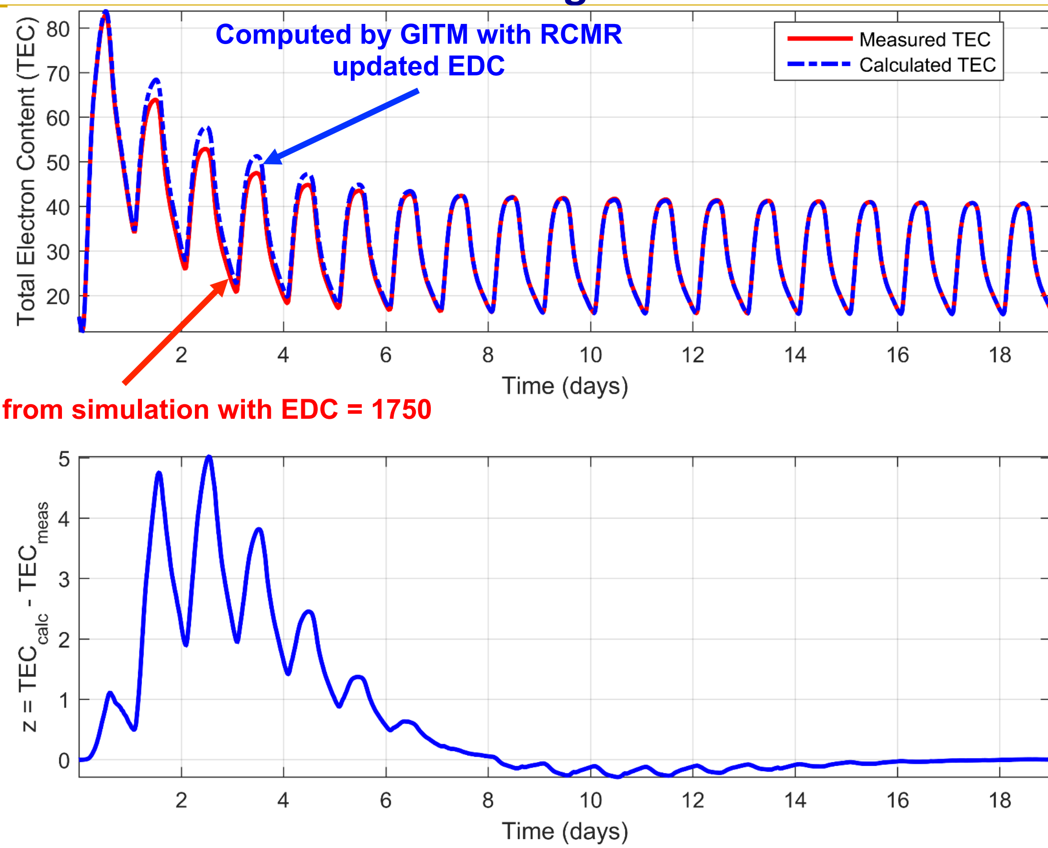



$$z = TEC_{calc} - TEC_{meas}$$

# Estimate Eddy Diffusion Coefficient in GITM using Total Electron Content



# Estimate Eddy Diffusion Coefficient in GITM using Total Electron Content





**TEC is measured at a fictional TEC station near Somalia**

# RCMR/RCAISE versus Standard Methods

- RCAISE does not provide statistical error measures
  - No estimate of covariance or probability distribution
  - Uses no priors---not Bayesian
  - Uses no ensemble---only a single simulation
- Uses only linear least squares techniques
  - Requires no adjoint code (none is available for GITM)
- Computationally inexpensive
  - Adds minutes to multi-hour ensemble data assimilation
  - But requires estimates of H's---determined by numerical testing
- May be useful as an adjunct to ensemble codes
  - For model refinement or input estimation in strongly driven systems----- systems whose evolution is primarily due to external inputs

## Latest in RCMR – Concurrent Optimization



- RCMR requires minimal modeling information (H values)
  - Since no analytical model is available, this modeling information has been found by numerical testing
  - For EDC estimation this is tedious
  - We seek an efficient technique for concurrent optimization

- For adaptive control we have developed concurrent optimization
  - Frantisek Sobolic, Ankit Goel, Dennis S. Bernstein, " Retrospective-Cost Adaptive Control Using Concurrent Controller and Target-Model Optimization," submitted to ACC 2016.

## Questions?