Application of DDDAS to Space Weather Monitoring

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Project Objectives

- Develop new ideas and techniques within DDDAS to facilitate the creation of a constellation of small spacecraft for space weather monitoring

- DDDAS Team: Aaron Ridley, Jamie Cutler, Amy Cohn
  - Aaron Ridley: Developed ionosphere-thermosphere model code
  - Amy Cohn: Develops and applies optimization techniques
  - James Cutler: Designs, builds, and flies sensors and spacecraft
  - Angeline Burrell: Postdoc
Advances in DDDAS with Application to Space Weather Modeling

- **Scientific Motivation**
  - Unknown changes to the atmospheric density degrade the accuracy of GPS and impede the ability to track space objects

- **Project Scope and Objectives**
  - Apply DDDAS concepts and methods to space weather monitoring
  - Key goals are input estimation and model refinement to facilitate higher-accuracy data assimilation
  - Input reconstruction is used to estimate atmospheric drivers that determine the evolution of the ionosphere-thermosphere
  - Model refinement is used to improve the accuracy of atmospheric models
  - DDDAS supported by space physics modeling and mission planning and analysis

Auroral Heating

Wind Field Estimation

RAX-2 CubeSat

Space Debris
Nanosat Constellation Measurement Tracks
Adaptive physics: Ionospheric and thermospheric density can vary dramatically, both spatially and temporally, after energy input.

Upper atmospheric heating due to currents and the aurora takes place on small scales, but over a broad region.

RAX—Radio Aurora Explorer
RAX-1 launched Nov. 19, 2010
RAX-2 launched Oct. 28, 2011

RAX-2 is currently performing scientific experiments and downloading daily to a global ground network.

CADRE—prototype for a future 50-nanosat fleet

Armada—50-nanosat constellation with continuously varying orbits

Small Satellite Operational Challenges

1) Downloading is challenging due to lack of centralized control of low-cost, inefficient, independently owned and operated globally distributed ground networks.

2) Current stations track only a single or handful of satellites. Capacity could increase significantly if they tracked multiple satellites.

3) Small satellites are highly constrained in mass, size, and power, which limits their ability to download large amounts of scientific data.

Research Goal: Optimize satellite operations and global ground networks.
On-Orbit Magnetometer Calibration

**Problem:** Magnetometer measurements are degraded by nearby electronics
- Physical separation or magnetic cleanliness requirements add complexity to the vehicle design

**Idea:** Compensate for the magnetometer errors using only flight data
- Remove the need for pre-flight calibration and location constraints

**Approach:** Minimize the difference between the measured and expected (IGRF) field magnitudes
- Include current monitoring from spacecraft health monitoring in the measurement model
- Estimate constant parameters that map time-varying electrical activity to magnetometer bias

**Result:** Removes magnetic field bias caused by the spacecraft and requires no pre-flight calibration
- Uncertainty in magnetometer measurements reduced to nearly that of the stand-alone, de-integrated sensor
- Method has been demonstrated with attitude-grade magnetometers on-orbit

Measured magnitude & IGRF without compensation for time-varying error

Measured magnitude after calibration

RAX-1 Flight Unit
Optimization Techniques for Satellite Scheduling – Stochastic and Deterministic Approaches

- Competing, scarce resources (energy, ground station availability, etc.) make the scheduling of data downloads a complex optimization problem
  - Deterministic version:
    - All data known in advance – energy cost, data acquisition and transmission rates, storage capabilities, ground station access
    - Solvable using cutting-edge modeling and integer programming techniques

Comparison of download strategies
Space weather refers to the conditions in the Solar system caused by variations in the Sun.

- Long term variations in the solar irradiance, radiation, and magnetic field occur on the scale of decades.
- Short term solar disturbances can occur in minutes or persist for days.

Figures: SDO/AVI; NOAA/SWPC
Space weather affects many regions of the terrestrial environment.

Typical space weather disturbances are limited to specific regions, where they 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.

Figures: NASA; CEDAR Strategic Plan (2010)
Orbit Determination

- Orbit determination is an essential part of communications, navigation, and space exploration
- Orbital prediction error is principally caused by problems estimating atmospheric drag
- Predicting atmospheric drag requires the prediction of the atmospheric density and an understanding of 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 Knowledgebase
  - EMBRACE – Estudo e Monitoramento Brasileiro do Clima Espacial

- **Models**
  - Empirical
  - Physics-based
  - Assimilative

Figures: NASA
Space Weather at the University of Michigan

- **Instruments**
  - FPI Network
  - Satellites
    - ACE (1997-Present)
    - STEREO (2006-Present)
    - CADRE (2014)
    - MMS (2015)

- **Models**
  - BATSRUS
  - HEIDI
  - AMIE
  - GITM
CADRE – CubeSat investigating Atmospheric Density Response to Extreme driving

- 3-unit CubeSat that will test the WINCS instrument and the implementation of deployable solar panels
- WINCS - Wind Ion Neutral Composition Suite
  - Measures ion and neutral densities, temperatures, compositions, and velocities
  - Composed of 4 electrostatic analyzers and 3 mass spectrometers
  - Currently deployed on the International Space Station
- Will have a low earth orbit that passes through the auroral oval
- Precursor to the future Armada mission, which will deploy a network of nano satellites using similar instrumentation to CADRE
- Simultaneous observations of ion and neutral particles makes it possible to investigate ion neutral coupling processes, as well as the state and dynamics of the ionosphere and thermosphere
GITM – Global Ionosphere Thermosphere Model

- Physics-based model of the ionosphere-thermosphere
  - Currently configured to model Earth, Titian, or Mars
  - Solves for neutral winds, ion and electron velocities, as well as neutral, ion, and electron temperatures
  - Uses non-steady state explicit chemistry
- Uses a 3D spherical grid that can be stretched in latitude and altitude or a 1D altitude profile
  - Altitude-based grid allows the model to consider solutions other than hydrostatic equilibrium
    - Coriolis
    - Vertical ion drag
    - Altitude-dependent gravity
    - Massive heating in auroral zone
- Flexible initialization process, many source term and modeling methods may be specified without changing or recompiling the code
Running GITM

- Physical drivers and boundary conditions can be specified at input
  - Different high-latitude models are available to specify the ionosphere-magnetosphere boundary
  - Several models for lower-atmospheric tides are provided
  - A simple dipole or apex magnetic field can be used
  - Solar and geomagnetic inputs can be provided to simulate disturbed or quiescent conditions

- GITM is fully parallel
  - The number of processors is determined by the resolution
  - Typical resolutions are (longitude blocks)x(latitude blocks):
    - 2x2 (4 processors) – Testing purposes
    - 8x8 (64 processors) – Low resolution physical runs
    - 8x12 (96 processors) – Medium resolution physical runs
    - 12x24 (288 processors) – High resolution physical runs
  - Can be restarted if a run is interrupted

- Different output formats are available
  - Maximum temporal resolution of 3 minutes
  - 2D and 3D files with different magnetic, ionospheric, and thermospheric quantities
  - Altitude profiles can be output along a specified satellite track
Investigating Space Weather Events with GITM

GITM runs using the spectra from a solar flare seen on July 14, 2000

Figures: SOHO, Jie Zhu

- Current sub-solar point
- Sub-solar point at time of flare
- Current midnight point
Investigating Space Weather Events with GITM

GITM run during geomagnetic storm Dec 11-16, 2006

Photoelectron Heating Efficiency = 0.06

Photoelectron Heating Efficiency = 0.12
DDDAS Supporting Technology

- State estimation (data assimilation)
  - Use measurements and the model to estimate unmeasured states

- Input estimation (extension of data assimilation)
  - Use measurements and the model to estimate unmeasured inputs

- Model refinement
  - Use measurements to improve an initial model
    - Full or reduced, high or low resolution
  - How? Identify inaccessible subsystems!!
Model Refinement as Inaccessible Subsystem Identification

These signals are not accessible

These missing physics are identified
Retrospective Cost Model Refinement

- Retrospective cost methods provide estimates of the inaccessible signal, which can then be used in estimation and identification.

\[ w(k) \rightarrow \text{Physical System} \rightarrow y_0(k) \]

\[ u(k) \rightarrow \text{Unknown Subsystem} \]

\[ y(k) \rightarrow \text{Physical System Model} \rightarrow \hat{y}_0(k) \]

\[ \hat{u}(k) \rightarrow \text{Adaptive Feedback System} \rightarrow \hat{y}(k) \]

\[ z(k) \rightarrow \text{Output Optimization} \]

1) Use \( z(k) \) to obtain optimized inputs.
2) Use optimized inputs to update the adaptive feedback system.
3) Use the adaptive feedback system to obtain \( \hat{u}(k) \).
Input Reconstruction Is Adaptive Control!
Example 1: Series RLC circuit

- Driving signal is circuit voltage.
- Measurement is voltage across the resistor.
- Equations of Motion are analogous to MCK systems
- We assume that the inductance and the capacitance are unknown.

\[ L\ddot{x} + R\dot{x} + \frac{1}{C_d} x = u, \]
Estimates of L and C

- True value
- Refined estimate
- Initial estimate

Estimated inductance

- Initial estimate
- True value
- Refined estimate

Estimated capacitance
These parameters are all related to $U_0$

\[
\begin{bmatrix}
& \delta \alpha \\delta \theta \\
\delta \alpha & & & \delta \theta \\
\delta \theta & & & \delta \theta \\
\end{bmatrix}
= 
\begin{bmatrix}
X_{U_0} + X_{T_{\alpha 0}} & X_{\alpha_0} & X_{q_0} & -g \\
\frac{Z_{U_0} + Z_{T_{\alpha 0}}}{U_0} & \frac{Z_{\alpha_0}}{U_0} & \frac{U_0 + Z_{q_0}}{U_0} & M_{q_0} \\
M_{U_0} + M_{T_{\alpha 0}} & M_{\alpha_0} + M_{T_{\alpha 0}} & M_{\alpha_0} + M_{T_{\alpha 0}} & M_{q_0} \\
0 & 0 & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
u \\
\delta \alpha \\
q \\
\theta \\
\end{bmatrix}
+ 
\begin{bmatrix}
X_{\delta \alpha_0} \\
\frac{Z_{\delta \alpha_0}}{U_0} \\
\frac{U_0 + Z_{q_0}}{U_0} \\
M_{\delta \alpha_0} \\
\end{bmatrix}\delta e
\]

$y = \theta$ Only pitch angle measurement is used

$U_{0\text{ true}} = 675 \text{ ft} / \text{s}, U_{0\text{ true}} = 625 \text{ ft} / \text{s}$

RCMR estimates the trim speed

Trim speed estimate
**RCMR Example: Battery Health Monitoring**

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

### Diagram

- **Voltage/Current**
- **Film Thickness**
- **Estimated Film Thickness**
- **Main Battery System**
- **Unknown Film Growth Subsystem**
- **Resistive Film $d_{film}$**
- **Side Reaction**
- **Intercalation Current $j_S$**
- **Main Battery System Model**
- **Adaptive Film Growth Subsystem Model**
- **RCMR**
- **Sidecurrent**

### Graph

- **Film resistance [Ωm⁻²]**
- **Time [s]**

- Estimated value
- True value
Discretize the aircraft plant using zero order hold

\[ T_s \]

\( T_s = 0.1s \)

\[
x_1(k + 1) = x_1(k) + T_s x_2(k),
\]

\[
x_2(k + 1) = x_2(k) + T_s (1 - x_1(k)^2) x_2(k) - T_s x_1(k) + T_s u(k),
\]

\[
y(k) = x_1(k) + 0.2x_2(k),
\]

RCAISE Example: Van der Pol Oscillator

Figure 12. Phase portrait of the Van der Pol oscillator.

RCAISE estimates the states and the input

Unknown Input
Retrospective Cost Methods

- Optimize the error over a data window to determine the unknown input
  - Originally developed for adaptive control (RCAC)
  - Applicable to state and input estimation (RCAISE)
  - Applicable to model refinement (RCMR)

- Algorithm is computationally inexpensive
  - Uses minimal modeling details
  - Applicable to large-scale coded models (no analytic model needed)

- Algorithm is easy to implement
  - Uses only least squares techniques
RCMR/RCAISE versus Standard Methods

- RCAISE does not provide statistical error measures
  - Does not estimate covariance or PDF
  - Uses no priors---not Bayesian
  - Uses no ensemble---only a single simulation
- Uses only linear least squares techniques
  - Requires no adjoint code (not available for GITM)
- Computationally inexpensive
  - Simulation + 1%
- Limited to strongly driven systems
  - Can facilitate ensemble codes in other applications
Identification of NO (Nitrous Oxide) Cooling

These signals are not accessible

These missing physics are identified
Estimated Cooling Profiles Using Simulation Truth Data

(a) NO cooling as function of altitude at 0.5 days.
(b) NO cooling as function of altitude at 0.8 days.
(c) NO cooling as function of altitude at 1.6 days.
(d) NO cooling as function of altitude at 2.7 days.
**GITM Inaccuracies**

- GITM uses an empirical model (the EUVAC model) that determines solar flux in 37 wavelengths using daily and averaged $F_{10.7}$ values

- **Objective**: Use data from measurement satellites to estimate a value of $F_{10.7}$ that causes GITM outputs to more closely follow satellite data
  - Note: $F_{10.7}$ measurements are provided by an observatory in B.C., Canada but only once per day
  - $F_{10.7}$ is only a proxy for the EUV radiation, and does not capture the true solar irradiance at solar minimum
Case 1: Simulated (computed, not “real”) Satellite Data

- We first simulate the truth model with the true $F_{10.7}$ and record the computed neutral density output at CHAMP satellite locations
  - This is the truth CHAMP data
- Assuming that $F_{10.7}$ is unknown, we combine RCAISE with GITM to estimate $F_{10.7}$ using the truth CHAMP data
- As a validation metric, we compare estimates of the temperature at 400 km above Ann Arbor with the true values
- **Note:** In this case, there are no modeling inaccuracies.
Case 1: Simulated Satellite Data: Input Estimate

- The estimate of $F_{10.7}$ provided by RCAISE converges to the true value of $F_{10.7}$, and follows it afterwards.

![Graph showing the comparison of estimated and true values of $F_{10.7}$ over time.](image-url)
Case 1: Simulated Satellite Data: State Estimates

- The neutral density estimate from RCAISE+GITM converges to the truth CHAMP data
Case 1: Simulated Satellite Data: Another State Estimate

- The RCAISE estimate of the temperature above Ann Arbor converges to its true value

![Temperature Estimate Graph]
Case 2: Real Satellite Data with Pretuned Photoelectron Heating

- We assimilate CHAMP satellite data (neutral density measurements) from 2002-11-24 to 2002-12-06
- But these are no longer truth measurements---GITM has modeling errors!
- We pre-tune GITM’s photoelectron heating (PEH) so that its computed outputs with measured $F_{10.7}$ follow the real CHAMP measurements
  - $F_{10.7}$ values provided by the observatory in B.C., Canada are for pretuning but not for by RCAISE
- We see whether RCAISE can correctly estimate the measured $F_{10.7}$ used to pretune photoelectron heating
- As a validation metric, we use neutral density measurements from the GRACE satellite (but these are NOT assimilated)
- Why do this?? Because it provides:
  - 1) A test of RCAISE: If we knew PEH, we could estimate $F_{10.7}$
  - 2) An indirect approach to determining PEH physics assuming $F_{10.7}$ is accurate
Case 2: Real CHAMP Data with Pretuned PEH: F10.7 Estimates

- The 1-day average of the estimated $F_{10.7}$ converges to within 6 SFU of the measured $F_{10.7}$
  - GITM reconstructed the measured $F_{10.7}$ from CHAMP measurements
  - SFU = solar flux

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<thead>
<tr>
<th>Case</th>
<th>Real CHAMP Data with Pretuned PEH: F10.7 Estimates</th>
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<tbody>
<tr>
<td>2</td>
<td>Averaged RCAISE Estimate</td>
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F10.7 from RCAISE
Averaged RCAISE Estimate
Measured F10.7
Case 2: Real CHAMP Data with Pretuned PEH: CHAMP Location Estimates

- GITM+RCAISE reduces the error in neutral density by 6% at CHAMP locations as compared to GITM with measured $F_{10.7}$ but no RCAISE

- True neutral density (via CHAMP)
- GITM with measured $F_{10.7}$ (no estimation)
- GITM+RCAISE (estimates $F_{10.7}$ and neutral density)
**Case 2: Real CHAMP Data with Pretuned PEH: GRACE Location Estimates**

- GITM with RCAISE yields a 11% reduction in error in neutral density at **GRACE** locations as compared to GITM with measured $F_{10.7}$.

![Graph showing the comparison of neutral density estimates](image)

- True neutral density (via GRACE)
- GITM with measured $F_{10.7}$
- GITM+RCAISE
Summary and Future Work

- Our goal is to make models more accurate (RCMR) and estimate states and inputs (RCAISE)
  - RCAISE is applicable to strongly driven systems
  - RCMR refines models by identifying inaccessible subsystems

- Future research: RCMR for 3D GITM----in search of new physics
  - Heating/cooling models, eddy diffusion, other physics and data

- RCAISE and RCMR are potentially applicable to other DDDAS applications with unknown inputs and significant modeling errors