Global Snow from Space: Development of a Satellite-based, Terrestrial Snow Mission Planning Tool

Prof. Bart Forman (PI, UMD)

Dr. Sujay Kumar (Co-I, GSFC)

Dr. Jacqueline Le Moigne (Co-I, GSFC)

Dr. Sreeja Nag (Co-I, GSFC)

Dr. Yeosang Yoon (GSFC)

Dr. Rhae Sung Kim (GSFC)

Matthew Holland (GSFC)

Dr. Yonghwan Kwon (UMD)

Jongmin Park (UMD)

Lizhao Wang (UMD)

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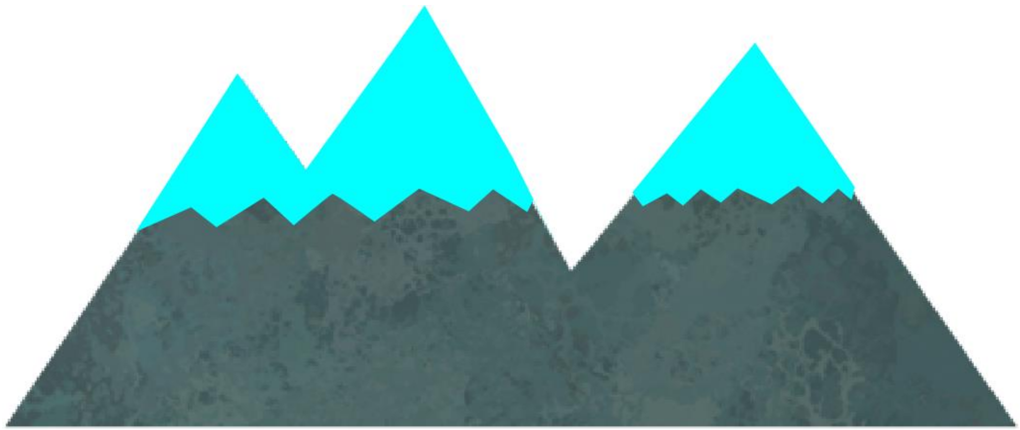
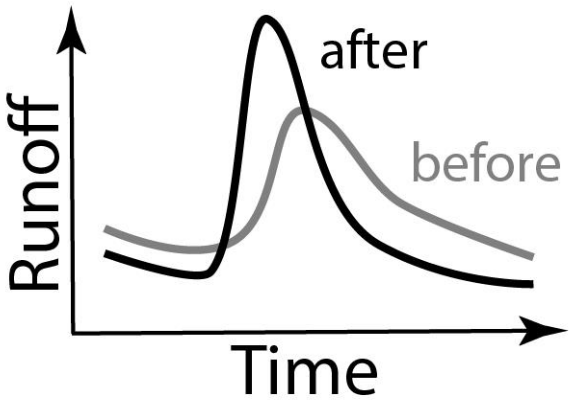
Importance of Snow

- Snow is a **significant contributor** to terrestrial freshwater supply
  - Up to 80% of runoff in some Western states
- Vital resource for **~billion people** worldwide
  - Not exactly sure **how much snow** is out there
  - **Difficult to measure**; significant uncertainty;
- Global warming → rising snow line
  - **reduced** virtual reservoir; **accelerated** hydrologic cycle;





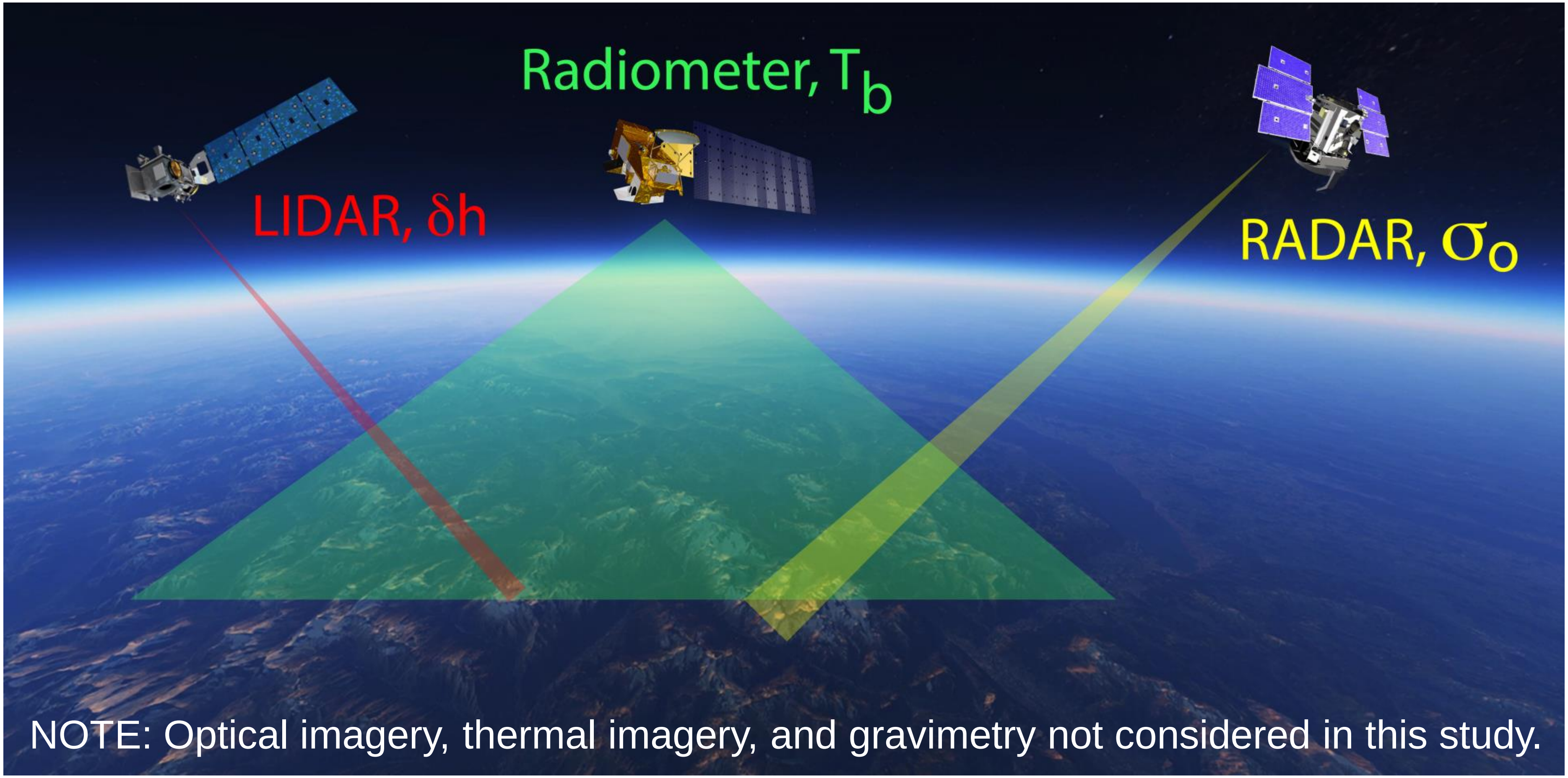
NASA Decadal Survey

- Global warming → rising snow line → **reduced virtual reservoir**
- Goal is to improve snow mass estimation at regional / continental scales
  - **No dedicated snow mission**
  - **Water security** → food+energy security → national security

TABLE S.1 Science and Applications Priorities for the Decade 2017-2027

Science and Applications Area	Science and Applications Questions Addressed by **MOST IMPORTANT** Objectives
Coupling of the Water and Energy Cycles	**(H-1)** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods? **(H-2)** How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally and globally and what are the short- and long-term consequences?

Satellite-derived Snow "Information"

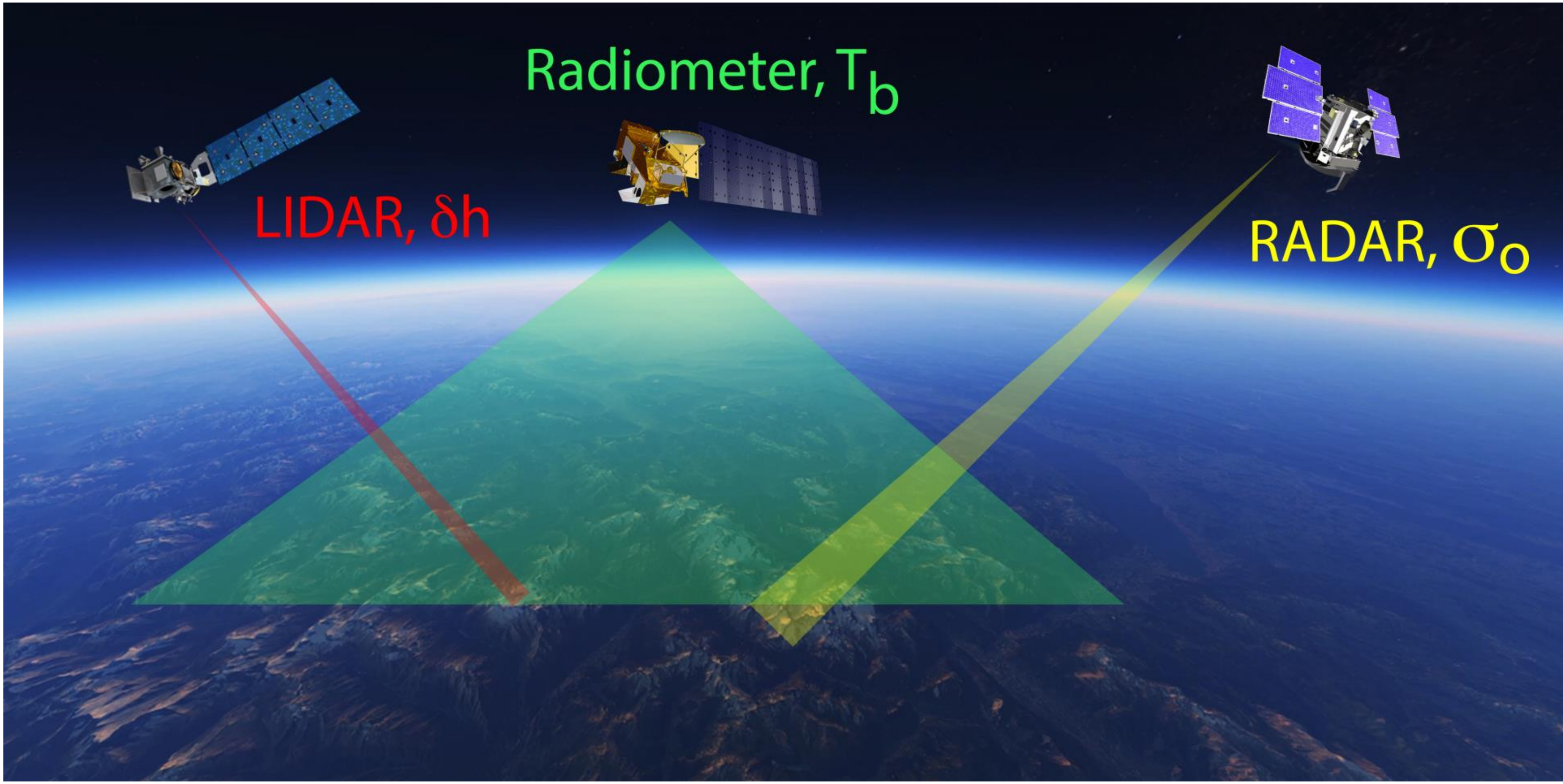


Research Objectives

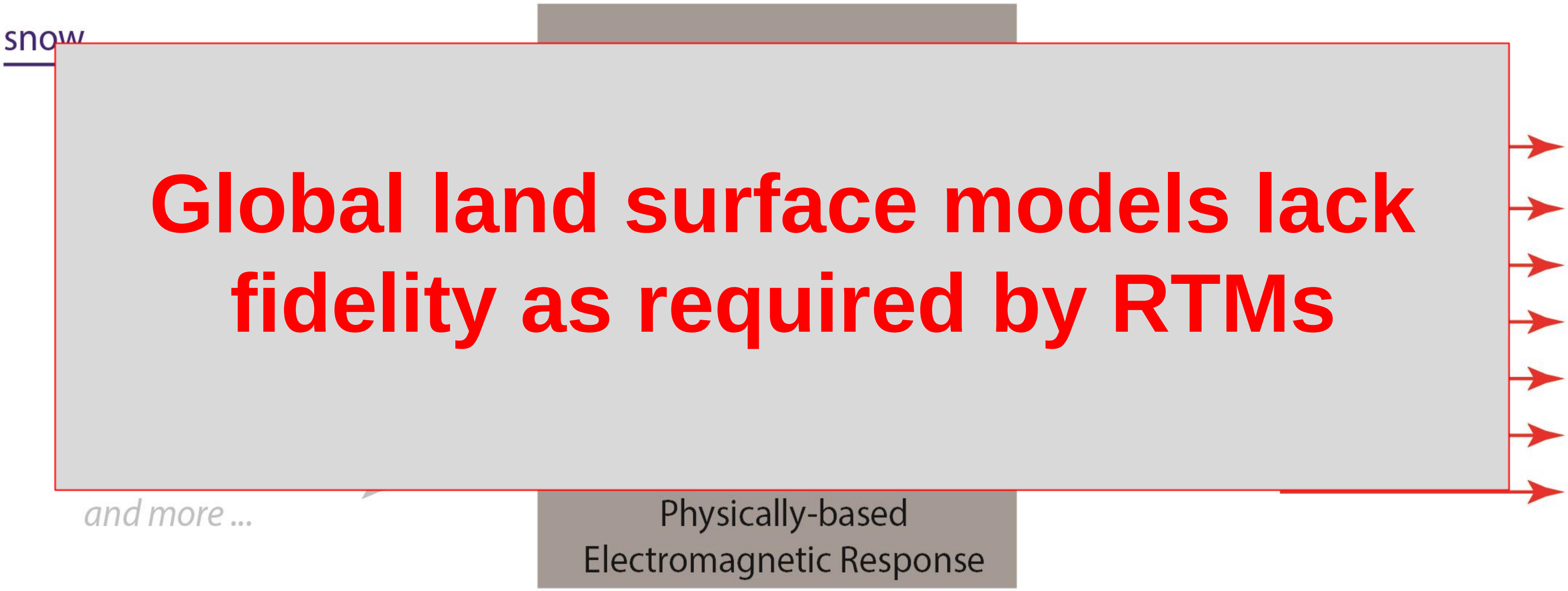
Science and mission planning questions

1) What observational records are needed (in space and time) to maximize terrestrial snow experimental utility?
2) How might observations be coordinated (in space and time) to maximize this utility?
3) What is the additional utility associated with an additional observation?
4) How can future mission costs be minimized while ensuring Science requirements are fulfilled?

Geophysical to Observational Space



Radiative Transfer Models (RTMs)



Inputs from
Snow Hydrology Model

Tb Observation Operator
Microwave Emission Model
(a.k.a., Radiative Transfer)

Multi-frequency,
Multi-polariztion
Brightness Temperatures

Machine Learning "Emulators"

atmosphere

$T_{2\text{-meters}}$

vegetation

T_{skin}

snow

SWE

$\rho(z)$

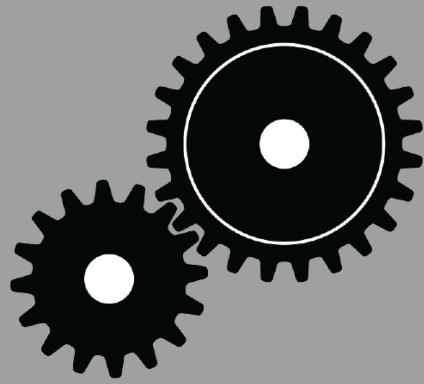
$T(z)$

SLWC

soil

T_{surf}

NASA Catchment
Land Surface Model
(Koster et al., 2000)



Xue and Forman, 2015
Remote Sensing of Environ.

Tb Observation Operator
(Forman et al., 2014;
Forman and Reichle, 2014;
Forman and Xue, 2016)

backscatter

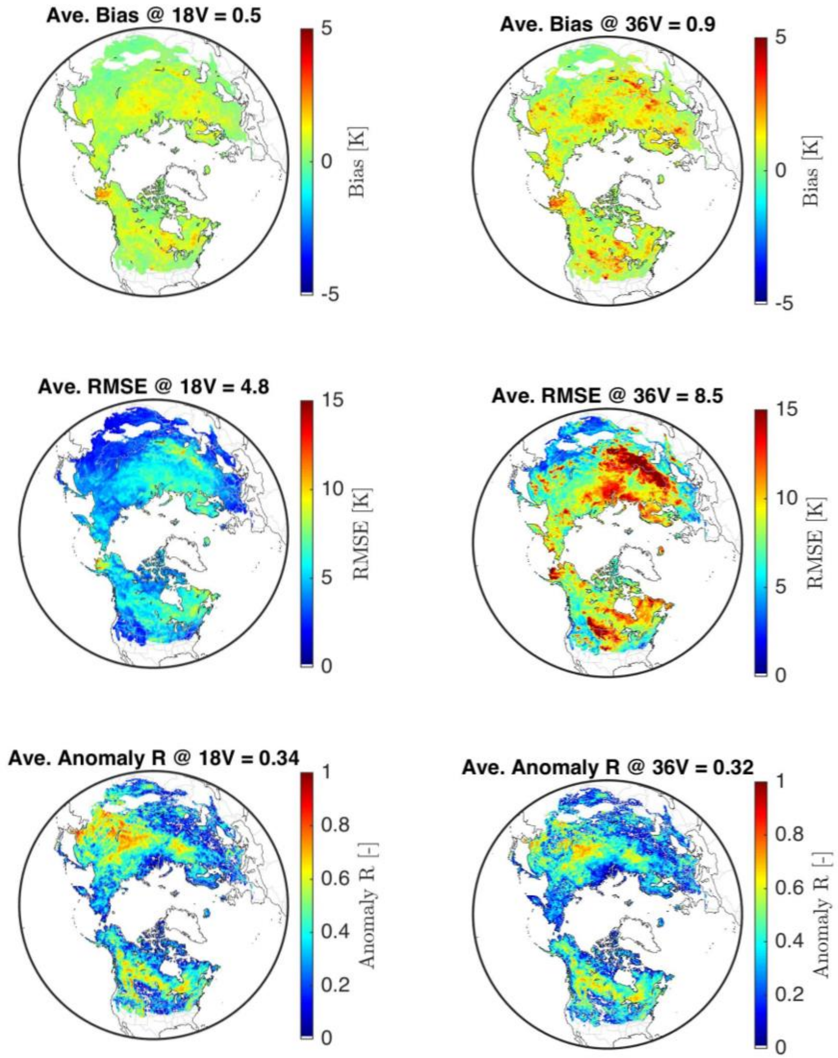
σ_{VH}

σ_{VV}

Multi-frequency,
Multi-polariztion
Training Targets

Machine Learning Performance

18.7 GHz, V-pol | **36.5 GHz, V-pol**



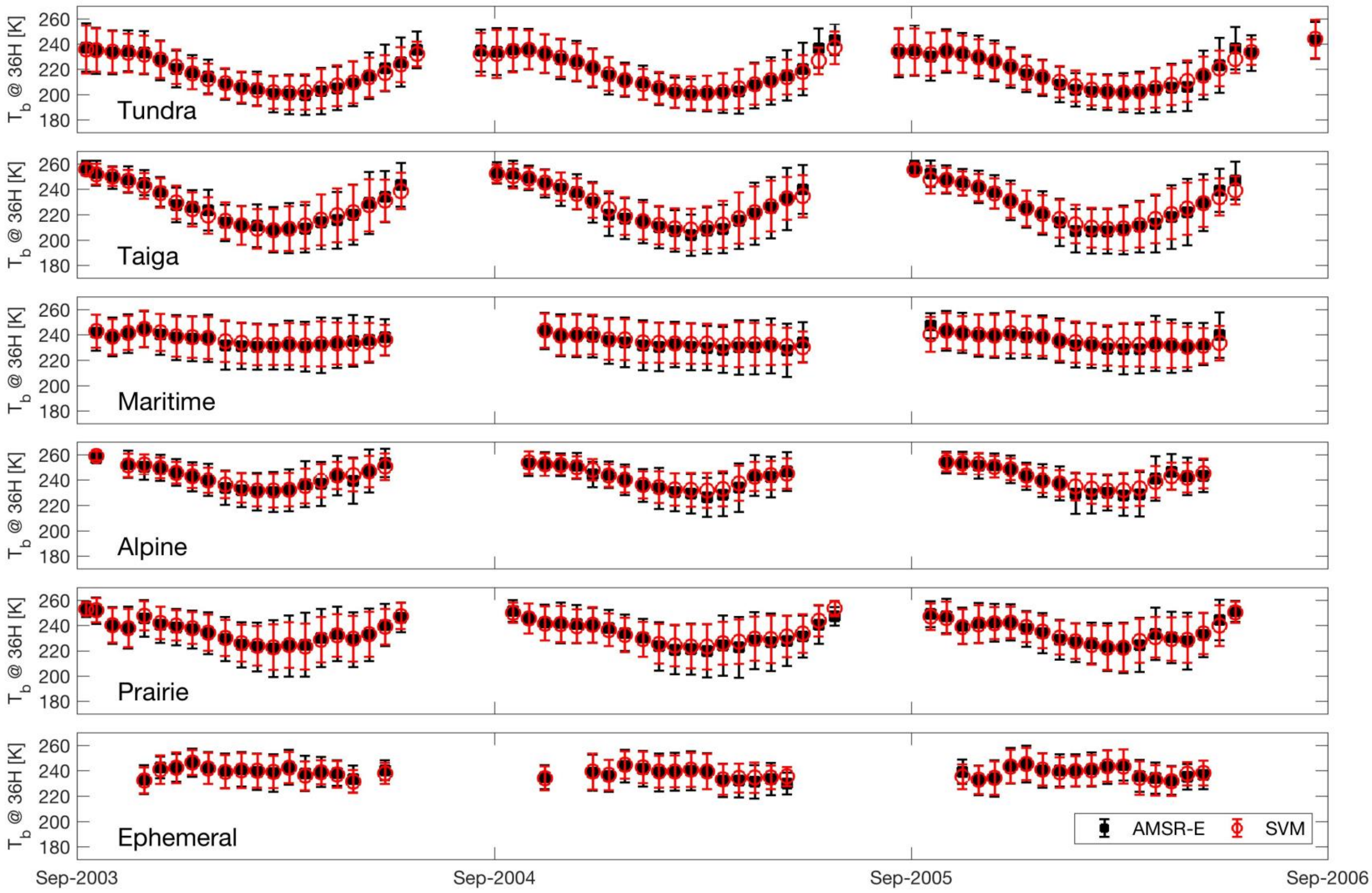
Bias

RMSE

Anomaly Correlation

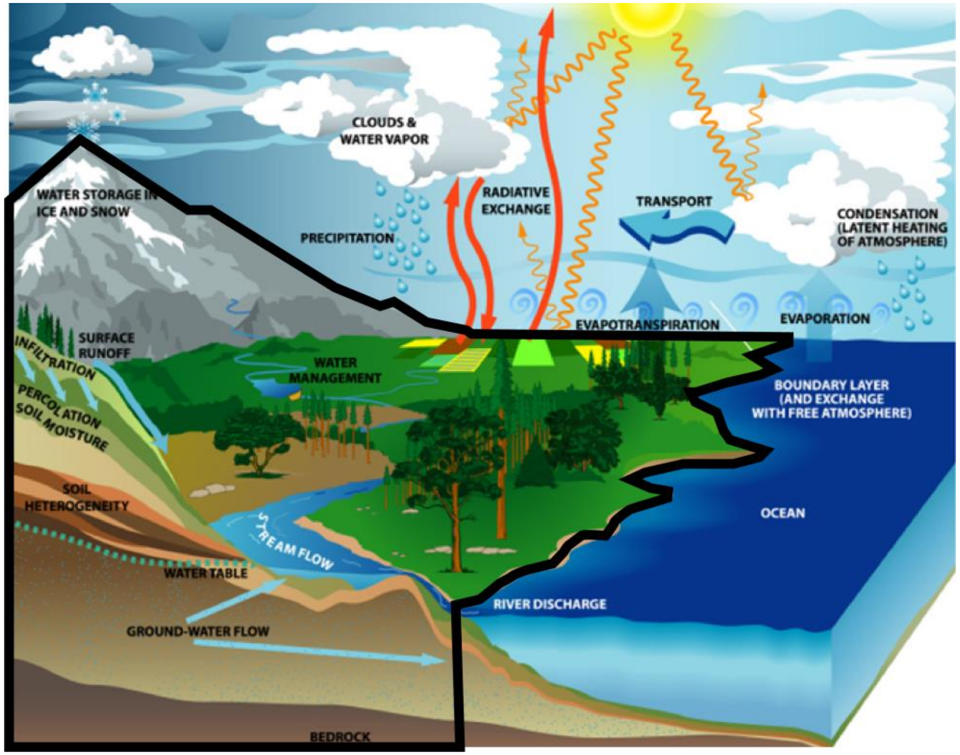
NOTE: Comparisons against AMSR-E observations ***not*** used during training.

Spatiotemporal Variability



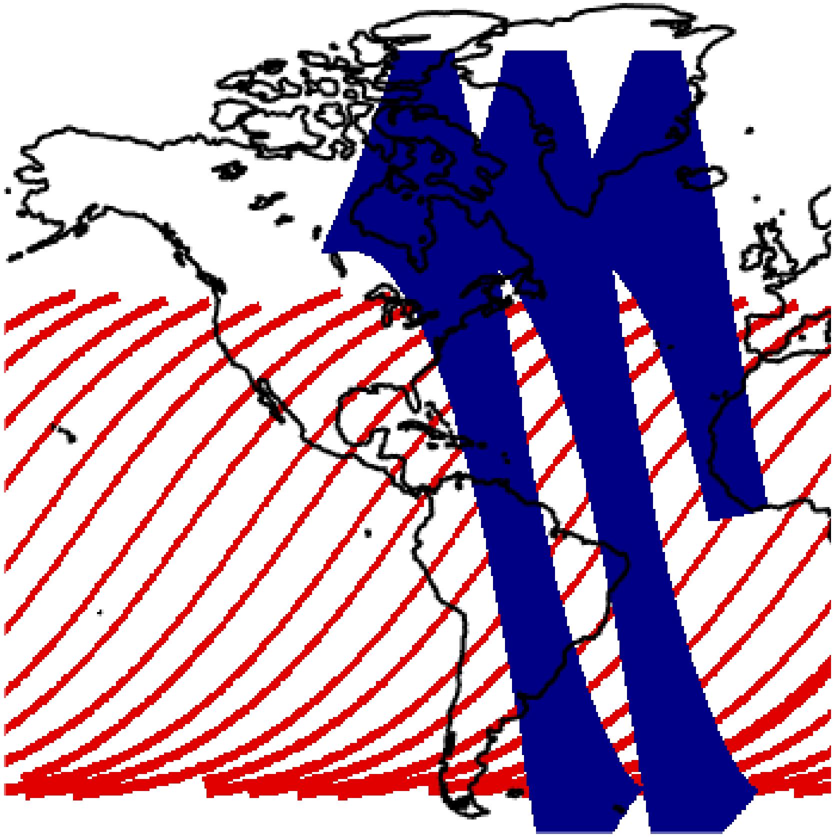
NASA Land Information System (LIS)

- Models **land surface processes** (including snow)
- Integrates satellite-based **observational data** products with land surface **modeling and data assimilation techniques**



Kumar et al. (2006), Land Information System: An interoperable framework for high resolution land surface modeling, Environmental Modeling and Software

Trade Space Analysis Tool for Constellations (TAT-C)

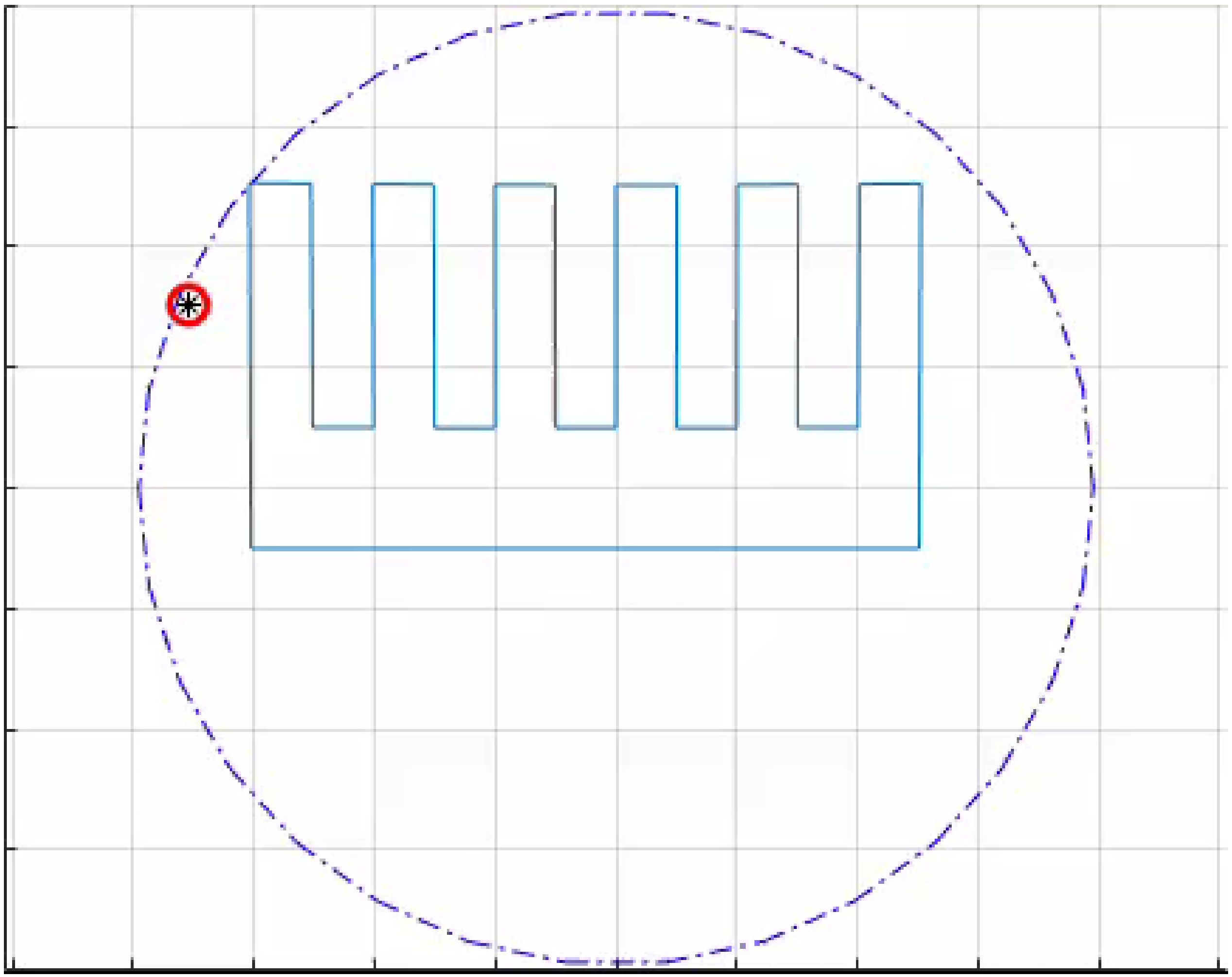


- Explore **trade-off** between engineering and science
  - Field-of-View (FOV)?
  - Platform altitude?
  - Orbital configuration(s)?
  - Single platform vs. constellation?
  - Repeat cycle?
- How do we get the most **scientific bang** for our buck?

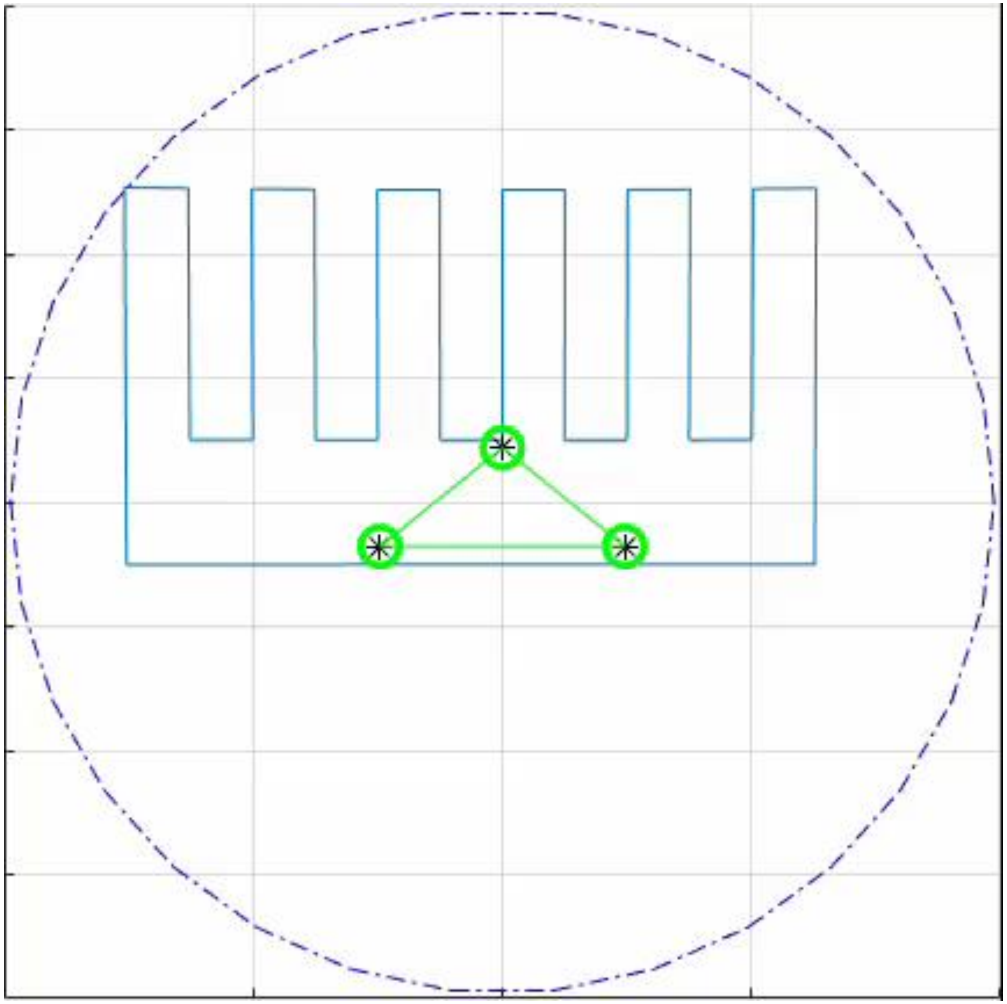
4-hour Radiometer Viewing in Polar Orbit (Ascending Overpasses Only, e.g.)

4-hour RADAR Viewing in Inclined Orbit (Descending Overpasses Only, e.g.)

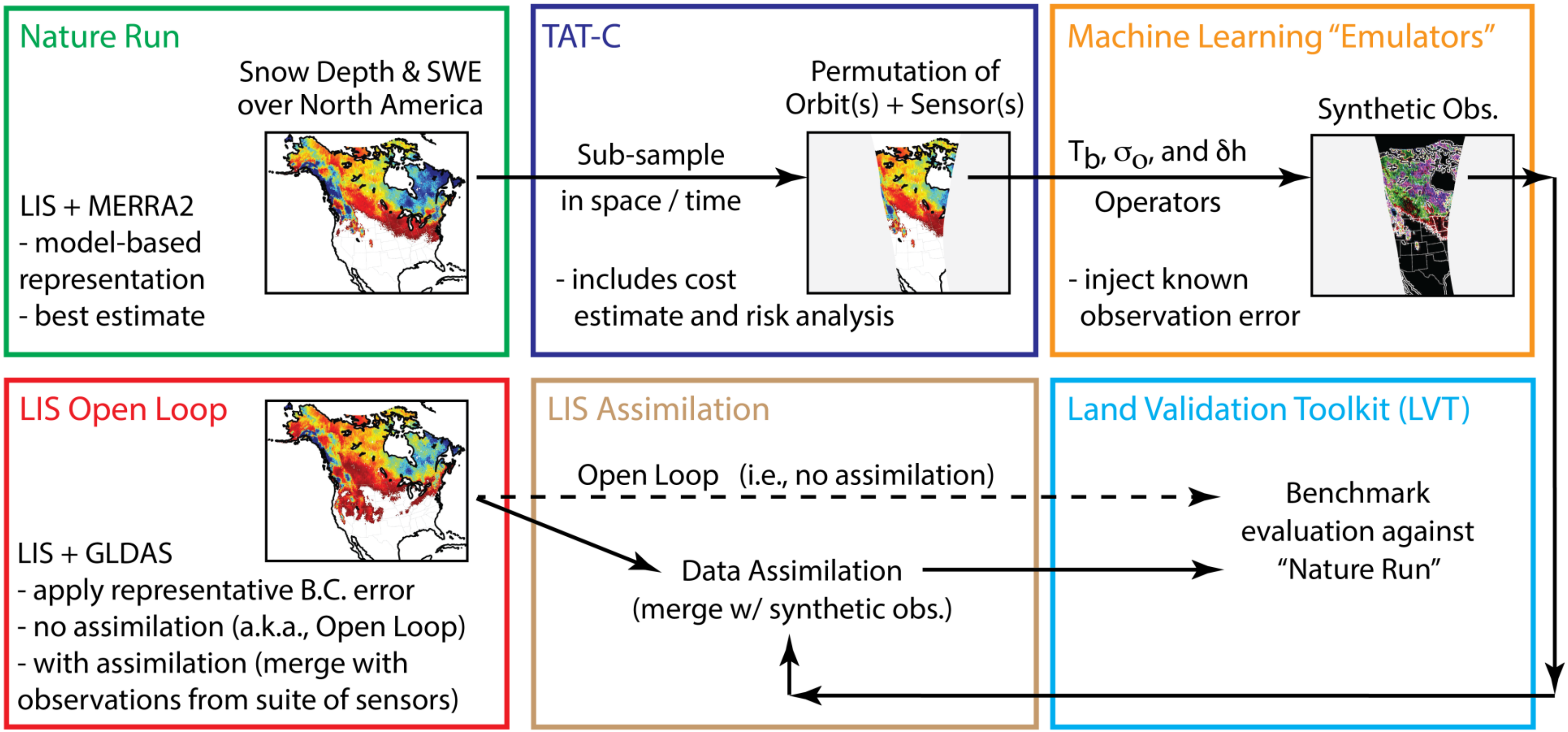
TAT-C: “Comb Viewing” via Single Platform



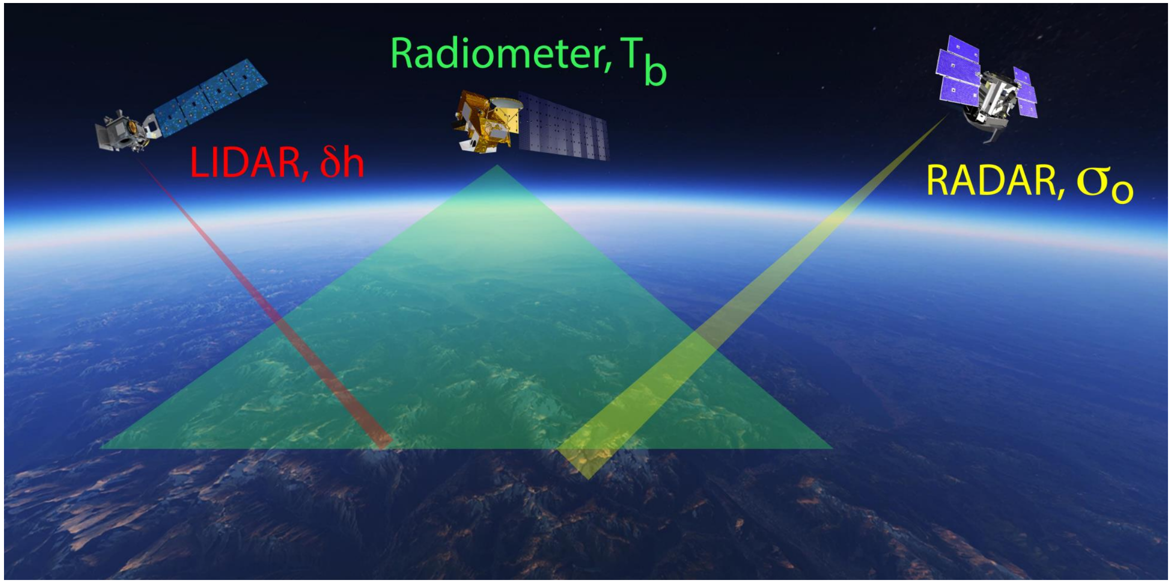
TAT-C: “Comb Viewing” via Constellation



Observing System Simulation Experiment (OSSE)



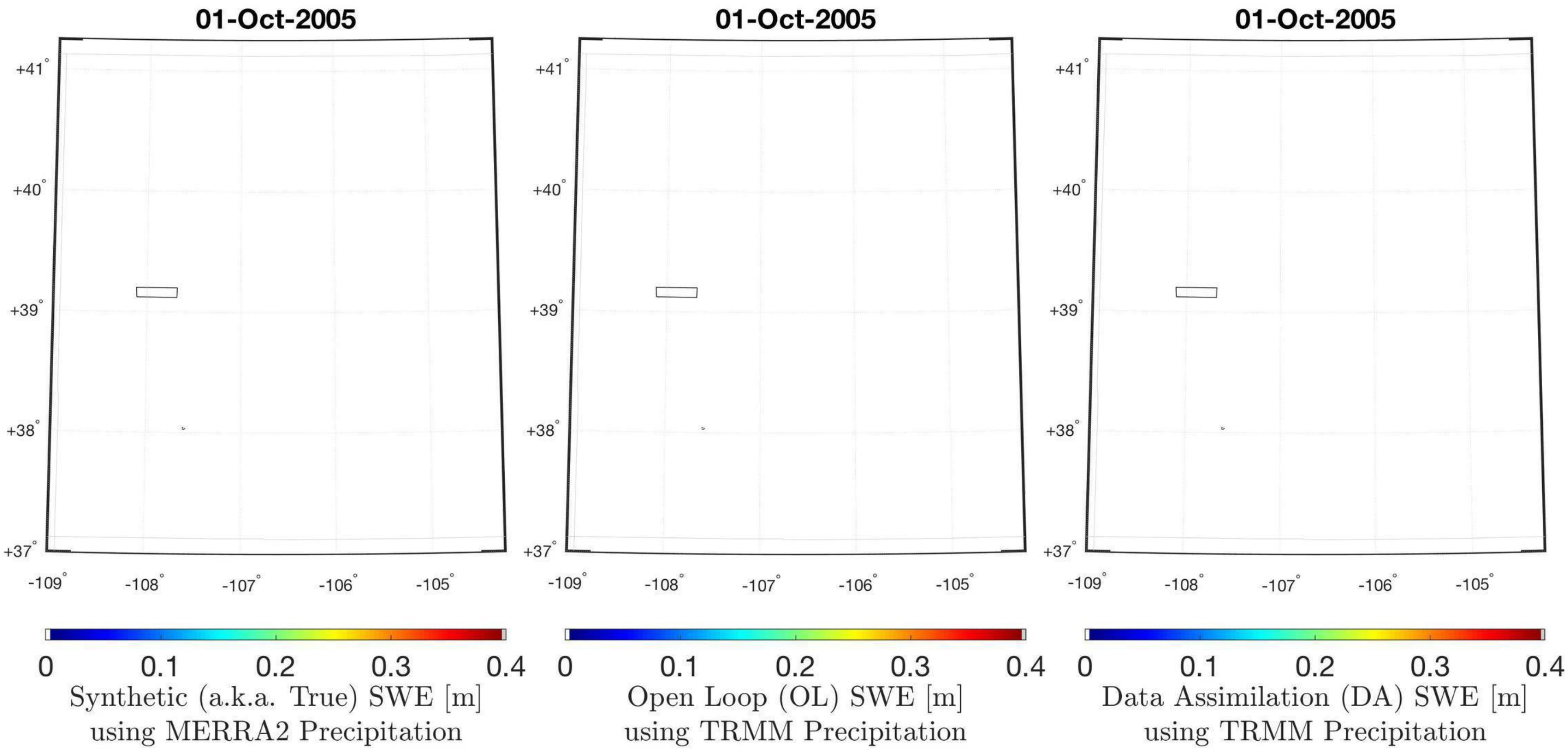
Data Assimilation via Ensemble Kalman Filter



$$\underbrace{\mathbf{y}_i^+}_{\substack{\text{posterior}\\ \text{SWE}}} = \underbrace{\mathbf{y}_i^-}_{\substack{\text{prior}\\ \text{SWE}}} + \underbrace{\mathbf{K}}_{\substack{\text{Kalman}\\ \text{gain}}} \Bigg[\underbrace{Z}_{\substack{\text{synthetic}\\ \text{measurements}\\ \text{LIDAR snow depth}\\ \text{and/or}\\ \text{C-band SAR}\\ \text{and/or}\\ \text{K-,Ka-,X-band PMW}}} - \underbrace{h(\mathbf{y}_i^-)}_{\substack{\text{observation}\\ \text{operator}\\ \text{spatiotemporal } \mathbf{H}\\ \text{and/or}\\ \sigma_0 \text{ machine learning}\\ \text{and/or}\\ T_b \text{ machine learning}}} \Bigg]$$

Synthetic Snow Depth Retrieval Results

"Truth" **OL** **DA**



Research Summary

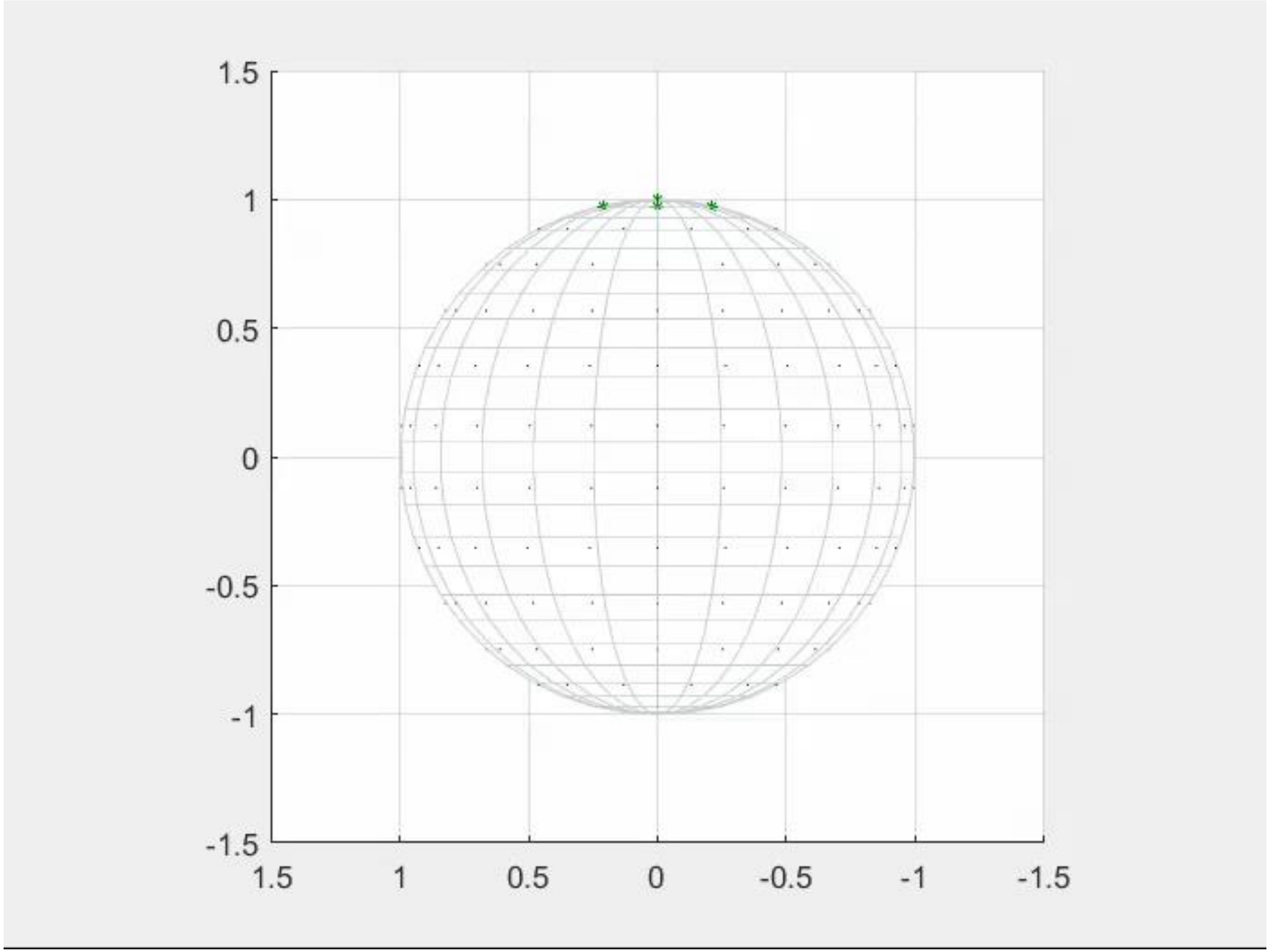
- Global snow mission will require **evidence of achievable science** via OSSE . . . or some other means
- NASA LIS provides **"nature run"** plus assimilation framework
- TAT-C provides **spatiotemporal sub-sampling** of observations, including **cost estimates and risk assessments**
- Machine learning **maps model state(s) into observation space** (i.e., T_b and σ_0)
- Snow **OSSE is on-going** . . . open to ideas + suggestions!

Thank You!

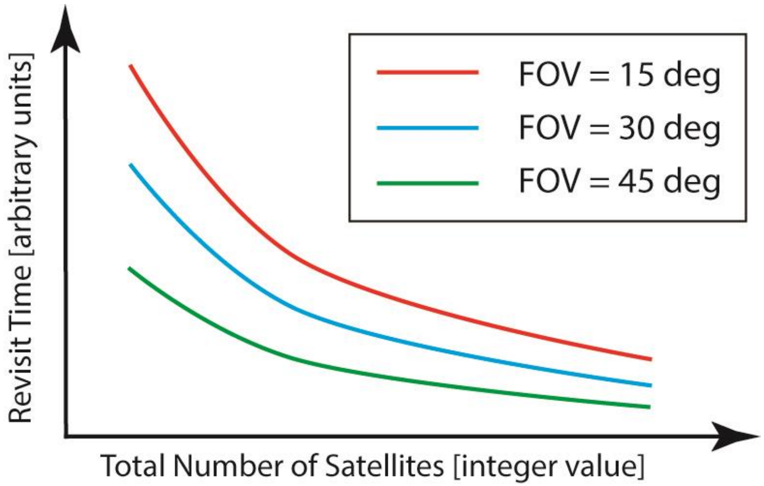
Questions and/or comments?

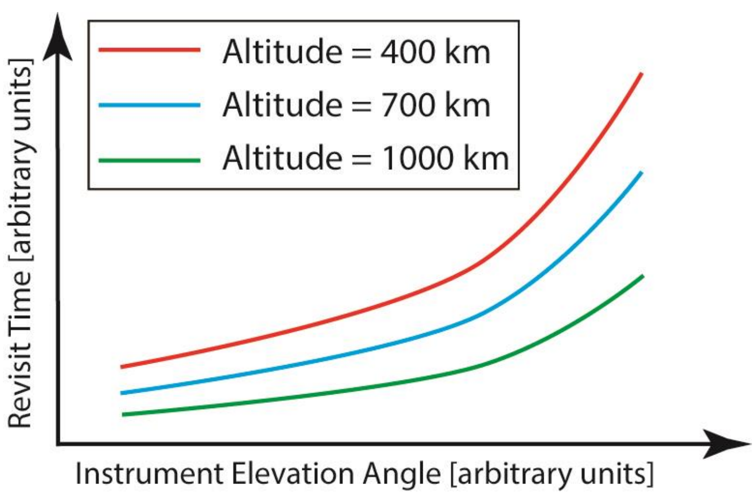
Extra Slides

TAT-C Orbital Simulator



Trade-off Space: Coverage vs. Resolution





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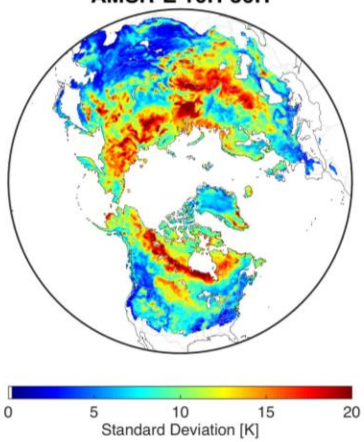
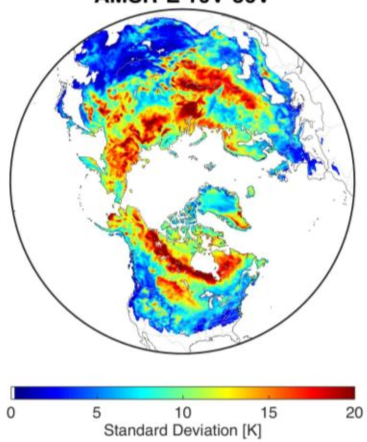
Spatiotemporal Variability

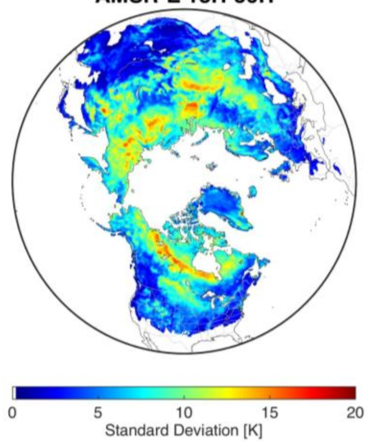
AMSR-E 10H-36H



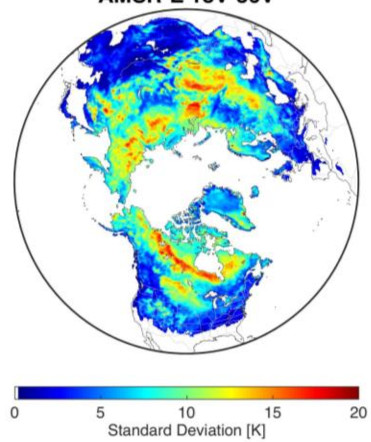
AMSR-E 10V-36V



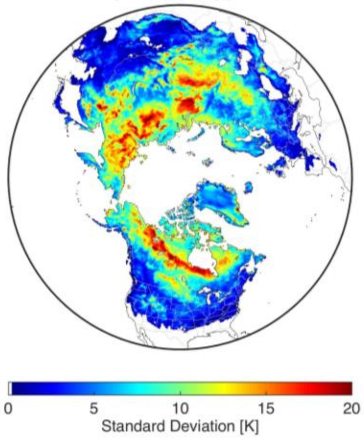
AMSR-E 18H-36H



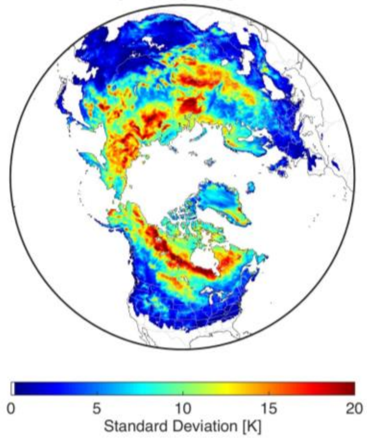
AMSR-E 18V-36V



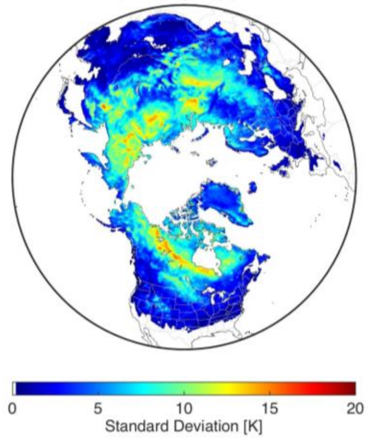
SVM 10H-36H



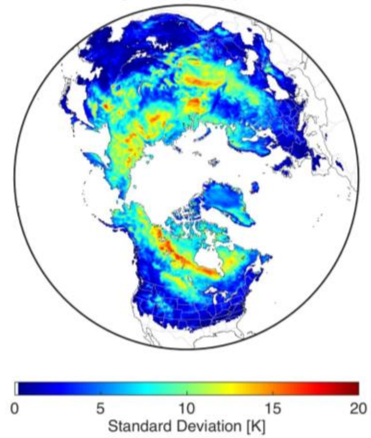
SVM 10V-36V



SVM 18H-36H



SVM 18V-36V



SVM Mathematical Framework (1 of 2)

For parameters $C > 0$ and $\varepsilon > 0$, the **standard (primal)** form is:

$$
\begin{aligned}
\underset{\mathbf{w},\, \delta,\, \boldsymbol{\xi},\, \boldsymbol{\xi}^*}{\text{minimize}} \quad & \frac{1}{2}\langle \mathbf{w} \cdot \mathbf{w} \rangle + C \sum_{i=1}^{m} (\xi_i + \xi_i^*) \\
\text{subject to} \quad & \langle \mathbf{w} \cdot \phi(\mathbf{x}_i) \rangle + \delta - z_i \leq \varepsilon + \xi_i \\
& z_i - \langle \mathbf{w} \cdot \phi(\mathbf{x}_i) \rangle - \delta \leq \varepsilon + \xi_i^* \\
& \xi_i, \xi_i^* \geq 0, i = 1, 2, \ldots, m.
\end{aligned}
$$

where m is the available number of T_b measurements in time (for a given location in space), z_i is a T_b measurement at time i, and $\boldsymbol{\xi}$ and $\boldsymbol{\xi}^*$ are slack variables.

SVM Mathematical Framework (2 of 2)

Primal optimization is commonly solved in **dual form** as:

$$\underset{\alpha_i\,,\,\alpha_i^*}{\text{minimize}} \quad \frac{1}{2}\sum_{i,j=1}^{m}\left(\alpha_i-\alpha_i^*\right)\left(\alpha_j-\alpha_j^*\right)\langle\phi(\mathbf{x}_i)\cdot\phi(\mathbf{x}_j)\rangle$$

$$+\,\varepsilon\sum_{i=1}^{m}\left(\alpha_i+\alpha_i^*\right)-\sum_{i=1}^{m}z_i\left(\alpha_i-\alpha_i^*\right)$$

$$\text{subject to} \quad \sum_{i=1}^{m}\left(\alpha_i-\alpha_i^*\right)=0,$$

$$\alpha_i\,,\,\alpha_i^*\in[0\,,\,C]\,,\; i=1,2,\ldots,m$$

where α_i and α_i^* are Lagrangian multipliers, $\langle\phi(\mathbf{x}_i)\cdot\phi(\mathbf{x}_j)\rangle$ is the inner dot product of $\phi(\mathbf{x}_i)$ and $\phi(\mathbf{x}_j)$, ε is the specified error tolerance, and C is a positive constant that dictates a penalized loss during training.