Ocean Surface Vector Wind, Sea Ice and Soil Moisture Retrievals from Microwave Radiometer Measurements

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Outline

- Background
  - Environmental Product Verification and REmote Sensing Testbed (EVEREST)
- Ocean wind vector retrieval
  - Theoretical basis
  - Performance assessment
- Other MW data products
  - Sea ice concentration
  - Soil moisture
- Summary and future work

Environmental Product Verification and REmote Sensing Testbed (EVEREST)

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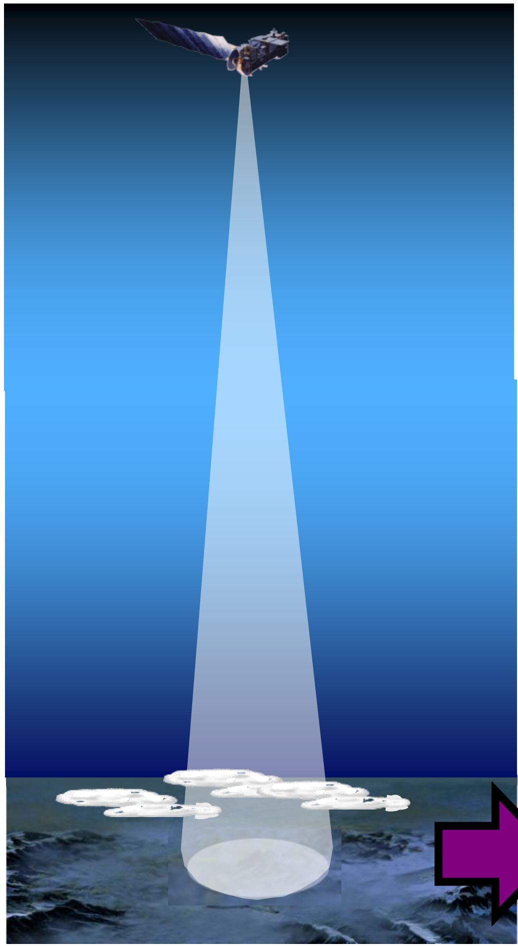


Sensor Radiometric Image/Data

- Radiance arriving at sensor along single or multiple lines-of-sight
- L1b (SDR) is "estimate" of this radiance after removing known sensor biases

Radiometric Elements of a 3-D Scene

- Atmospheric attenuation, emission, dispersion
- Extinction and dispersion by water/ice clouds, aerosols and rain
- Terrain/ocean scattering and emission

Physical Elements of a 3-D Scene

- Atmospheric profiles of P, T, RH, ozone, aerosols, haze/fog/cloud layers and rain
- Background definition

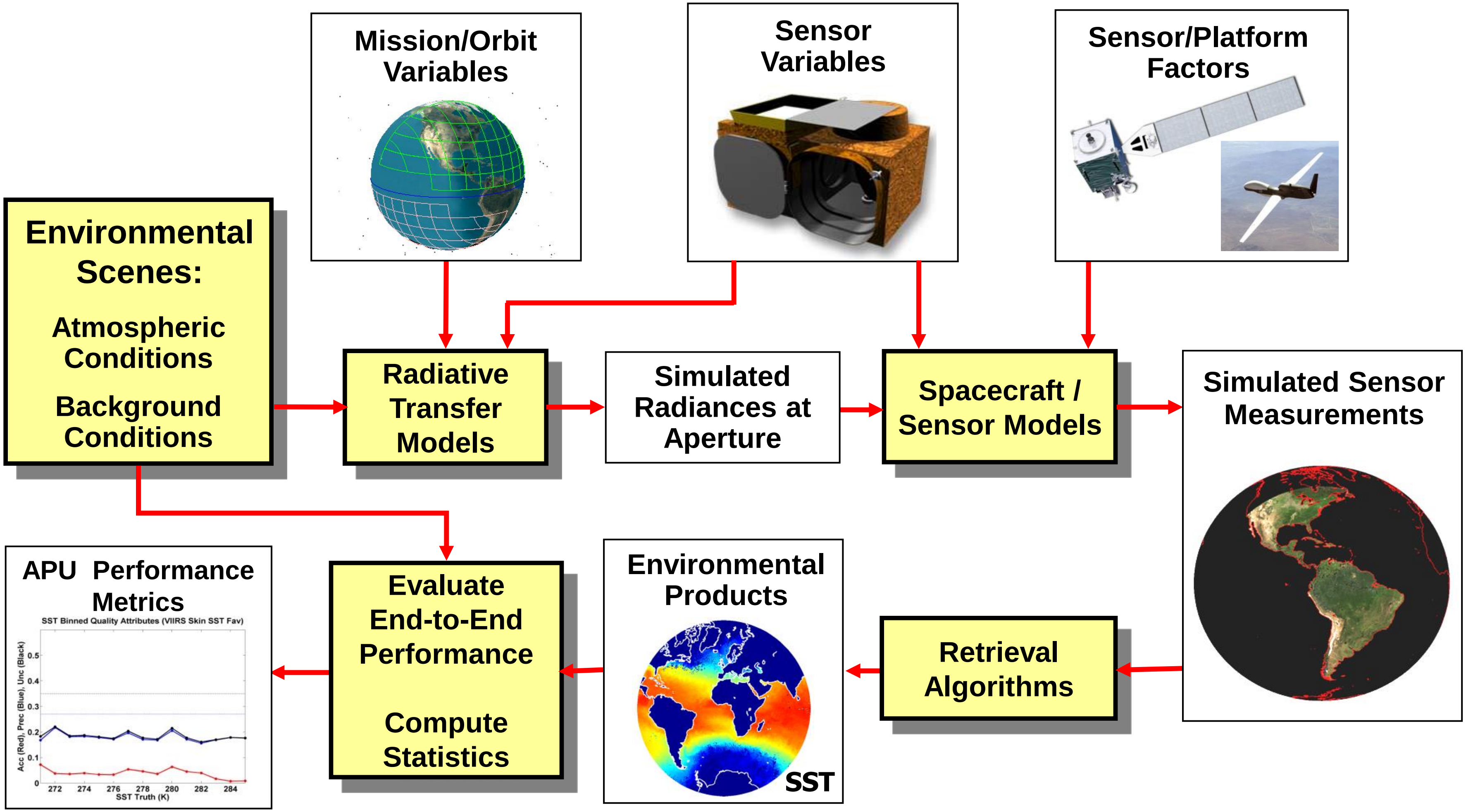
Predicted Geophysical Properties of 3D Scene

Sensor L1b (SDR) data, as well as auxiliary and ancillary data, are used in statistical regression and physical retrieval algorithms to predict geophysical properties of the environmental scene being viewed

Comparison of Predicted Geophysical Properties with Scene "Truth"

Physics-based phenomenology and sensor/spacecraft models are used to verify and validate data product performance against requirements

End-to-End Architecture for Assessing Data Product Quality vs. Requirements



Common tools, independently validated, are used to assess system performance for both Space and Airborne Systems

EVEREST Capability Useful in Multiple Program Phases

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Program Phase	Typical Focus/Tasks
User Analysis/Models	▪ Develop more accurate models ▪ Prepare for expected data ▪ Determine/recommend future directions of data/system requirements

Planning, Requirements Definition, Procurement	▪ Assess potential new element designs
	  ▪ Sensors
	  ▪ Platforms
	  ▪ Algorithms / processing
	▪ Requirements definition
	▪ IV&V

System Design and Build	▪ Predict system and element performance ▪ Verify and validate requirements to assure compliance
Operations	▪ Post-launch Cal / Val ▪ Anomaly resolution; remediation

EVEREST Applicability and Adaptability

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- Existing EVEREST elements can be adapted as needed
  - Models span EM regime, various instrument types, wide range of geophysical (background + atmosphere) conditions
  - Detailed satellite/sensor ground track / FOV simulation
  - Interfaces with spacecraft ACS simulations for pointing/jitter impacts and Image Navigation and Registration (imagery implications)
  - Large set of product retrieval algorithms – NPP, POES, DMSP, EOS, GOES-R
  - Detailed statistical analysis tools

- The more similar to existing EVEREST applications, the less resources required for adaptation
  - Platforms: LEO / polar, GEO, HEO, airborne
  - "Heritage mission" sensors: OLS, AVHRR, MODIS, AMSU, AMSR, SSMIS, TMI, WindSat
  - NPP/NPOESS/DWSS sensors: VIIRS, CrIS, ATMS, CMIS, OMPS, GPSOS
  - GOES-R sensors: ABI, HES
  - Airborne applications: HAMSR and HATI on Global Hawk

MW End-to-End Capability Key Components

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- Advanced Radiative Millimeter-wave/Microwave Scene Simulator (ARMSS)
  - Comprehensive atmospheric attenuation and emission model (including clouds, fog, haze & rain)
  - “First-principles” physical models for surface scattering & emission (including multiple layers & shadowing)
    - Two-scale ocean model for sea surface wind speed and direction
  - Full 3D scene generation & ray tracing solution of MW radiative transfer equation
  - Explicit integration over far-field antenna pattern & sensor channel bandwidth

- Generic sensor model to simulate sensor measurement errors
  - Thermal noise, temperature-induced gain drifts, noise power stability, calibration errors, residual non-linearity, and sidelobe contamination

- Data product retrieval algorithms
  - Ocean surface wind speed, direction and temperature
  - Total precipitable water (TPW) and cloud liquid water (CLW)
  - Sea ice concentration
  - Soil moisture
  - Snow depth

Ocean Wind Vector Physical Retrieval Algorithm

- The physical retrieval algorithm simultaneously retrieves
  - Ocean surface properties: temperature, wind speed, wind direction
  - Atmospheric radiometric properties: transmittance, downwelling radiance and upwelling radiance
    - Total precipitable water (TPW) and cloud liquid water (CLW)
- The physical retrieval algorithm uses a parameterized RTM (LUT) to compute ocean surface emission and scattering from geophysical state parameters (SST, wind speed, and wind direction)
- The physical retrieval algorithm can be easily adapted for any existing and future multichannel polarimetric MW radiometers
  - Development and test of the retrieval algorithm was based on a WindSat-like instrument

Algorithm Theoretical Basis (1)

- Radiative Transfer: $$T_B = \tau\varepsilon T_S + \tau(1-\varepsilon)(T_D^*) + T_U$$
  - Ocean surface emissivity (ε) varies with surface temperature (T_S), wind speed, wind direction, frequency, and polarization
  - Deep space temperature (T_{DS}) and atmospheric transmission and emission (τ, T_U ,T_D) are un-polarized but otherwise vary with frequency
  - Corrected downwelling radiances

$$T_D^* = T_D + \tau T_{DS} + \Omega(T_D + \tau T_{DS} - T_{DS})$$

- The retrieval algorithm seeks to solve the radiative transfer equation using the Bayesian approach, which is equivalent to find a set of state parameters (X) that minimize the following cost function:

$$(\hat{T}_B - T_B)S_T^{-1}(\hat{T}_B - T_B) + (\hat{X} - X_a)S_a^{-1}(\hat{X} - X_a)$$

- S_T is measurement error covariance matrix, and the *a priori* (X_a and S_a) information are derived from climatology. The iterative solution is:

$$\hat{X}_{i+1} = X_a + (S_a^{-1} + K' S_T^{-1} K)^{-1} K' S_T^{-1}(T_B - \hat{T}_B(\hat{X}_i) - K(X_a - \hat{X}_i))$$

Algorithm Theoretical Basis (2)

- Ocean surface emissivity model (ε) is pre-computed at the specified EIA, frequency and polarization for variable surface conditions:
  - Temperature: 272-310K, grid interval 2K
  - Wind speed: 0.5-40m/s, grid interval 0.5m/s
  - Wind direction: 0-360°, grid interval 5°
- Downwelling radiance correction factor (Ω) is pre-computed at the specified EIA, frequency and polarization for variable wind speeds and atmospheric opaqueness
- The Jacobians (K) are scene dependent and computed at run time

$$\frac{\partial T_B}{\partial T_S} = \tau\varepsilon + \tau(T_S - T_D^*)\frac{\partial \varepsilon}{\partial T_S}$$

$$\frac{\partial T_B}{\partial W_S} = \tau(T_S - T_D^*)\frac{\partial \varepsilon}{\partial W_S} + \tau(1-\varepsilon)\frac{\partial T_D^*}{\partial W_S}$$

$$\frac{\partial T_B}{\partial W_D} = \tau(T_S - T_D^*)\frac{\partial \varepsilon}{\partial W_D}$$

$$\frac{\partial T_B}{\partial \tau} = \varepsilon T_S + (1-\varepsilon)T_D^* + \tau(1-\varepsilon)\frac{\partial T_D^*}{\partial \tau}$$

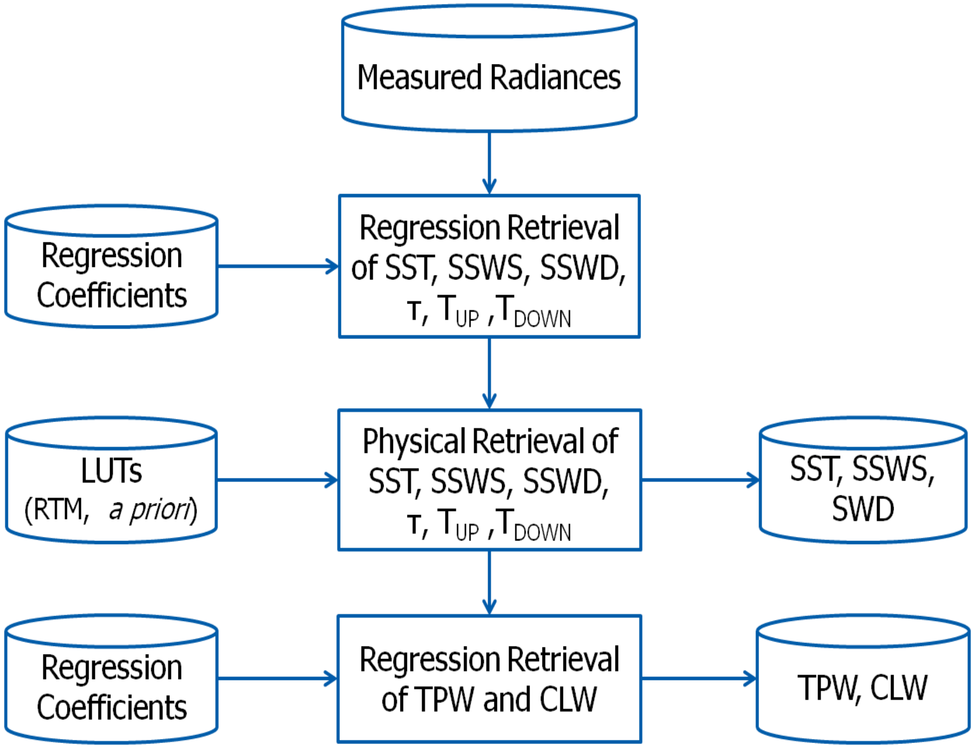
$$\frac{\partial T_B}{\partial T_D} = \tau(1-\varepsilon)\frac{\partial T_D^*}{\partial T_D}$$

$$\frac{\partial T_B}{\partial T_U} = 1$$

Algorithm Implementation Design

The physical retrieval algorithm consists of three steps:

- Step 1: regression retrieval of state parameters from radiances
  - To initialize the physical retrieval
- Step 2: physical retrieval
  - Iterative
- Step 3: regression retrieval of TPW and CLW from (τ, T_U ,T_D)



Algorithm Performance Assessment

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- EVEREST tools used in simulating the test data and generating the algorithm LUTs
  - Brightness temperatures
  - Emissivity LUTs
  - Atmospheric radiative property

Generic sensor specifications and viewing geometry

Frequency	Polarization	Band Width	EIA	NEdT
6.8 GHz	V, H	125 MHz	53°	0.1K
10.7 GHz	V, H, +45°, -45°, LC, RC	300 MHz	53°	0.1K
18.7 GHz	V, H, +45°, -45°, LC, RC	750 MHz	53°	0.1K
23.8 GHz	V, H	500 MHz	53°	0.1K
37.0 GHz	V, H, +45°, -45°, LC, RC	2000 MHz	53°	0.1K

Samples of Simulated Brightness Temperatures

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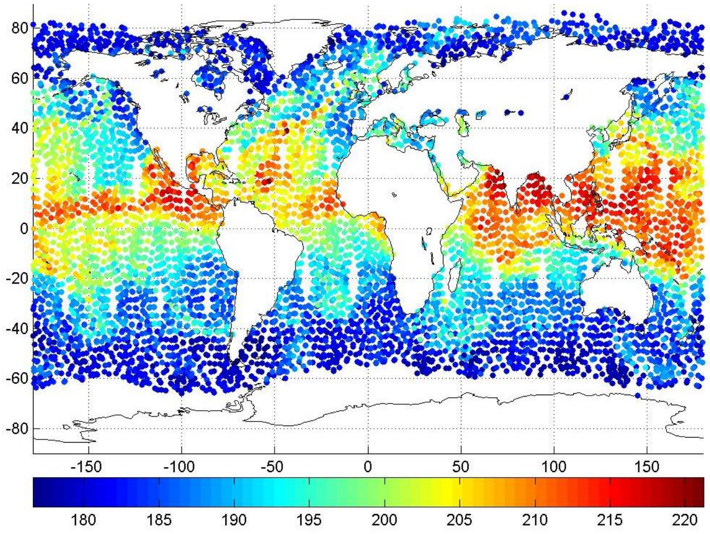
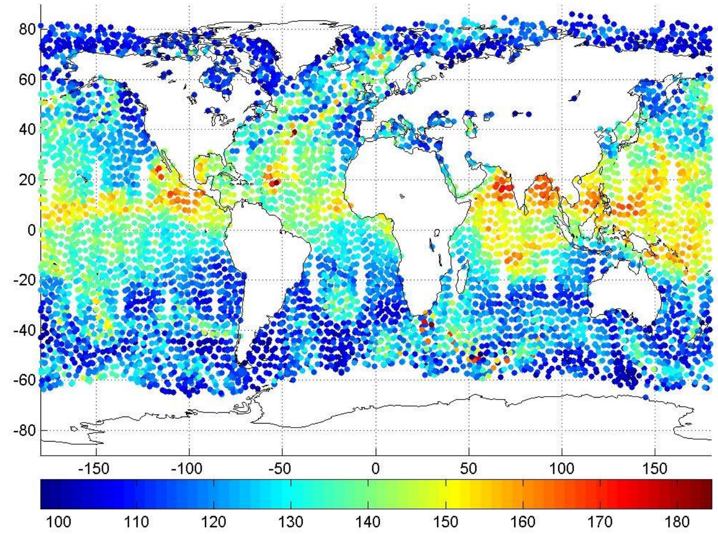
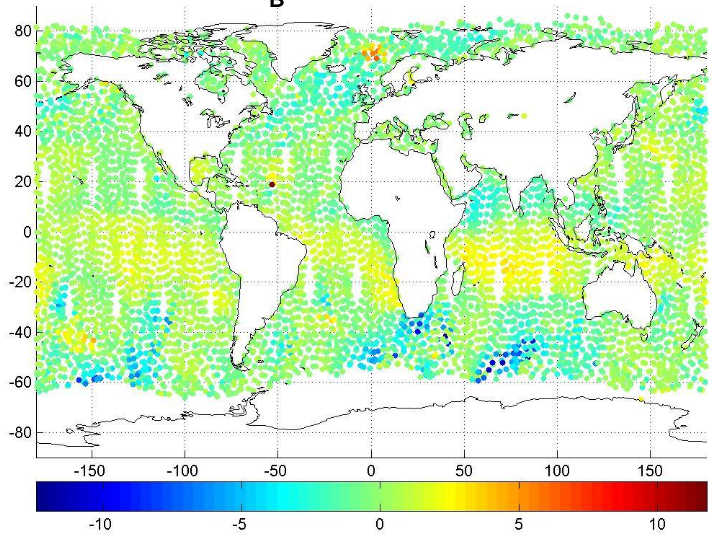
T_B-V 18.7GHz



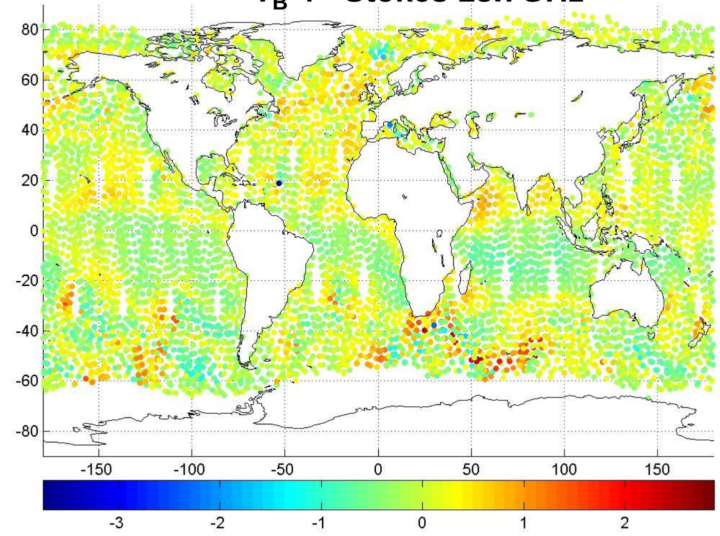
T_B-H 18.7GHz



T_B 3rd Stokes 18.7GHz



T_B 4th Stokes 18.7GHz



Algorithm Performance Test Results

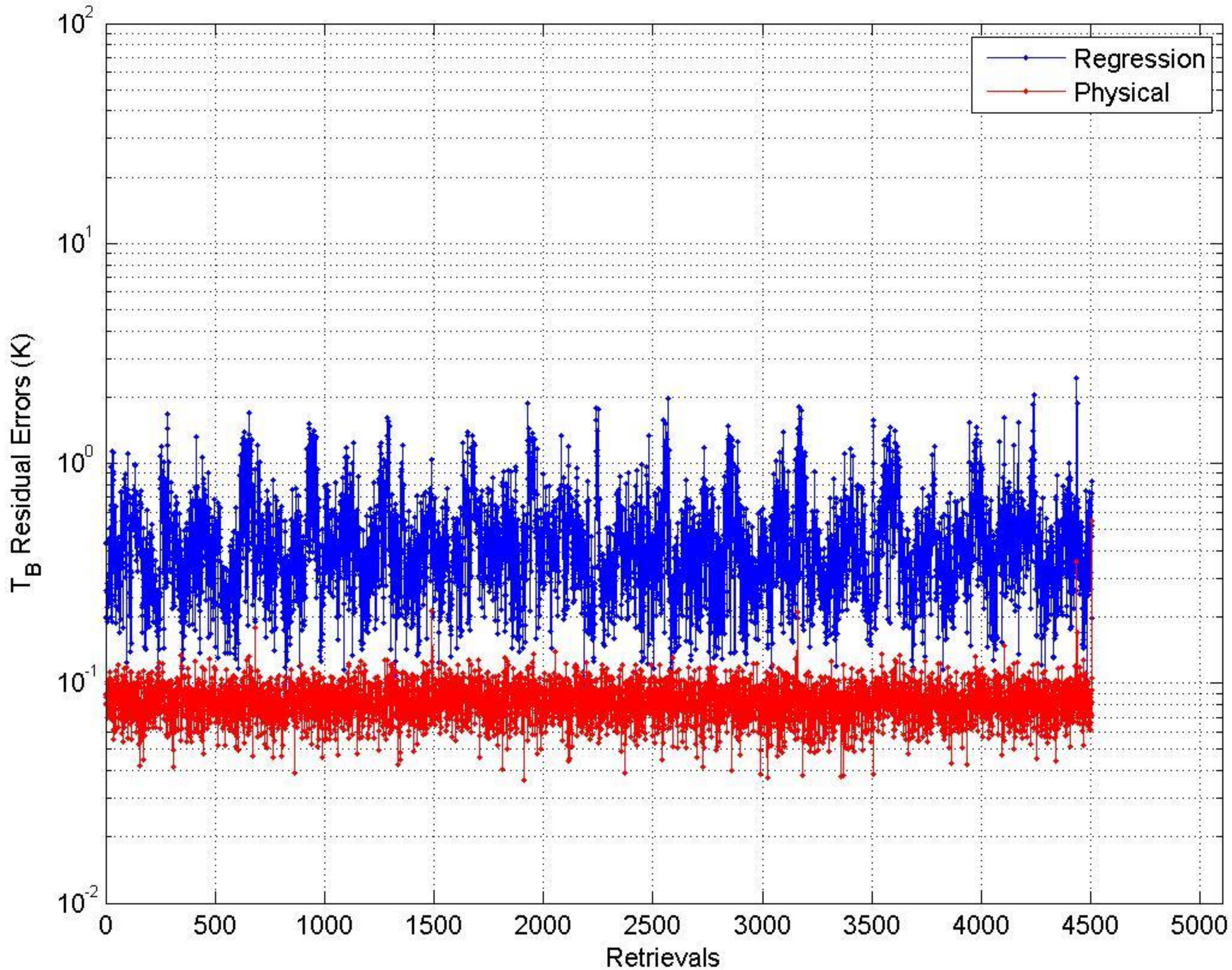
- Based on the simulated test data, the physical retrieval algorithm out-performs regression based algorithms with significant margin (except CLW)

Standard Deviation of Algorithm Retrieval Errors

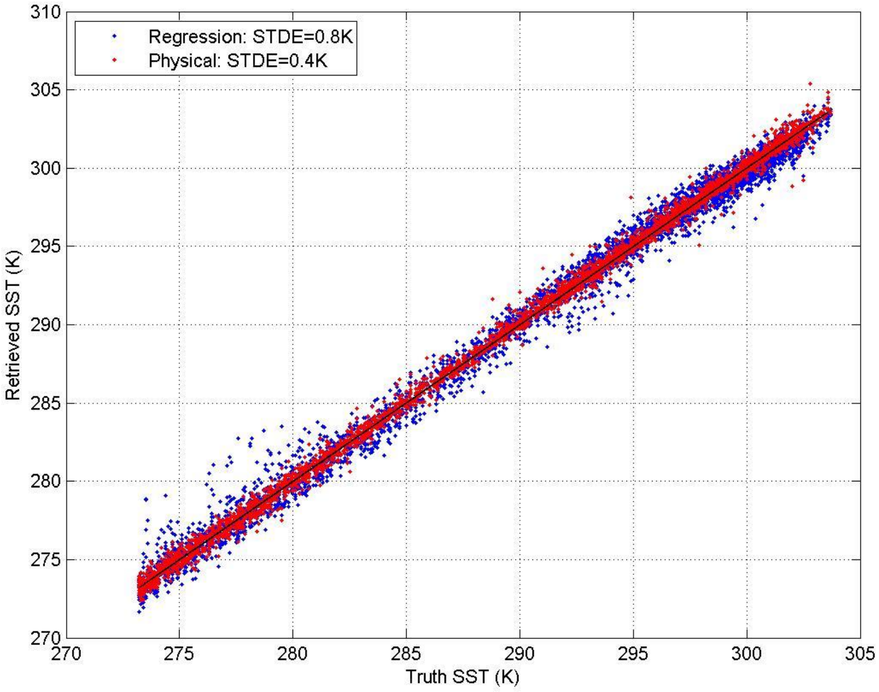
Product	SST (K)	W – Speed (m/s)	W-Direction (degree)	TPW (mm)	CLW (mm)
Regression	0.8	0.56	~18*	0.74	0.02
Physical	0.4	0.25	~12*	0.30	0.01

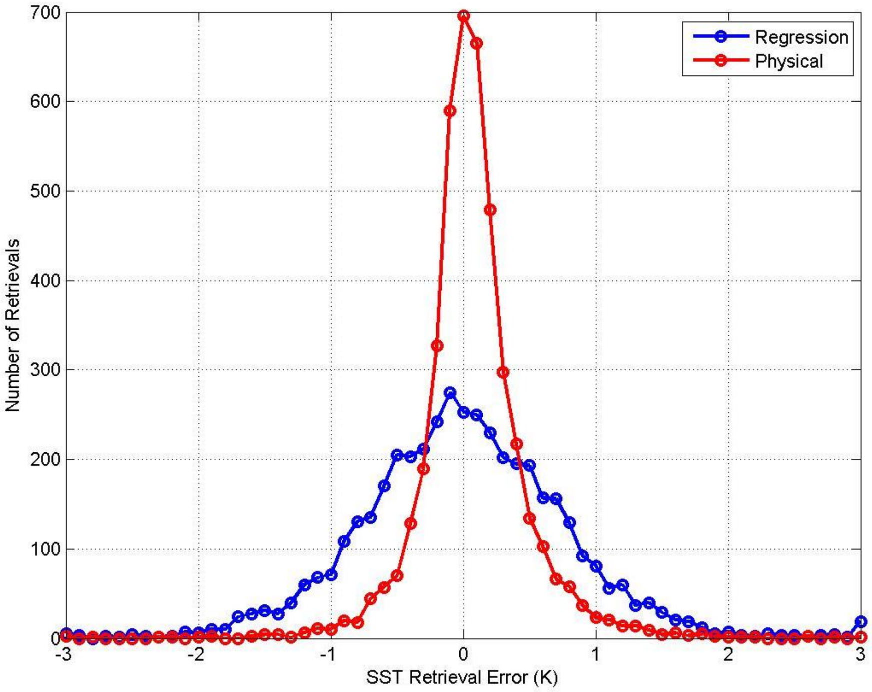
* Excluding ambiguity

Radiances Are More Accurately Matched Using the Physical Retrieval Algorithm

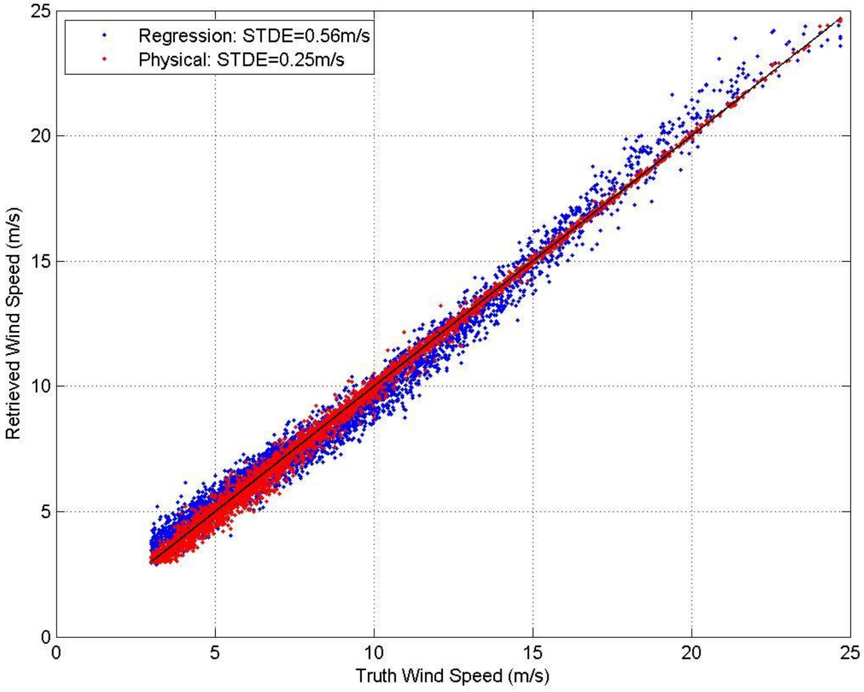


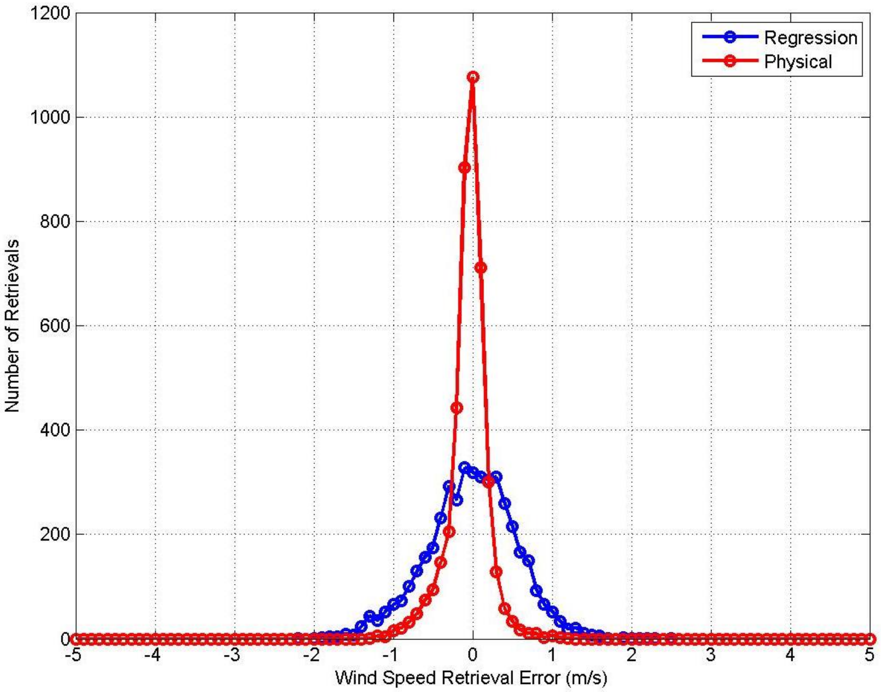
SST Retrieval Accuracy Assessment



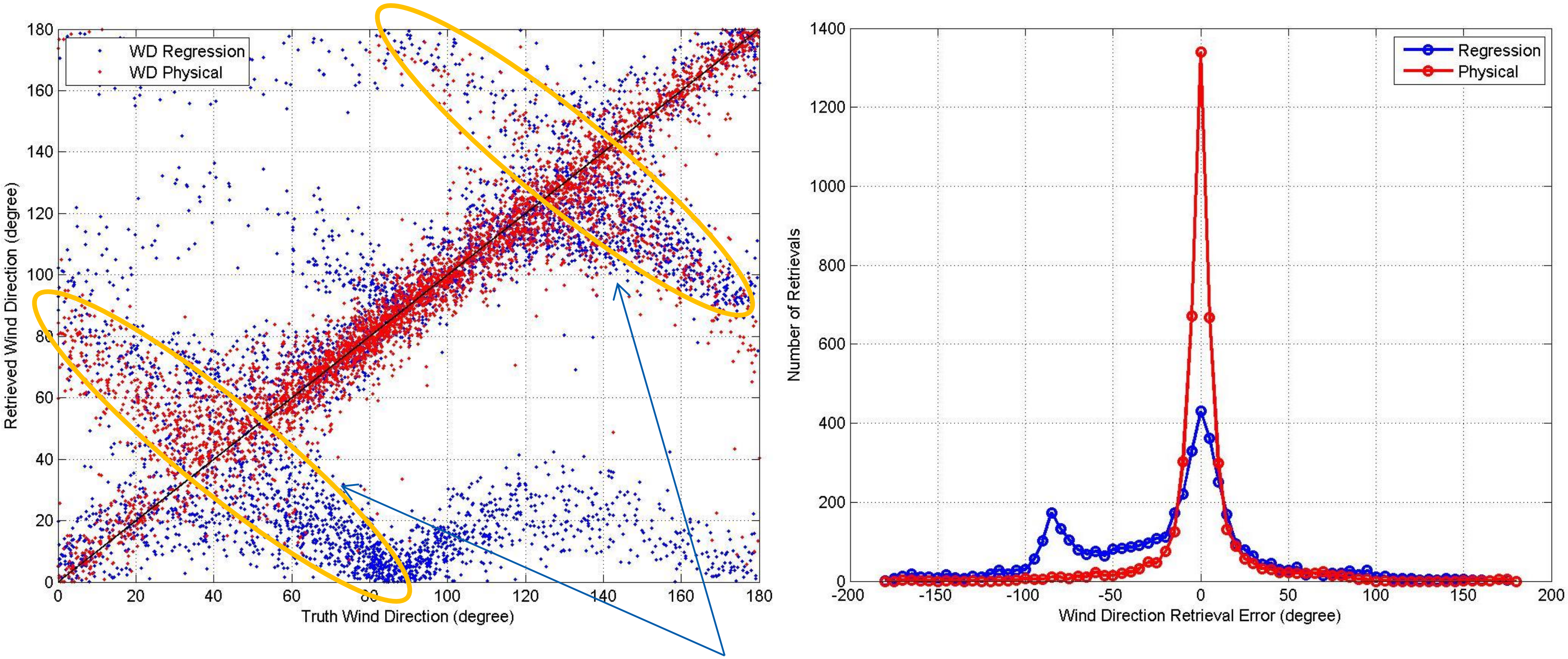


Wind Speed Retrieval Accuracy Assessment



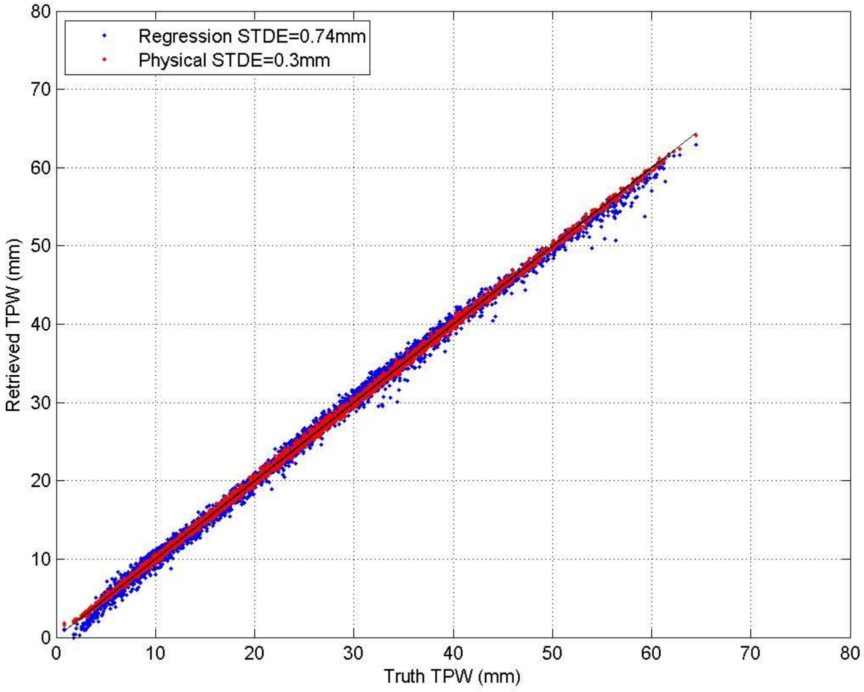


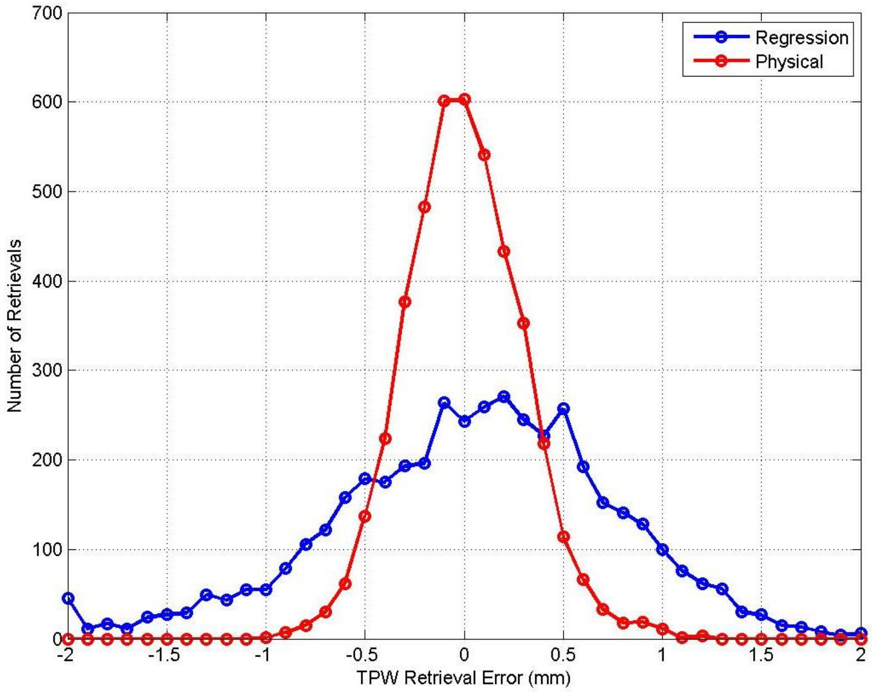
Improved Wind Direction Retrieval Accuracy



Wind direction
retrieval ambiguity

TPW Retrieval Accuracy Assessment

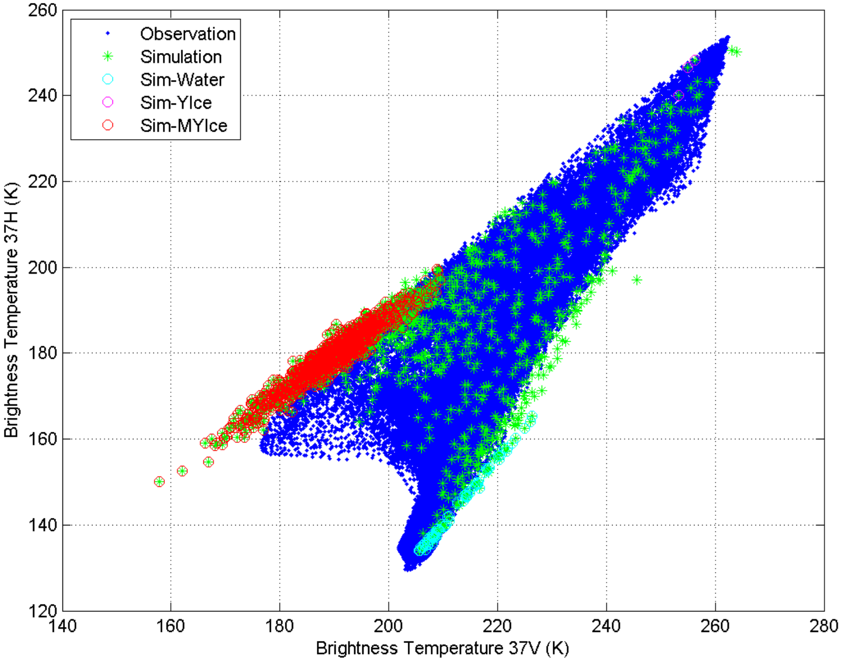




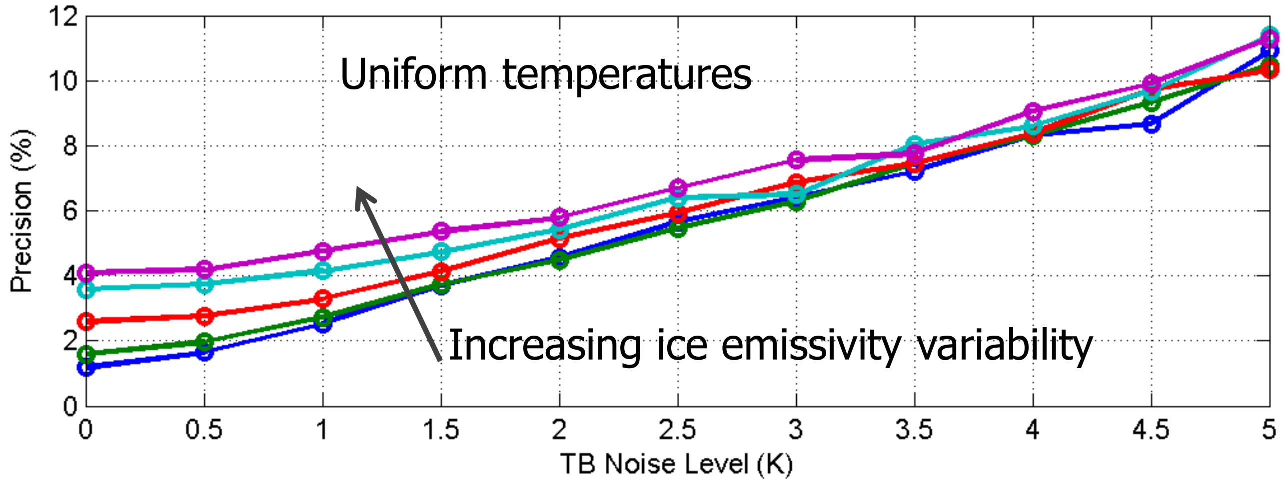
Sea Ice Concentration Accuracy Assessment

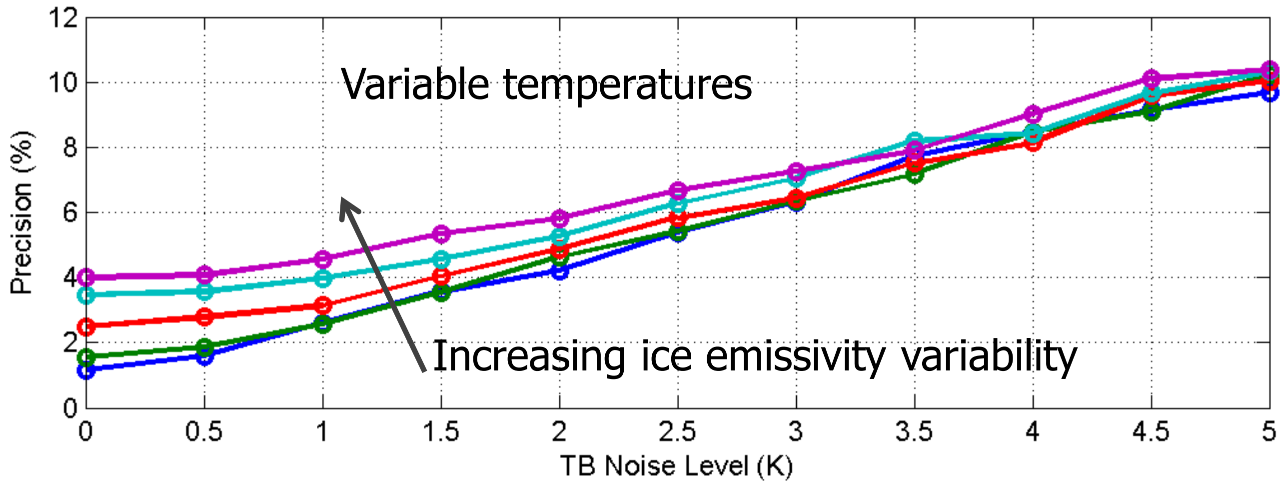
- Global synthetic datasets simulated to evaluate sea ice concentration algorithm performance
  - Scene uniformity
  - Emissivity variability
  - Sensor noise

- Bootstrap sea ice concentration retrieval algorithm



Sea Ice Concentration Retrieval Performance





Soil Moisture Retrieval Accuracy Assessment

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- Global synthetic datasets simulated to evaluate soil moisture retrieval algorithm performance
  - Variable soil types and surface roughness
  - Sensor noises
- Regression based algorithm using all available imaging channels
- Additional algorithm development efforts underway
  - Physical retrieval algorithm
  - Vegetation cover

Soil Moisture Retrieval Accuracy and Sensitivity

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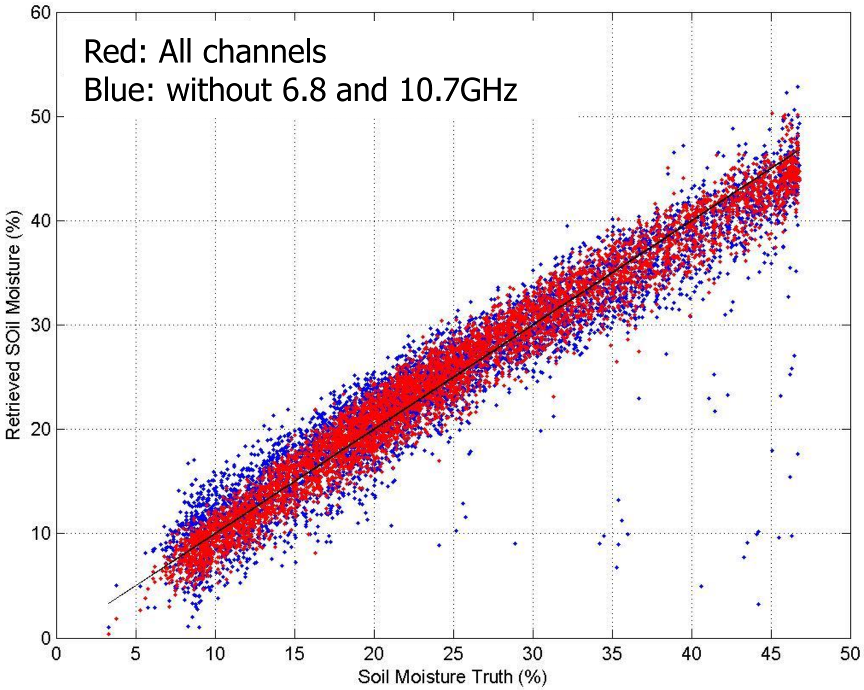
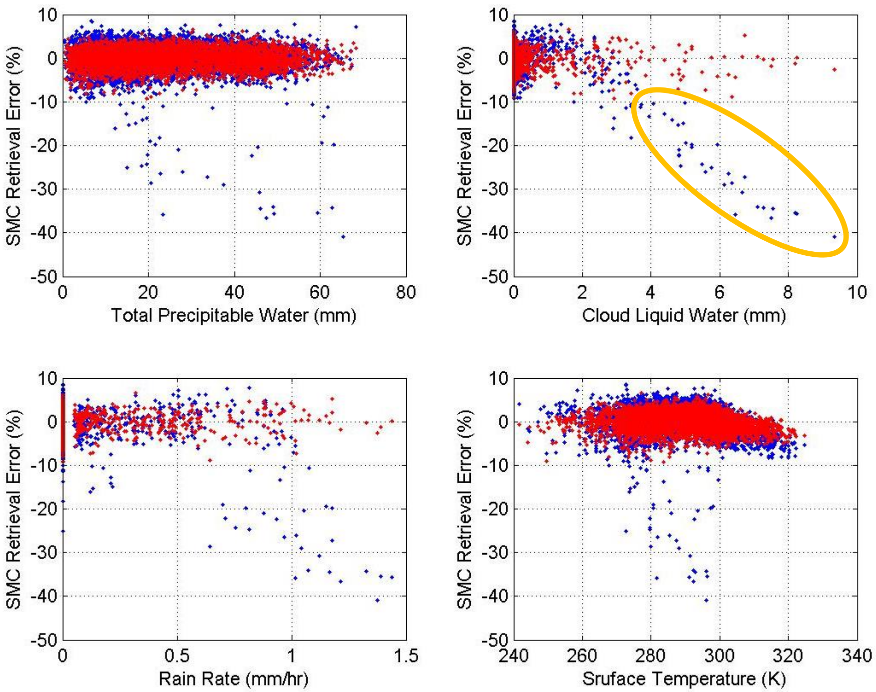
Soil moisture retrieved vs truth



Accuracy vs. scene conditions



Summary and Future Work

- EVEREST is a comprehensive end-to-end system verification and validation capability that can support a variety of environmental remote sensing programs
- The physical retrieval algorithm shows significantly improved performance compared to regression-based algorithms in retrieving ocean surface wind speed and direction, and other ocean suite data products
- We will continue to develop, enhance and validate our models, tools and algorithms
  - Physical retrieval algorithm for soil moisture and snow depth
  - Validation of emissivity models using operational data