Documenting the Spectral Character of Earth’s Emission with PREFIRE

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PREFIRE seeks to reduce uncertainty in polar energy fluxes, the processes that influence them, and, with improved modeling, the societal implications of polar climate change.
The Far-Infrared Observing Gap

Current Spectral Measurements

CERES/Libera

Annual-mean All-sky OLR in 2019

Estimated Far-Infrared Fraction

L’Ecuyer et al, BAMS (2021)
Far-infrared surface emissivity exhibits substantial variability across surfaces common in polar regions.

The atmospheric greenhouse effect is sensitive to thin clouds and small water vapor concentrations that have strong far infrared signatures.
Surface emissivity strongly influences surface energy balance, melt processes, and Arctic circulations.

**Impacts of $e_\lambda$ Errors on CESM Present Day Sea Ice Evolution**

**Impacts of $R_{SFC}$ Errors on ISSM Greenland Runoff**
PREFIRE fills the far-infrared observing gap by documenting variability in spectral fluxes from 5 - 53 µm on hourly to seasonal timescales.

L’Ecuyer et al, BAMS (2021)

PREFIRE maps polar far infrared emission spectra with two CubeSats flying in distinct 510–540 km altitude, near-polar (82°-98° inclination) orbits each carrying a miniaturized infrared spectrometer, covering 5-53 µm with 0.84 µm spectral sampling, operating for one seasonal cycle (a year).

https://prefire.ssec.wisc.edu
Mission Concept

Payload – TIRS
Thermal InfraRed Spectrometer
5 to 53 µm spectral range
8x64 spatial x spectral channels

Altitude
510-540 km
Inclination
82-98°
Duration
12 months

Two 6U CubeSats
in asynchronous orbits

https://prefire.ssec.wisc.edu
L’Ecuyer et al, BAMS (2021)
(updated)

Nominal Operations
90+ mins/orbit
‘Continuous’ Science Collection
Single Instrument Mode
Downlink up to 4x to KSAT Lite Stations

365 day primary mission

Sun Avoidance
Spacecraft will Yaw 180° as necessary
To prevent Sun intrusion on the apertures

Overlapping Measurements
Co-located ground scenes
Separated by 0-12 hours

Calibration Sequences
Internal/Space View Switching
~10 seconds each
Nominally 8x per orbit

May 2024
Launch to Polar Orbit
D = 0
Solar Array Deployment
D = +30 minutes
Detumble and Sun Acquisition
Up to 90 days
Checkout
BUS commissioning
TIRS commissioning
Nominally 30 days
L’Ecuyer et al, BAMS (2021)
(updated)

Payload
– TIRS
Thermal InfraRed Spectrometer
5 to 53 µm spectral range
8x64 spatial x spectral channels

Space View (calibration)
Earth View (FIR spectra)

S-Band Telecom 4x/Orbit

Arctic Science

Antarctic Science

https://prefire.ssec.wisc.edu
L’Ecuyer et al, BAMS (2021)
(updated)
Simulated Top of Atmosphere Brightness Temperatures

* Original TAFTS data courtesy J. Murray and H. Brindley (FORUM)
<table>
<thead>
<tr>
<th>Product</th>
<th>Contact</th>
<th>Details</th>
<th>Examples</th>
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<tbody>
<tr>
<td>L0 (telemetry+ instrument)</td>
<td>B. Drouin</td>
<td>Time-stamped instrument and spacecraft data</td>
<td></td>
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<tr>
<td>L1B Radiances/ Fluxes</td>
<td>B. Drouin</td>
<td>Instrument model</td>
<td></td>
</tr>
<tr>
<td>L2B Flux</td>
<td>X. Huang</td>
<td>3% accuracy (8 W/m² for total and 4 W/m² for FIR)</td>
<td></td>
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<tr>
<td>L2B Surface Emissivity</td>
<td>X. Huang</td>
<td>Surface type, temperature, and spectral emissivity to 0.01 accuracy; optimal estimation and neural-network</td>
<td></td>
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<tr>
<td>L2B Cloud Mask</td>
<td>B. Kahn</td>
<td>Detect 80-90% of clear-sky occurrences; confidence flags; neural-network and principal component</td>
<td></td>
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<tr>
<td>L2B Atmospheric Properties</td>
<td>A. Merrelli</td>
<td>T/q profiles; 10% accuracy for column water vapor; optimal-estimation</td>
<td></td>
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<tr>
<td>L2B Cloud Properties</td>
<td>N. Miller</td>
<td>Cloud top pressure, cloud optical thickness, effective cloud fraction, cloud phase, ice particle size</td>
<td></td>
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<tr>
<td>L3 Gridded Climatology</td>
<td>N. Vos</td>
<td>Daily and monthly gridded products for each CubeSat</td>
<td></td>
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</tbody>
</table>
Student-Led: Neural-Network Cloud Mask

Neural Network-Based Cloud Detection

Bertossa et al., submitted to J. Tech.

Truth (cloud = white)

Predicted Cloud Probabilities

$P_{ov}(\text{clear}) = 0.95$

$P_{ov}(\text{cloud}) = 0.05$
Synergy with CERES/Libera: Spectral Fluxes

- Longwave spectral fluxes using methods developed and validated for AIRS (Huang et al, 2008; 2010; 2014; and Chen et al, 2013) but spanning a factor of three larger spectral range
- Spectral flux for each TIRS channel estimated from a pre-constructed spectral ADM (anisotropic distribution model)
- Flux over spectral gaps not covered by the PREFIRE will be estimated using a PCA-based multilinear regression scheme
- Integrated OLR errors < 2 Wm$^{-2}$ for 90% of scenes
- CERES SNOs will provide an important constraint.

Fig.1: Mean bias for each sub-scene type over the sea ice surface, expressed in percentage difference.
Measuring the complete infrared emission spectrum distinguishes the fingerprints of several important feedback processes.
Student Led: Intersection Science

One Satellite

Two Satellites
(Altitude Difference: 15 km)
CubeSat 1 time: 6/27/2021 23:38 UTC
CubeSat 2 time: 6/28/2021 12:19 UTC

Orbit intersections (revisits) provide insights into the processes that influence the emission spectrum.

* Actual orbit tracks and intersections will not be known until after launch.
PREFIRE Intersections – Other Changes

*CubeSat 1 skin temp*  
*CubeSat 2 skin temp*  

Revisit Time: 12.7 hours

*CubeSat 1 low-level clouds*  
*CubeSat 2 low-level clouds*
PREFIRE Tests Two Hypotheses By Coupling Observations to Models

1. Time-varying errors in far infrared emissivities and atmospheric greenhouse effects (GHE) bias estimates of energy exchanges between the surface and the atmosphere in the Arctic.

2. These errors are responsible for a large fraction of the spread in projected rates of Arctic warming, sea ice loss, ice sheet melt, and sea level rise.

**Hypothesis 1** is addressed by comparing observed spectral fluxes with those simulated from model output using a **PREFIRE simulator** being developed for COSP.

**Hypothesis 2** is addressed by implementing new **emissivity models** and examining impacts on ice sheet dynamics, ice sheet melt, Arctic warming, sea ice loss, and sea level rise.
Anticipated Launches:

CubeSat 1: May 1, 2024
CubeSat 2: May 15, 2024
PREFIRE aims to reduce uncertainty in polar infrared fluxes, the processes that modulate them, and, by coupling to models, the implications of polar climate predictions.

Identical TIRS on two 6U CubeSats will measure far-infrared spectra from 5-54 μm at 0.84 μm resolution.

Observed radiances across the mid- and far-infrared will be used to derive surface properties, water vapor, temperature, and cloud properties.

Time-differenced measurements from two CubeSats will quantify the spectral signatures of sub-daily processes including melt and snow events.

Model simulations help translate this information into improved understanding of polar climate.
Ensuring that PREFIRE observations influence model development is essential to mission success.

PREFIRE observations interface with polar models in two ways:
- New spectral surface emissivity models that span the mid and far-infrared;
- Spectral signatures of the factors that force polar climate for model evaluation via simulators

**Modeling Activities**
- Develop general spectral emissivity coupler for surface-atmosphere interfaces
- Implement PREFIRE spectral surface emissivity models
- Develop and implement TIRS simulator in the CFMIP Observation Simulator Package (COSP)
- Conduct CESM simulations to assess impact of emissivity uncertainty on current and future climate
- Couple ISSM to CESM output to establish impacts on ice sheet dynamical processes

PREFIRE measurements improve Arctic climate predictions by anchoring spectral far infrared emission and atmospheric greenhouse effect.
In clear skies, TIRS radiances will be used to infer temperature and water vapor.

Full spectrum provides sensitivity to water vapor at different altitudes.

Two-stage retrieval:
- PC-Regression
- Optimal Estimation with the PCR result as a prior
An optimal estimation approach estimates surface emissivity in multiple channels
- Incorporates measurement uncertainty
- Yields uncertainty estimates
- May include water vapor constraint from ATM retrieval

**Optimal Estimate**

\[ \hat{\chi} \]

\textbf{a priori constraints}

mean \( x_a \) and its covariance \( S_a \)

\textbf{Observations}

\( y \) and its error covariance \( S_\epsilon \)

\textbf{Radiative transfer model}

Weighting function matrix

\[ K_{ij} = \frac{\partial y_i}{\partial x_j} \]
In cloudy scenes, TIRS radiances carry the spectral signatures of cloud phase and ice particle size.
Level-2 Validation Strategy and Examples

- PREFIRE level-2 products will be compared against satellite and ground-based active observations.
- Aggregated statistics computed from pixel-scale matches.
- Heritage in AIRS, CloudSat/CALIPSO, ARM comparisons: (Kahn et al., JGR, 2007 and Kahn et al., 2008, ACP)

Validation of L2 Cloud Products
Compare cloud fraction and cloud top temperature with JPSS VIRSS/CrIS SNOs.

Validation of L2 Spectral Fluxes
Compare broadband OLR with CERES OLR for all PREFIRE and JPSS-1 and Aqua SNOs.

Simultaneous overpasses (frequent over the poles) provide a wealth of information for verifying PREFIRE level-2 data products.
Arctic Rapid Revisits for Inter-Calibration

Rapid revisits

degrees latitude

relative orbit number
The subset of “rapid revisits” (intersections with very short time-differences) will be used to intercalibrate the two CubeSats. These occur around 77° and ARCSIX could provide valuable independent ground truth in such scenarios.
Implications for Ice Sheet Processes

![Diagram illustrating ice sheet processes with temperature, melt, and refreeze plots.](Schlegel and L’Ecuyer, in preparation)
Implications for Global Sea Level

Substantial Impacts on Predicted Rates of Greenland Runoff and Sea Level Rise

![Graph showing mass balance change and surface radiative flux error](image)

![Global sea level rise graph](image)
Thermal InfraRed Spectrometer (TIRS)

(a) RAM/WAKE

(b) TIRS views

(c) Spectral Sampling: 0.86 μm from 5-54 μm
   Spatial Resolution: 12-15 km
   Mass: < 3 kg
   Average Power: 4.5 W

(c) Pointing motor
    Pointing mirror
    Safing mechanism
    Calibration target

Dimensions:
- 117 mm
- 128 mm
- 90 mm
- 234 mm
- 15 mm
- 198 mm
- 70 mm
- 50 mm
- To wall