From Incubator to Orbit

Ten Years of Infrared Sensor Technology Development at NASA Langley

Marty Mlynczak, David Johnson, Richard Cageao, M. Nurul Abedin, David Kratz
NASA Langley Research Center

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Outline

- Review of Earth's Energy Budget and Infrared Greenhouse Effect
- Measurement of IR spectra at top (and bottom) of the atmosphere
- Measurement of IR spectra within the atmosphere
- On to orbit – to the CLARREO mission
- Summary

Acknowledgements

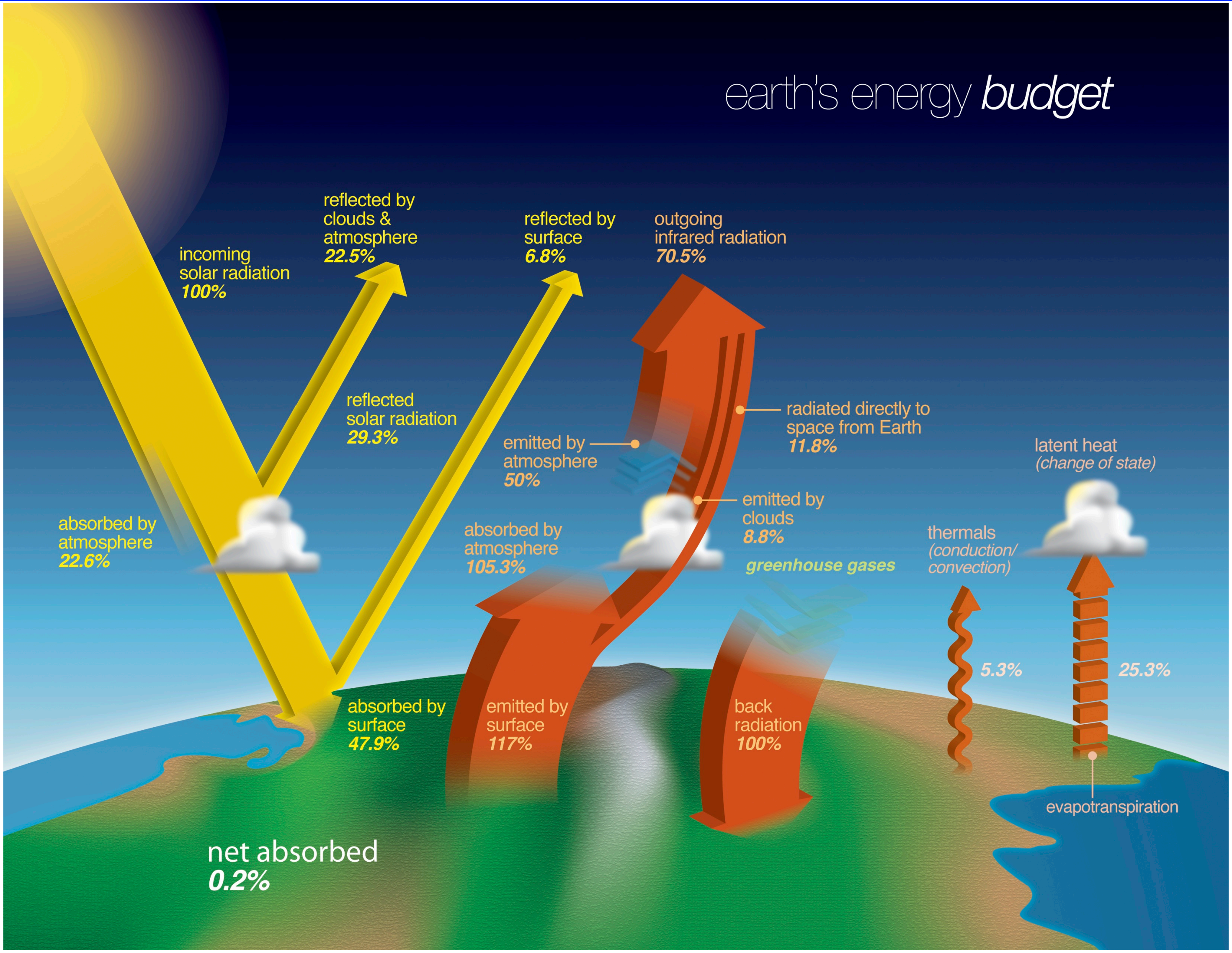
- Earth Science Technology Office (G. Komar)
- Radiation Sciences Program (H. Maring)
- NASA Langley Research Center (SD, SED, RTD)
- Corporate, Academic, and Government Partners
  - Space Dynamics Laboratory, Utah State University
  - Harvard Smithsonian Center for Astrophysics
  - DRS Technologies, Cypress, CA
  - Department of Energy
  - University of Wisconsin
  - AER, Inc.
  - SSAI, Hampton VA
  - ITT, Fort Wayne, IN
  - Raytheon Vision Systems, Santa Barbara, CA

Projects

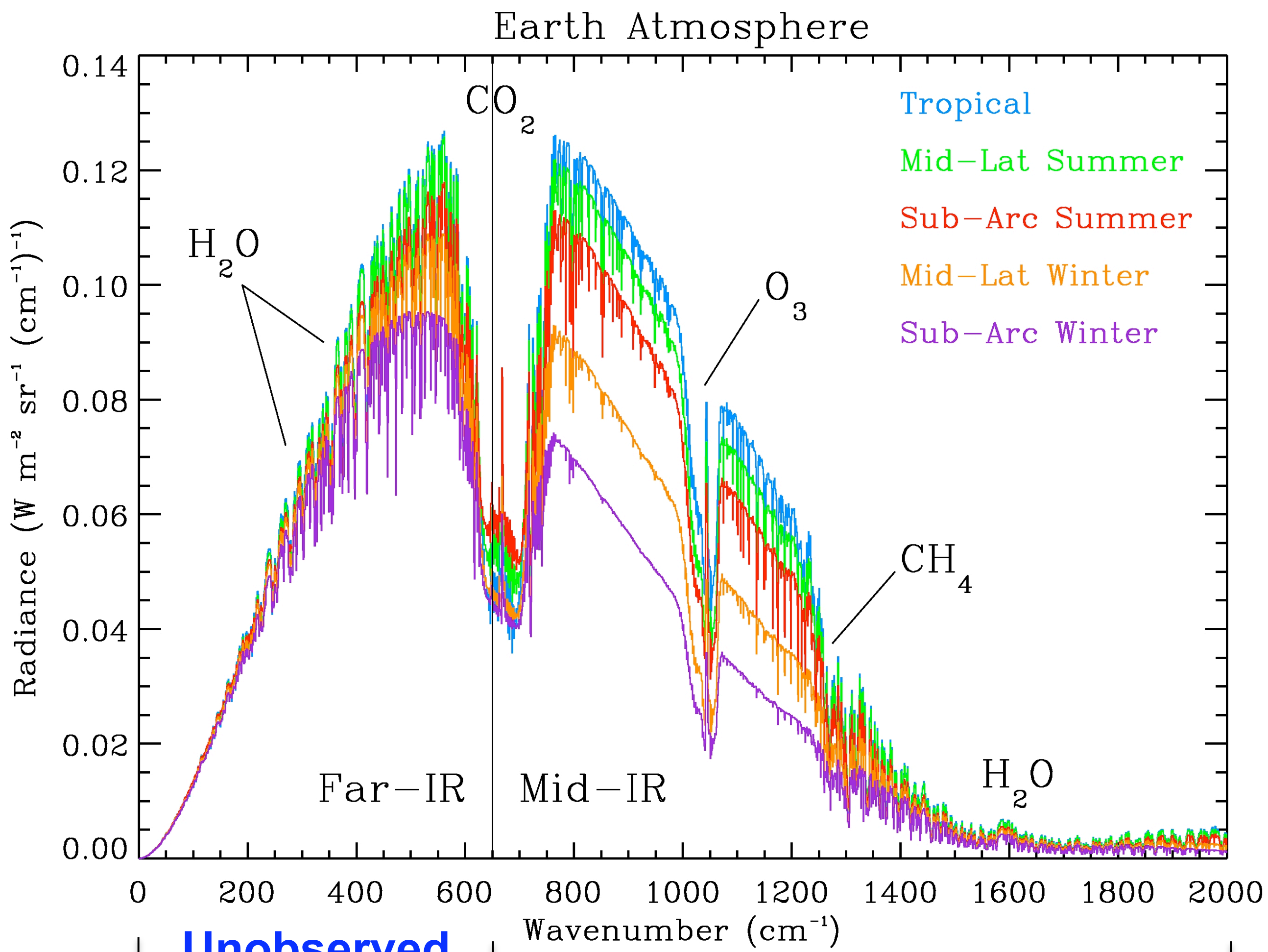
- **IIP 2001: FIRST**
  - Far-Infrared Spectroscopy of the Troposphere
- **IIP 2004: INFLAME**
  - In-situ Net Flux within the Atmosphere of the Earth
- **IIP 2007: CORSAIR**
  - Calibrated Observations of Radiance Spectra from the Atmosphere in the Infrared
- **ACT 2008: FIREBIB**
  - Far-Infrared Blocked Impurity Band Detectors
- **Radiation Sciences 2008: FORGE**
  - Far-Infrared Observations of the Radiative Greenhouse Effect

Goal: *To significantly advance ability to observe the infrared spectrum from space, within the atmosphere, and from the ground*

Earth’s Energy Budget



Earth's Outgoing Longwave Radiation



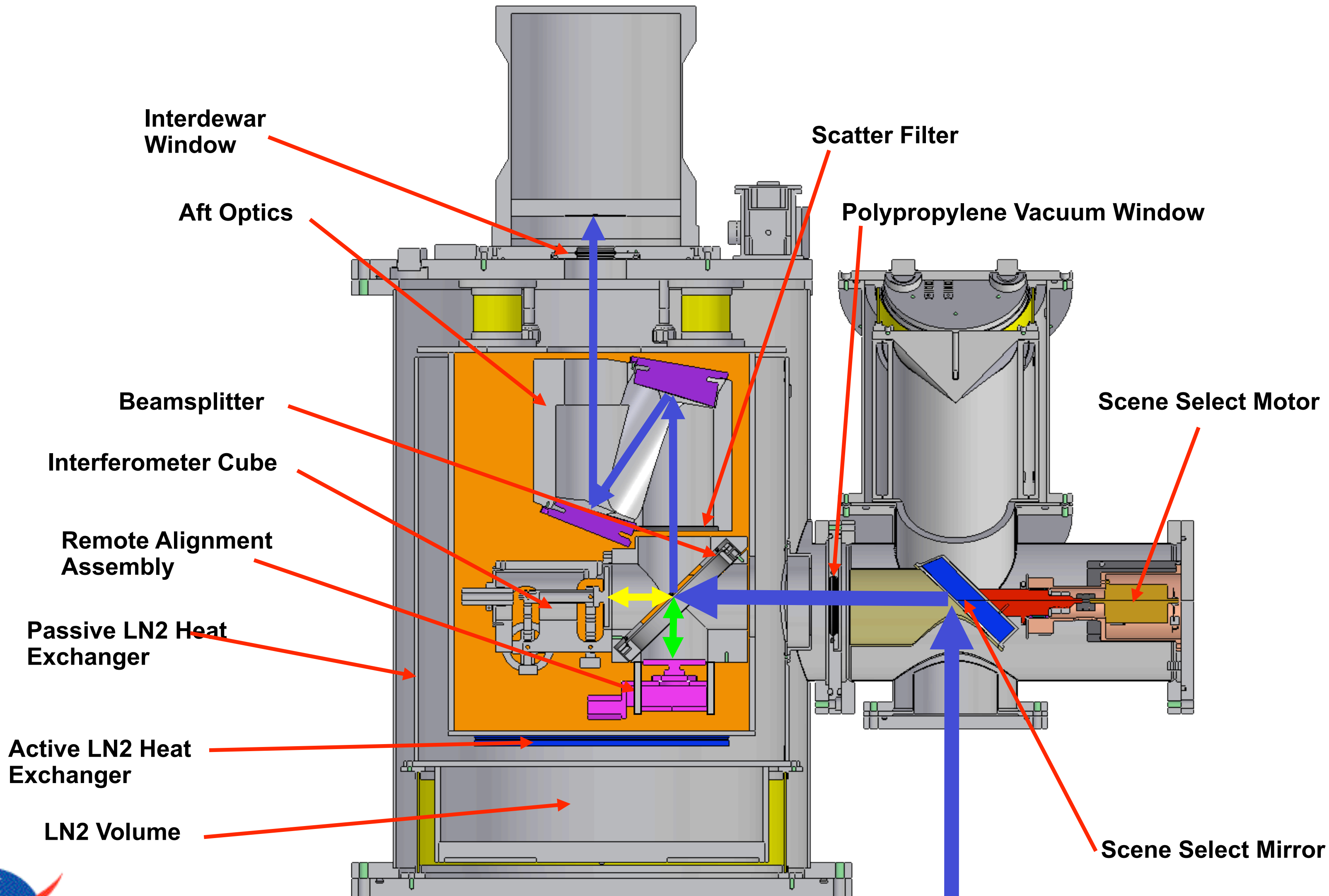
Unobserved From Space | **AIRS, IASI, CrIS**

FIRST Instrument

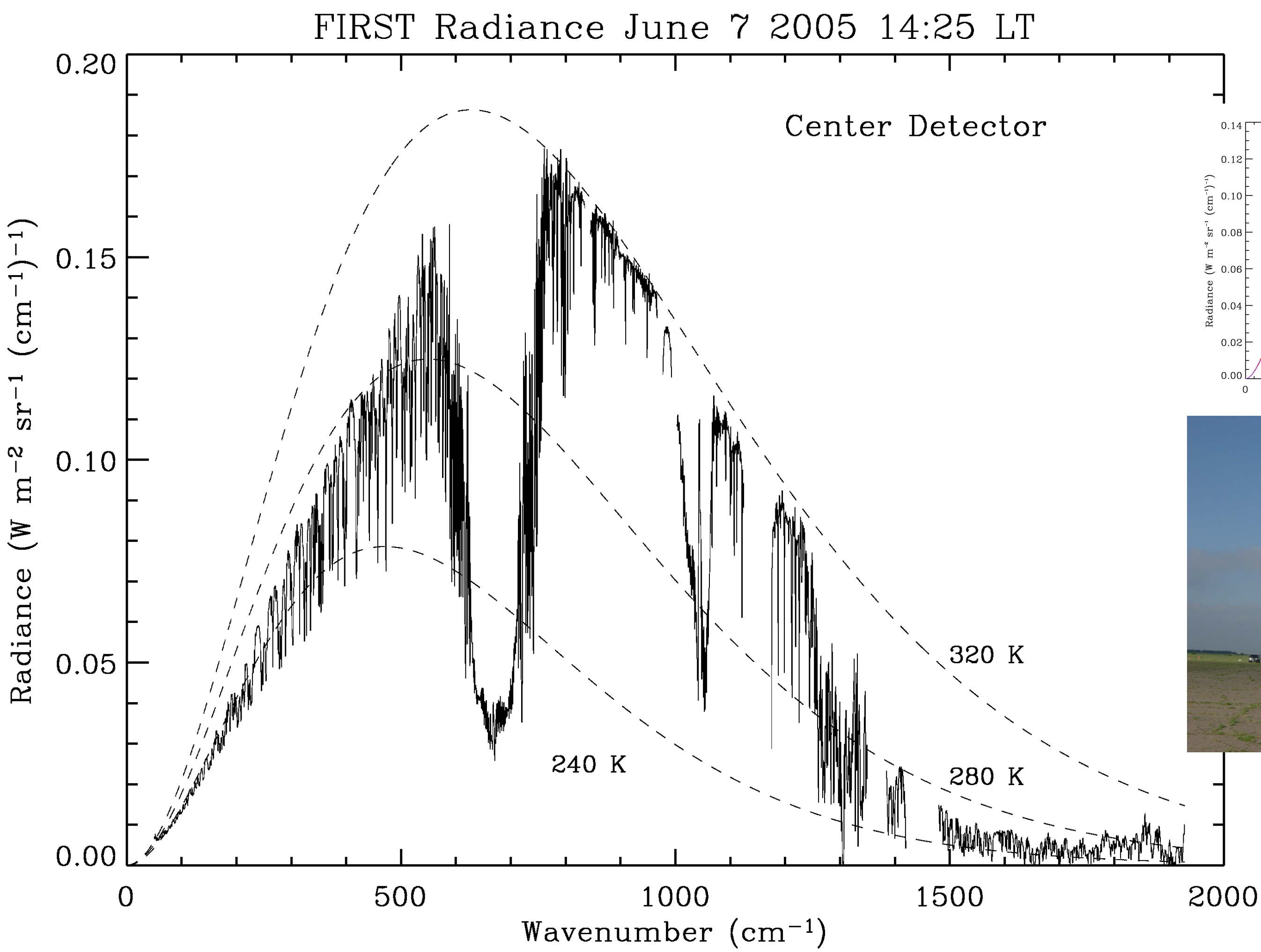
FIRST - Far-Infrared Spectroscopy of the Troposphere

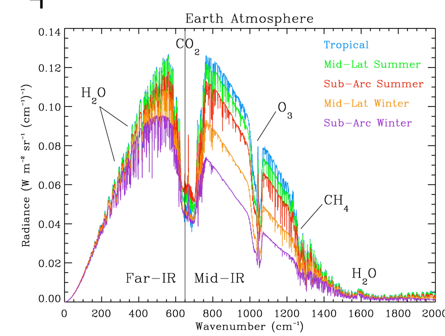
- Developed under NASA Instrument Incubator Program of ESTO
- Michelson Interferometer
  - *6 to 100 μm on a single focal plane*
  - *0.625 cm^{-1} unapodized (0.8 cm OPD)*
  - *Germanium on polypropylene beamsplitter*
  - *Bolometer detectors @ 4 K*
- Demonstrated on a high-altitude balloon flight June 7 2005
- Second balloon flight September 18 2006
- Ground-based capability demonstrated March 2007
- Selected by NASA for FORGE Campaign in Chile in 2008
- FORGE Campaign August – October 2009

FIRST Spectrometer Overview



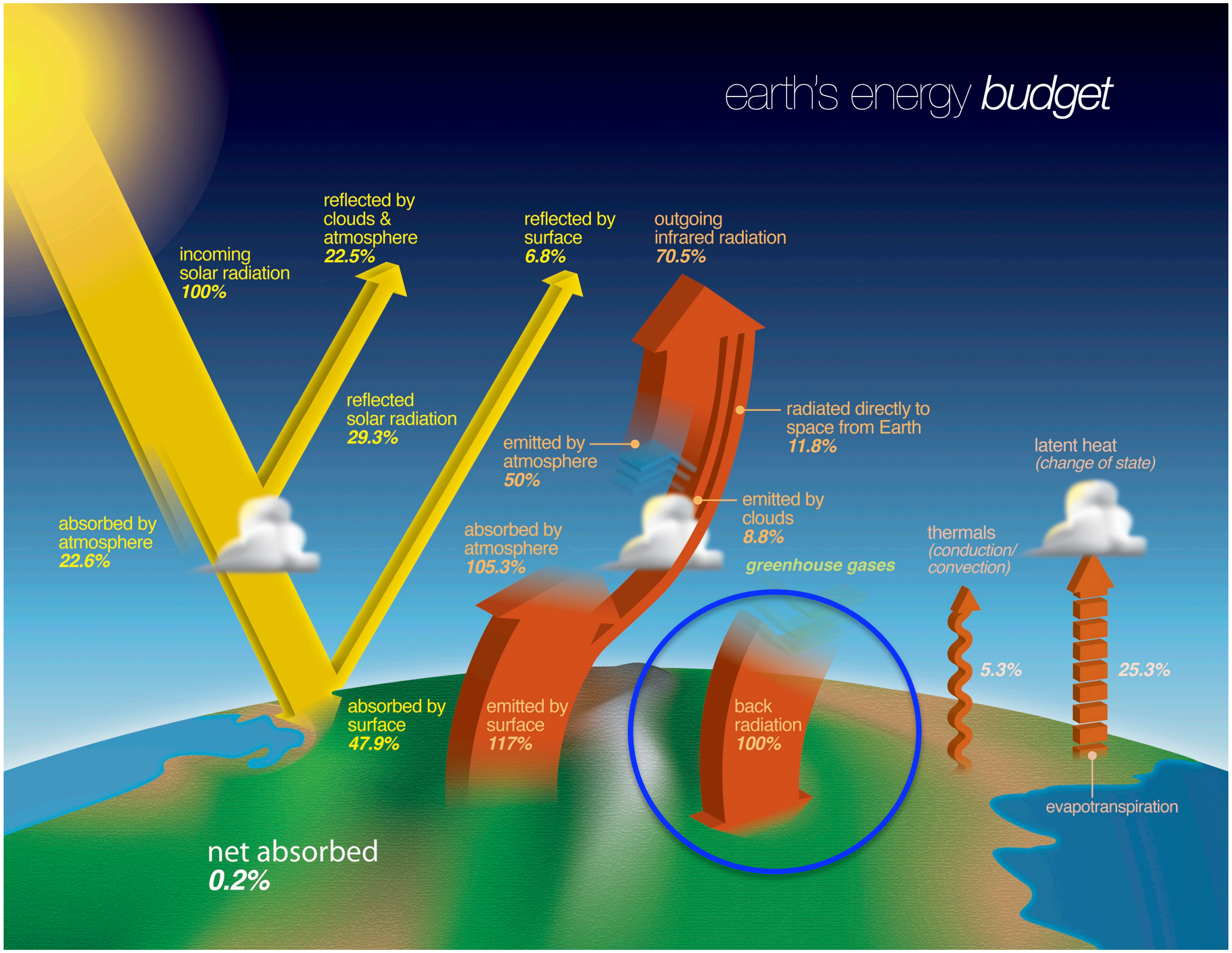
FIRST Thermal Infrared Spectrum - TOA



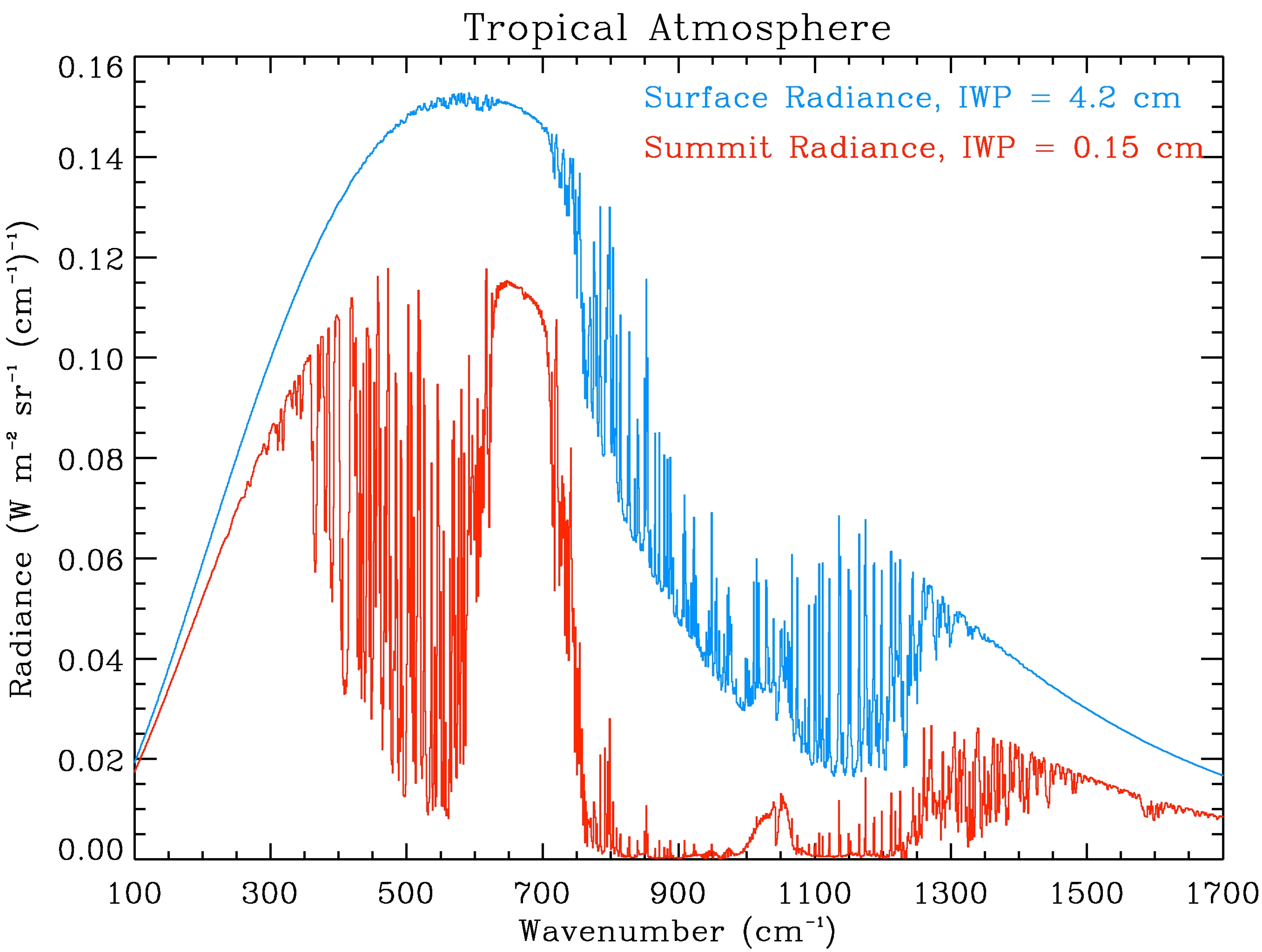


Mlynczak et al., GRL, 2006

Earth's Energy Budget



Earth's Downwelling Infrared Radiation – at Surface



The FORGE Project – Scientific Objective

- **Use new observational capability provided by FIRST to directly observe and quantify entire infrared greenhouse effect – *at Earth's surface***

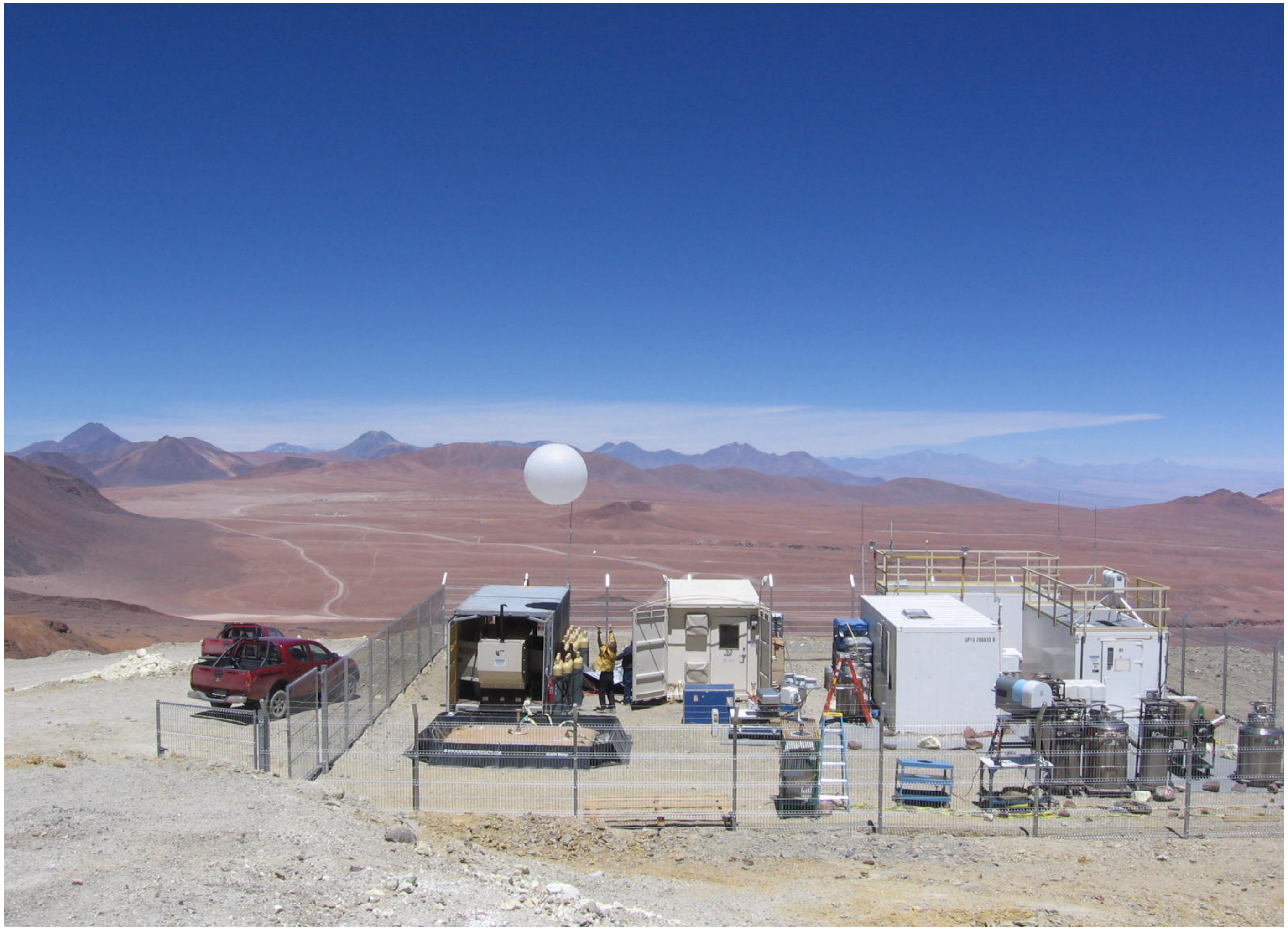
- **Conduct "radiative closure" experiment**
  - **Measure infrared radiation emitted by the atmosphere – *at Earth's surface looking up***
  - **Simultaneously measure temperature and water vapor profiles to provide inputs for theory**

- **Conduct experiment at high, dry location – Cerro Toco, Atacama Desert, Chile**
  - **Altitude: 17, 600 feet above sea level. Mean pressure ~ 0.5 Atmosphere**
  - ***Precipitable Water Vapor < 1 millimeter***

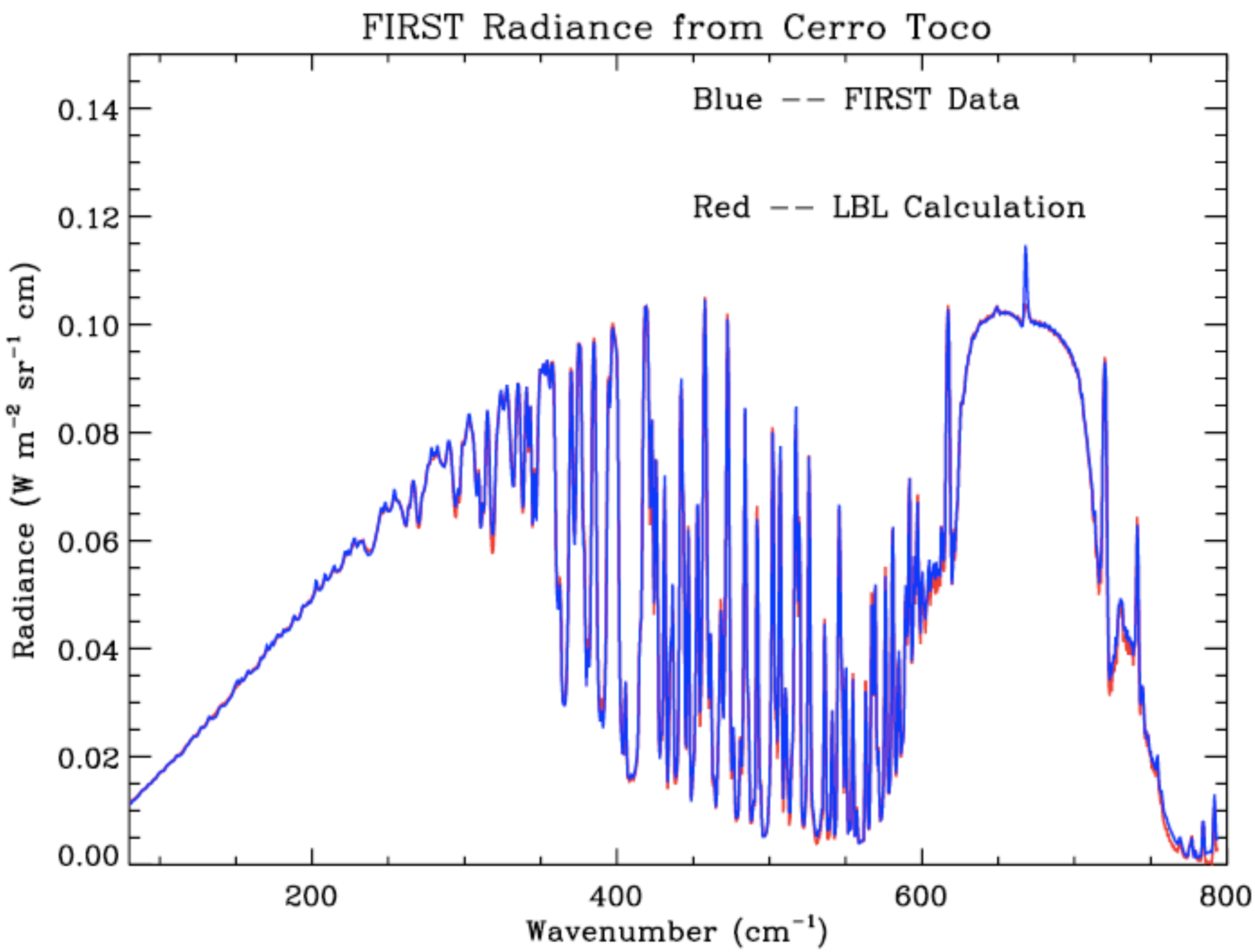
- **Part of larger "RHUBC-II" Campaign run by Dept. of Energy**
  - **Teams from U. Wisconsin, AER Inc., Italy, Germany, PNNL, Los Alamos NL, U. Denver, NASA Langley**

Safety of Team during deployment at altitude was paramount

Operations at 17,600 Feet

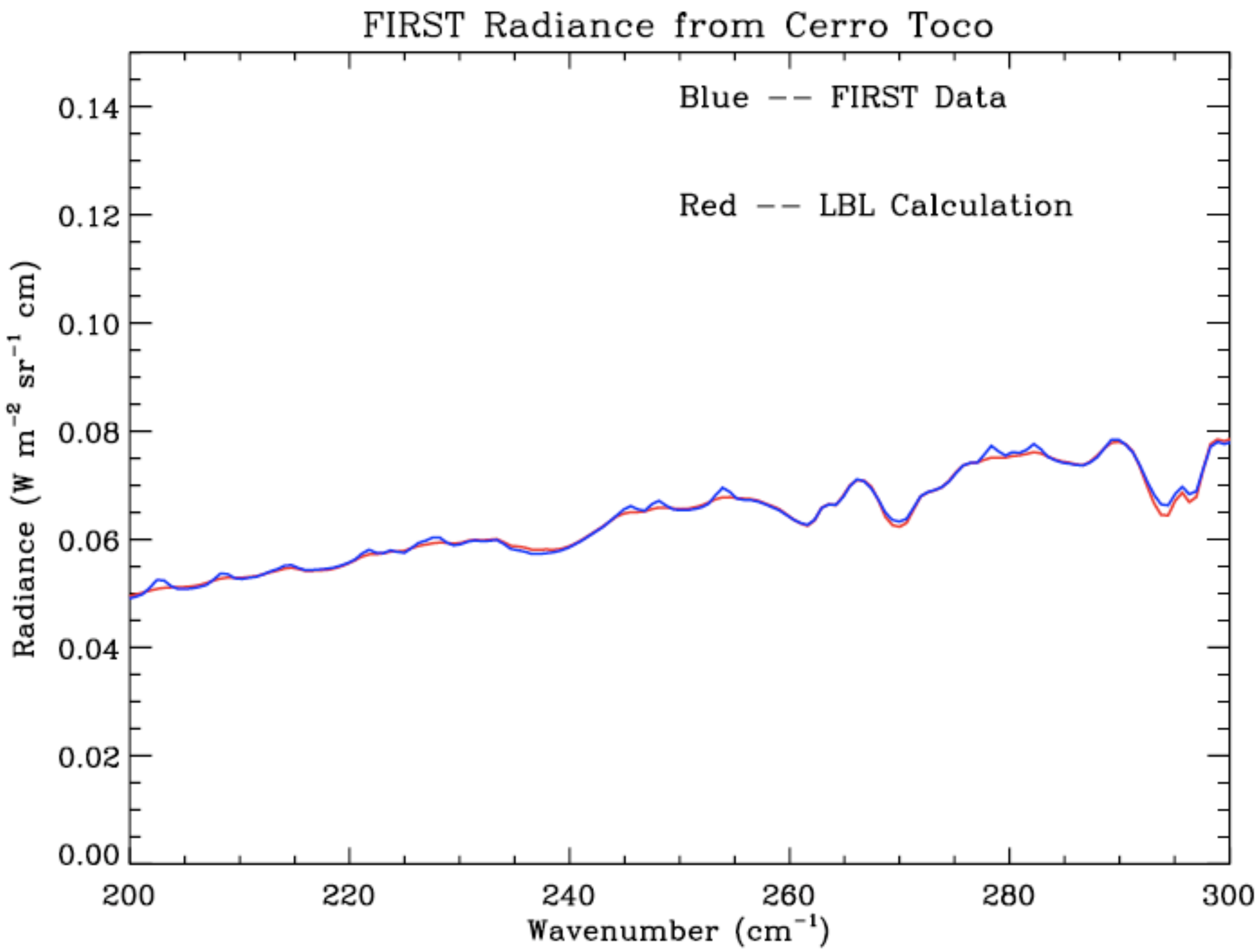


FIRST Far-IR Spectrum – 09/05/09



PWV = 0.75 millimeter ("wet" day)

September 5 2009 – PWV = 0.75 mm



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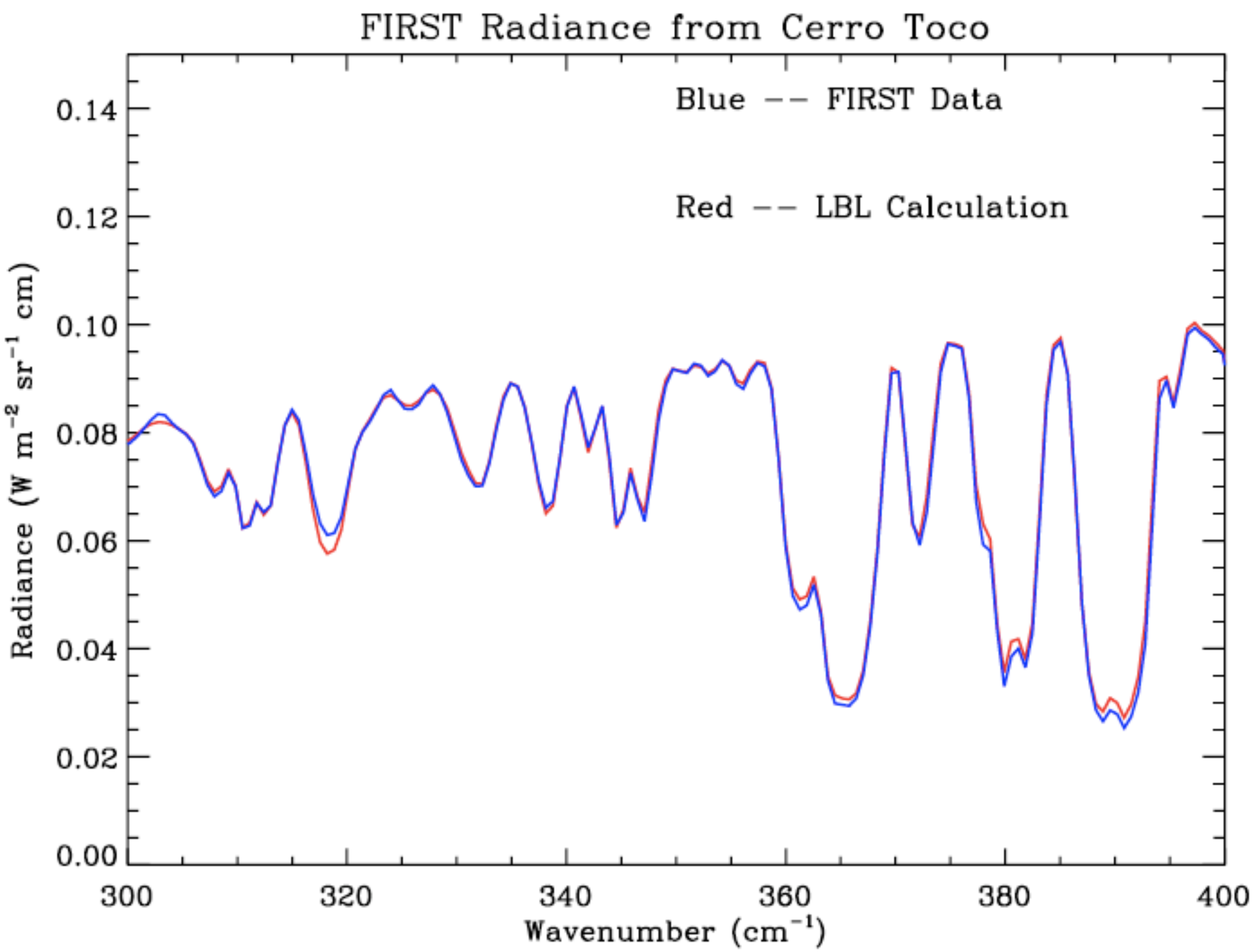
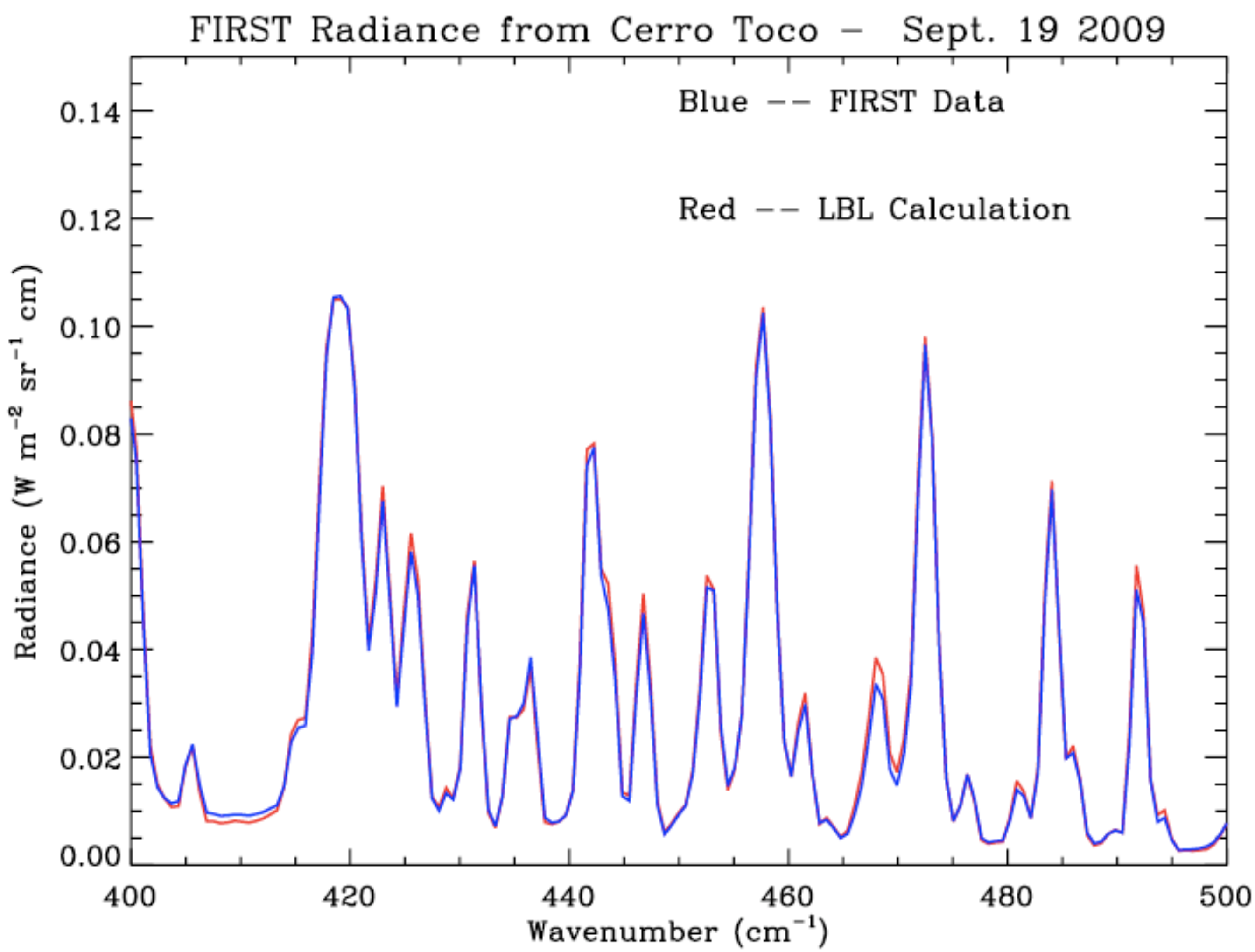


September 19 2009 – PWV = 0.4 mm



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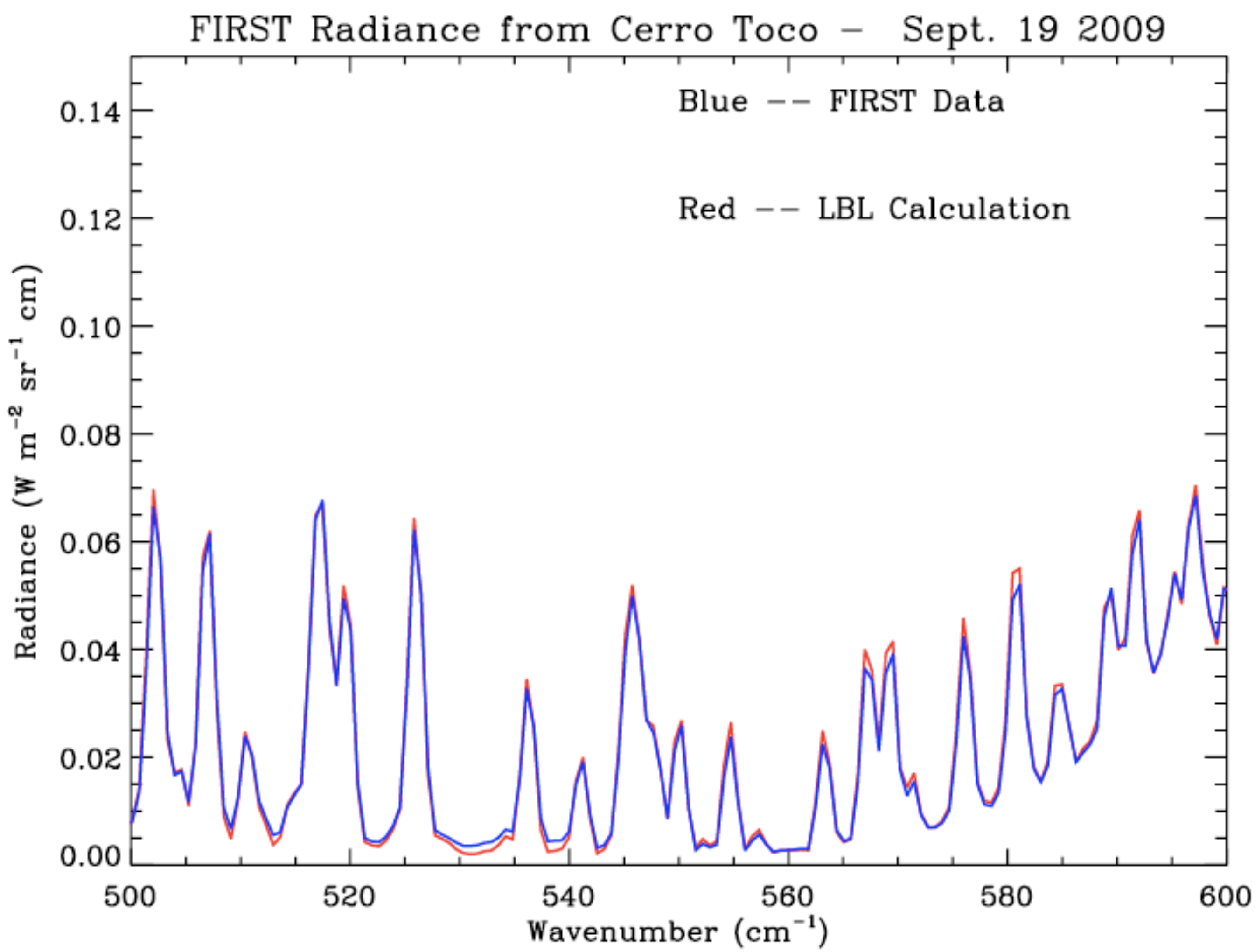


FIRST Summary

- **Successfully developed unique instrument to measure, at high spectral resolution, the complete infrared spectrum of the Earth and atmosphere**
- **Transitioned from "Incubator" to operational science instrument**
- **Demonstrated technologies in:**
  - **FTS**
  - **Beamsplitter**
  - **Focal Plane**

- ***Onto INFLAME and measurement of IR radiation within the atmosphere***

INFLAME – Fundamental Aspects

Every atmospheric model has essentially 3 equations:

- Momentum: (F = ma)
- Continuity: (Conservation of mass)
- Energy: (First Law of Thermodynamics)

Energy equation requires knowledge of rate at which atmosphere heats and cools:

- Radiation
- Latent process (water condensation/evaporation)
- Conduction

INFLAME Goal: Measure the rates of heating & cooling of the atmosphere by visible and infrared radiation

In-Situ Net Flux within the Atmosphere of the Earth

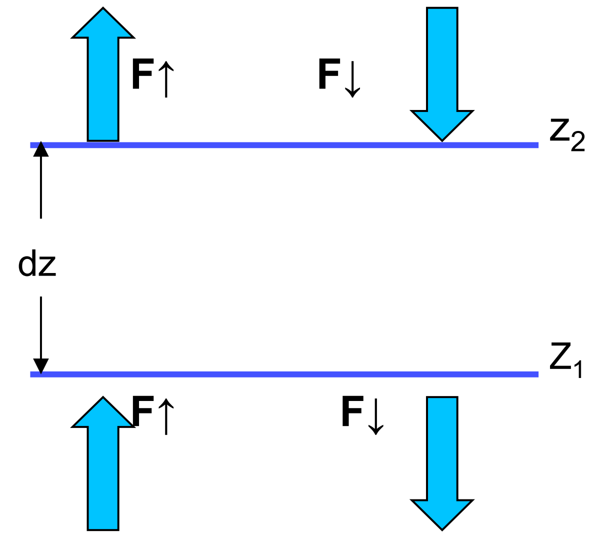
Atmospheric Heating and Cooling Rates

$$F\uparrow(z) = \int_{0}^{1} I(z)\,\mu\, d\Omega$$

$$F\downarrow(z) = \int_{-1}^{0} I(z)\,\mu\, d\Omega$$

$$F_{net}(z) = F\uparrow(z) - F\downarrow(z)$$

$$\frac{\partial T}{\partial t} = \frac{1}{\rho\, C_p}\frac{\partial F_{net}(z)}{\partial z}$$



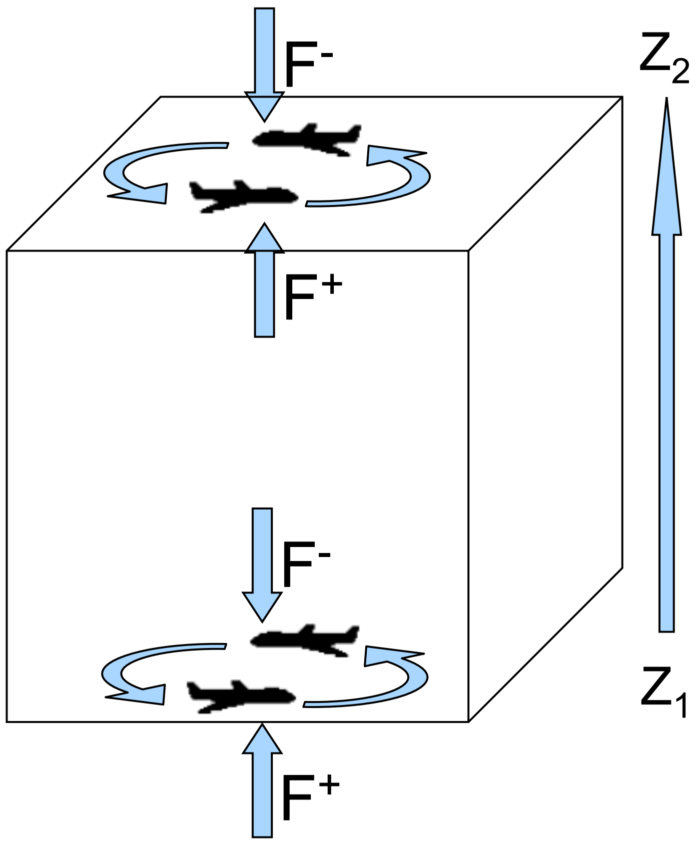
Require an instrument to *directly* measure the net flux

Measuring Net Flux Divergence

- **From an airborne platform:**
  - **Measure Net Flux at Z_1**
  - **Measure Net Flux at Z_2**

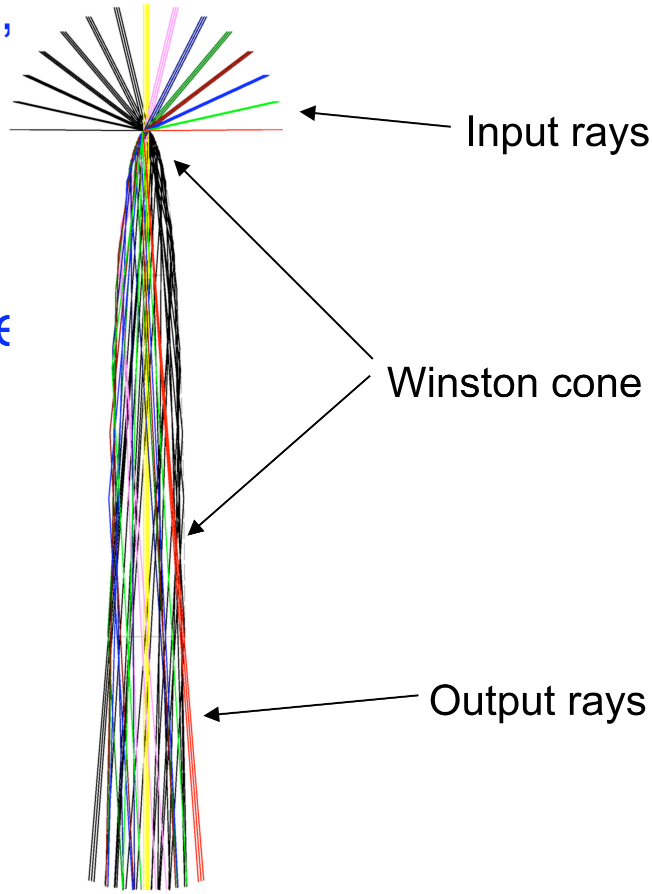
- **Approximate Heating Rate by:**

$$\frac{\partial T}{\partial t} = \frac{1}{\rho\, C_p} \frac{F_{net}(z_2) - F_{net}(z_1)}{(z_2 - z_1)}$$



INFLAME Approach: F+ and F-

- Most instruments measure radiance, not flux.
- Measuring flux requires collecting light over a full hemisphere.
- We use a non-imaging Winston cone to collect radiation and collimate it into an f/6.8 beam.
  - Input aperture is 1 mm diameter.
  - Output aperture is 13.6 mm diameter.



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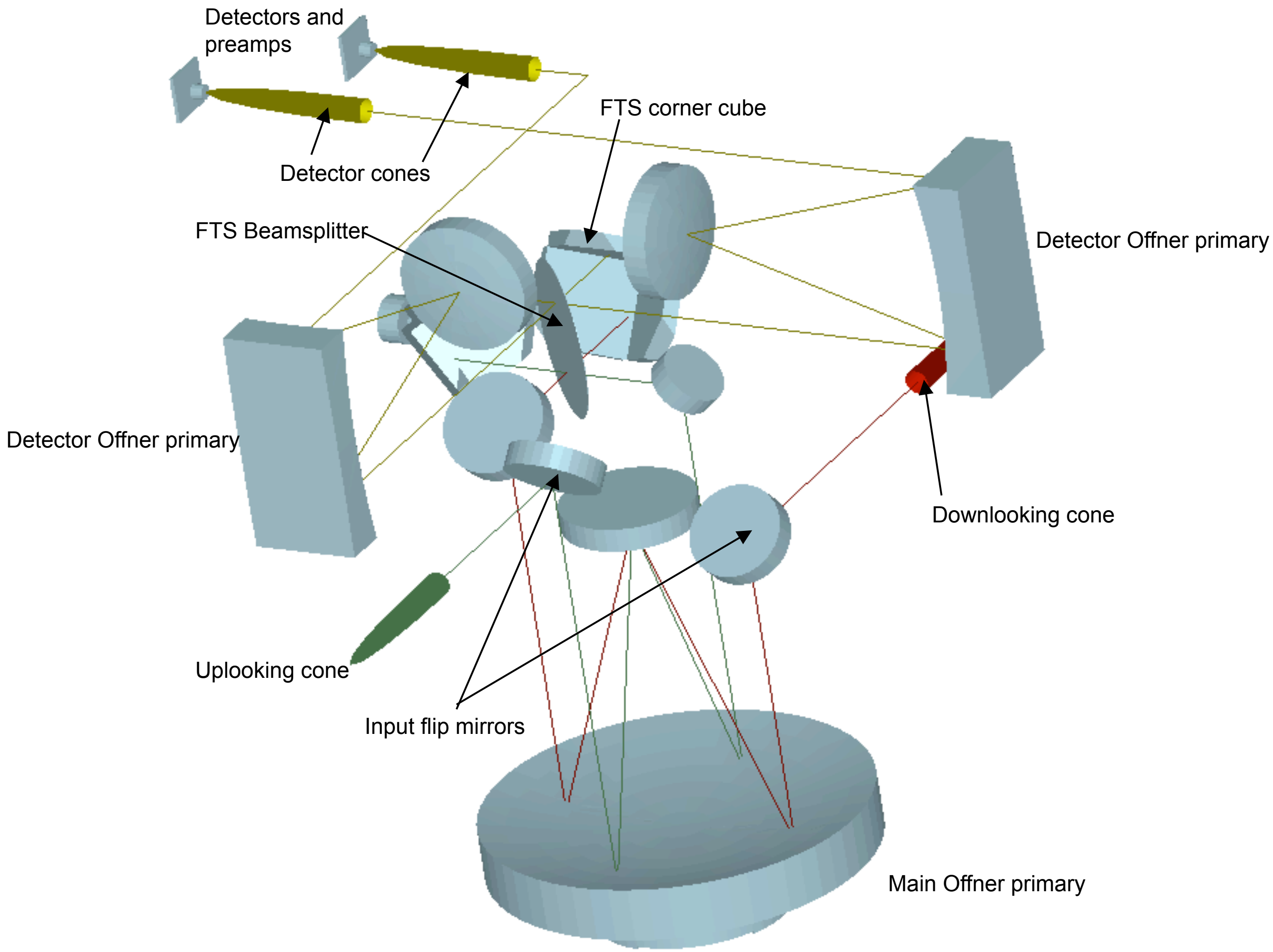
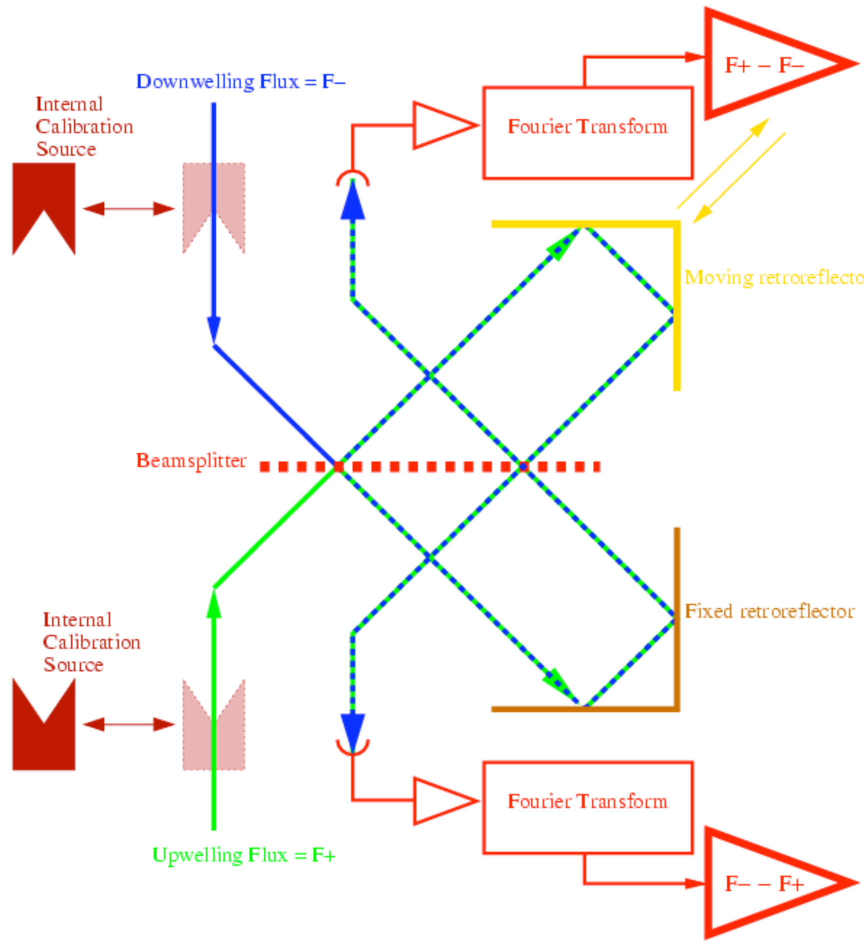
INFLAME Optical Layout



INFLAME Approach: Fz

- Direct uplooking and downlooking apertures to the two inputs of a 4-port Fourier transform spectrometer (FTS);
- Scan FTS to produce complimentary interferograms at two outputs;
- Fourier transform interferograms to estimate the spectrum of the net flux

$$Fz = F+ - F-$$



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INFLAME Measurement Platform

INFLAME mounted in wingtip fuel tanks

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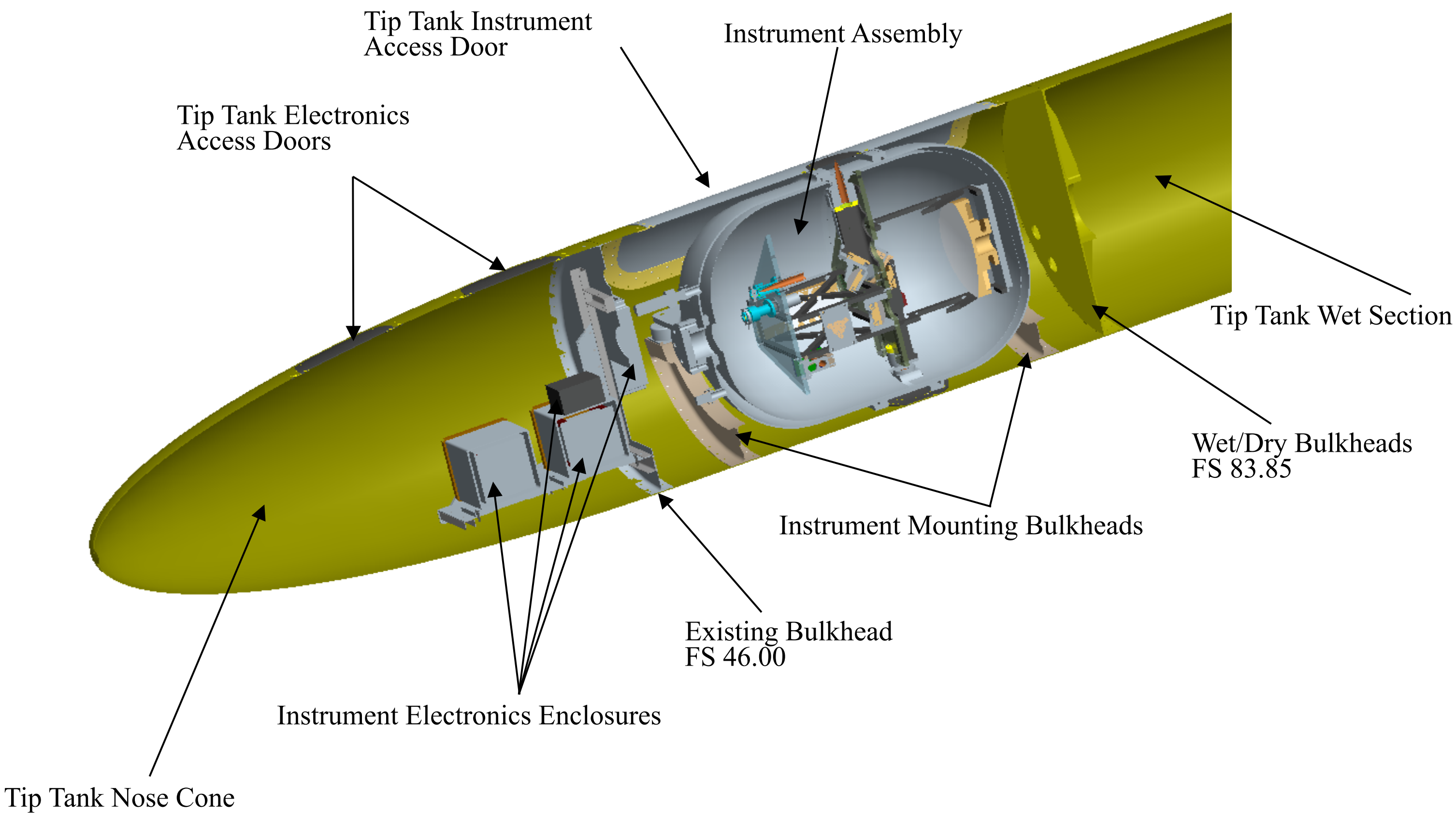
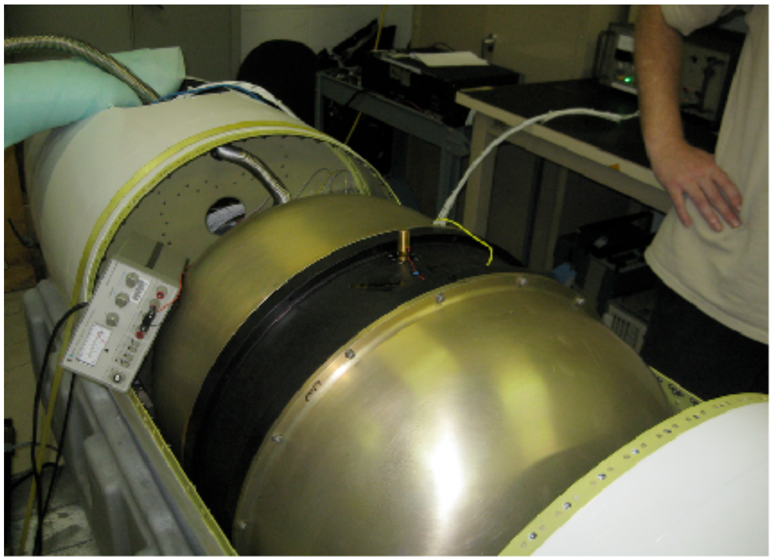
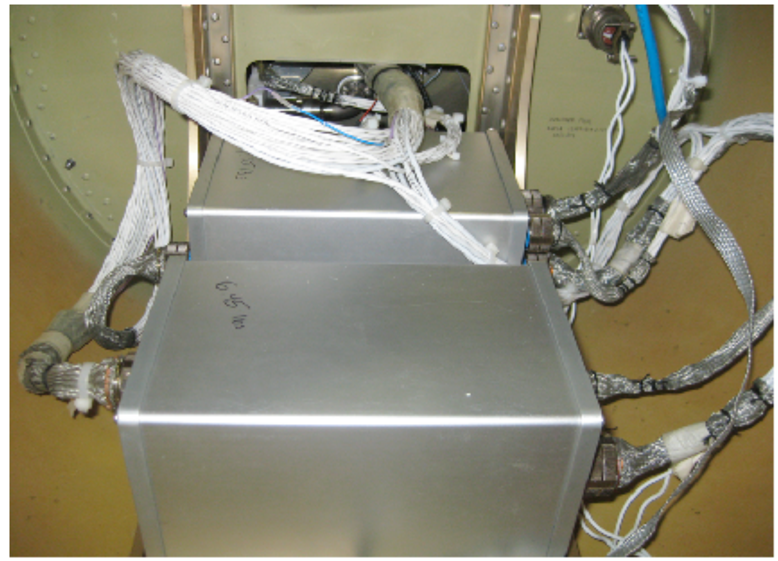
Fuel Tank Integration



LW Compatibility: 7/29/2009





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LW Flight Install: 1/4/2010

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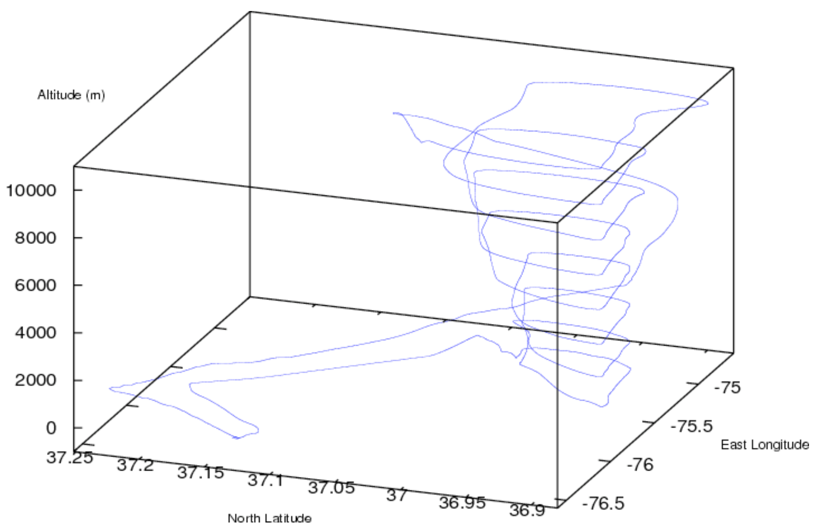
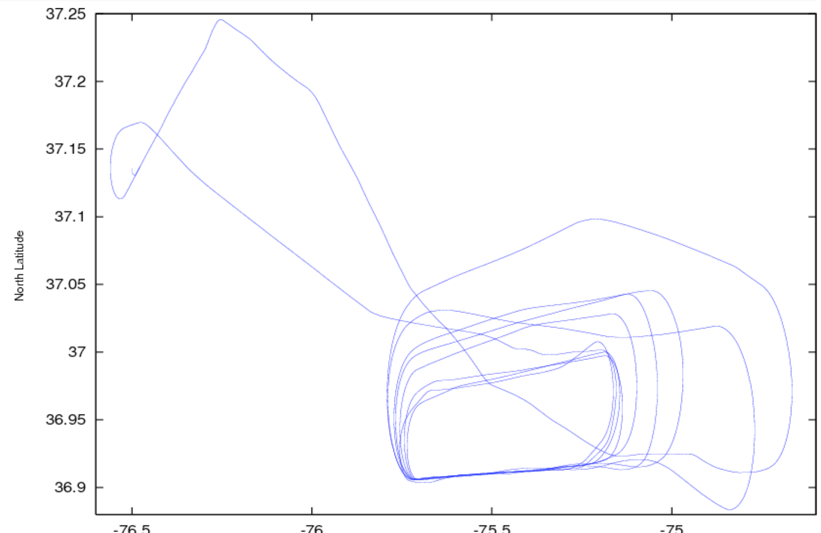
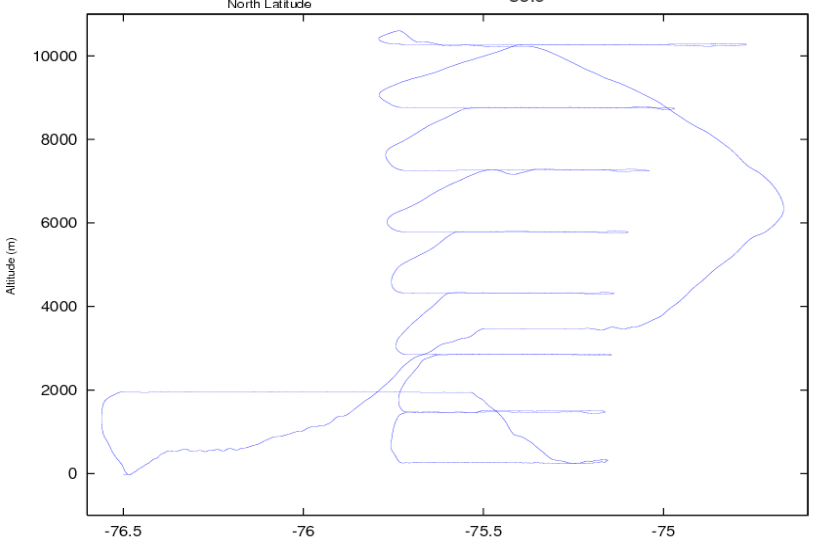
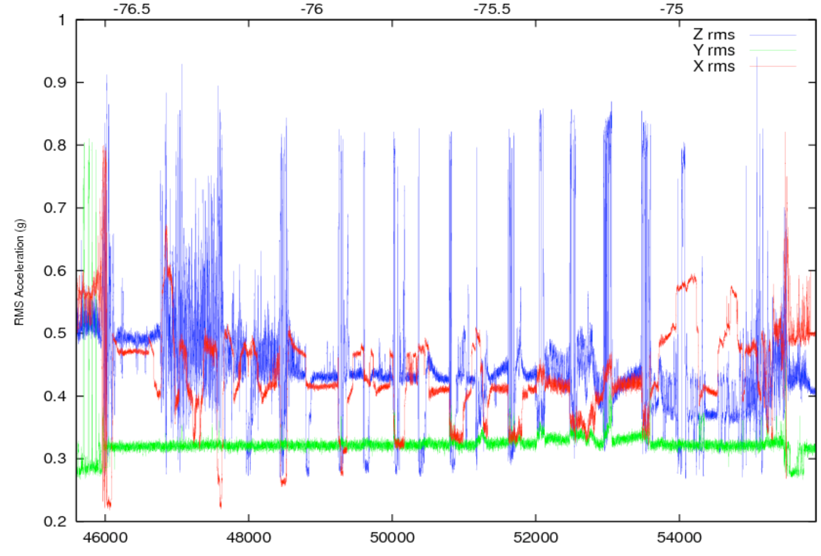
Flight Track and Accelerometer









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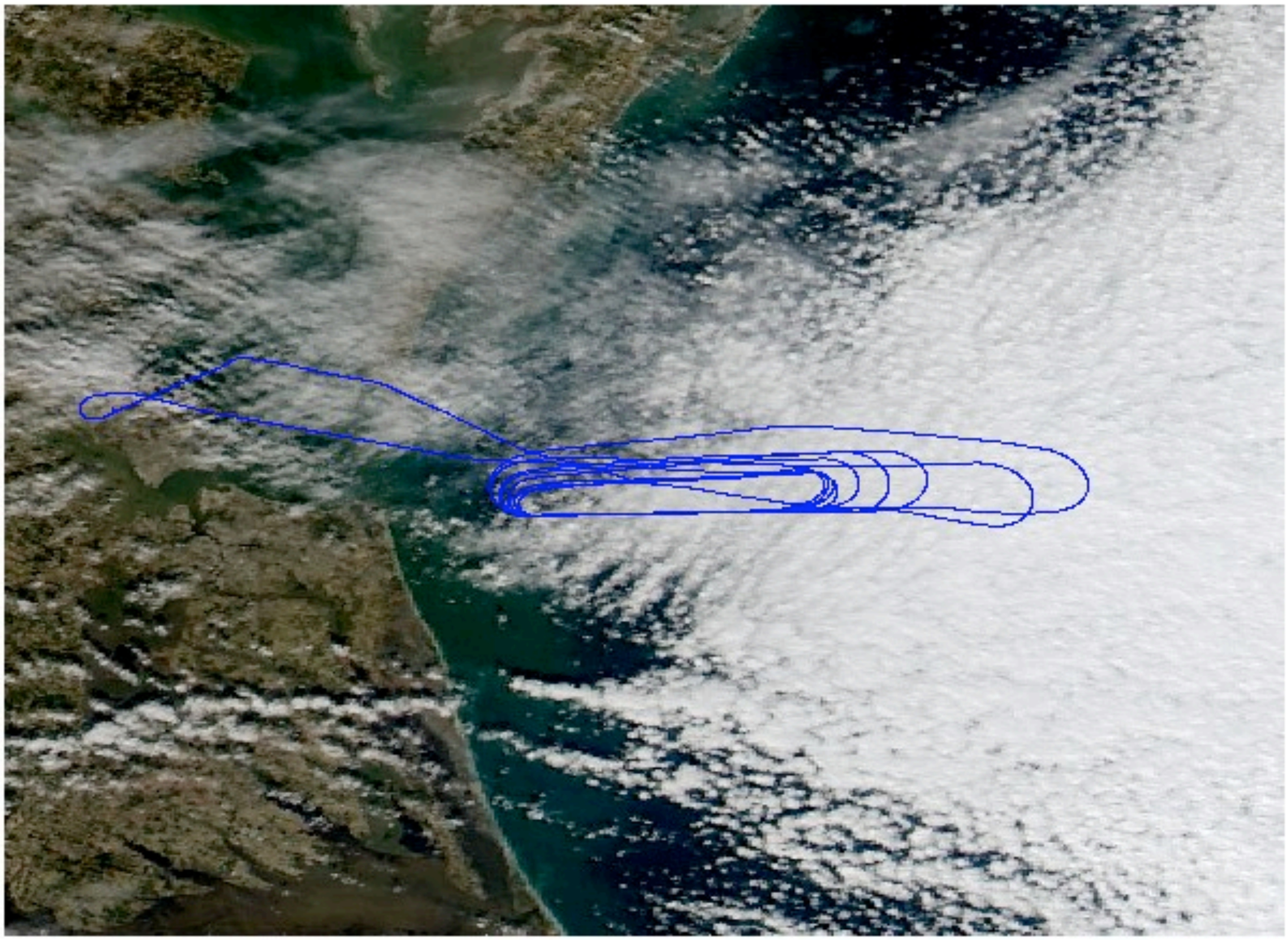
MODIS Visible Imagery



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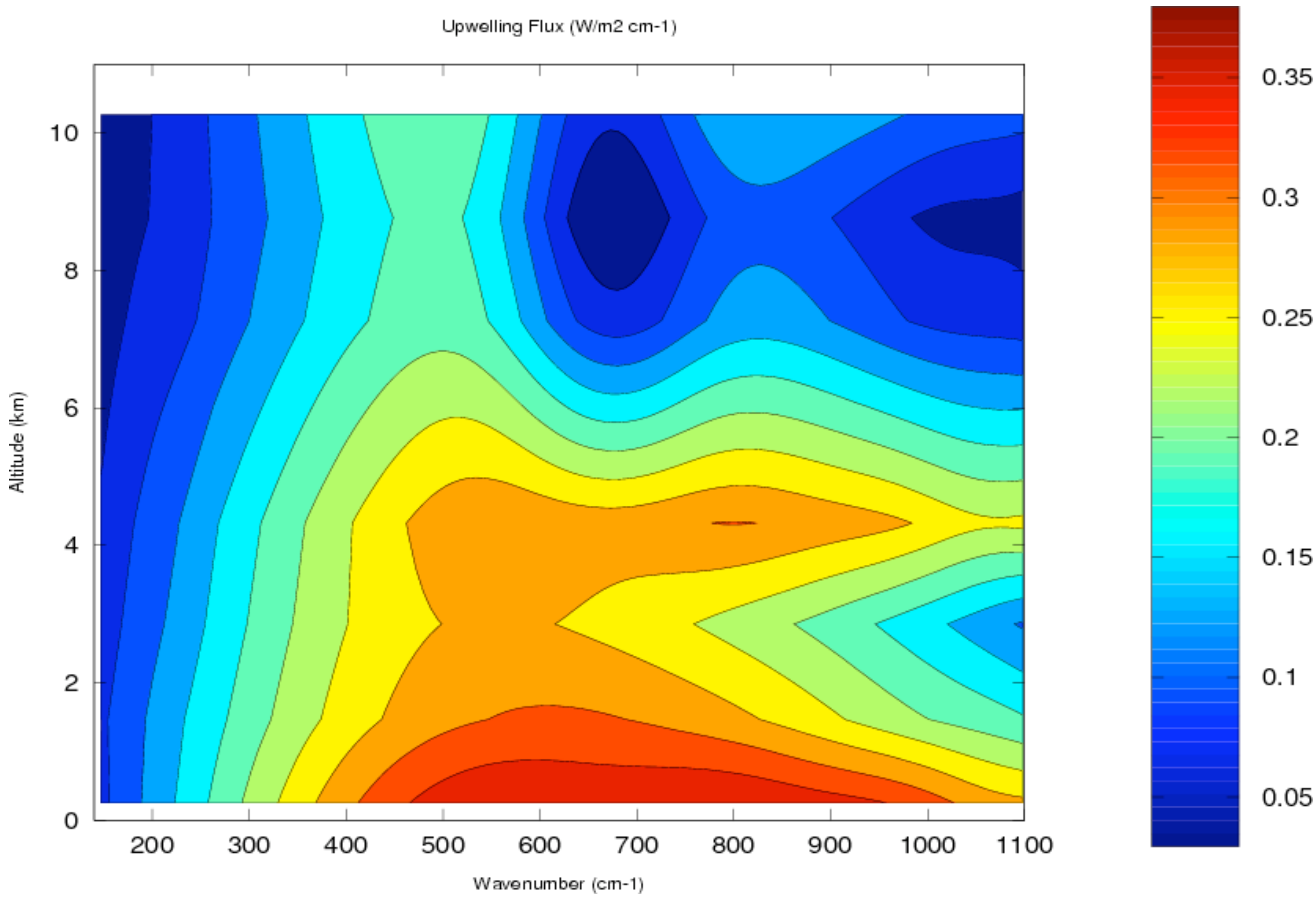
INFLAME Data Product



INFLAME LW Net Flux

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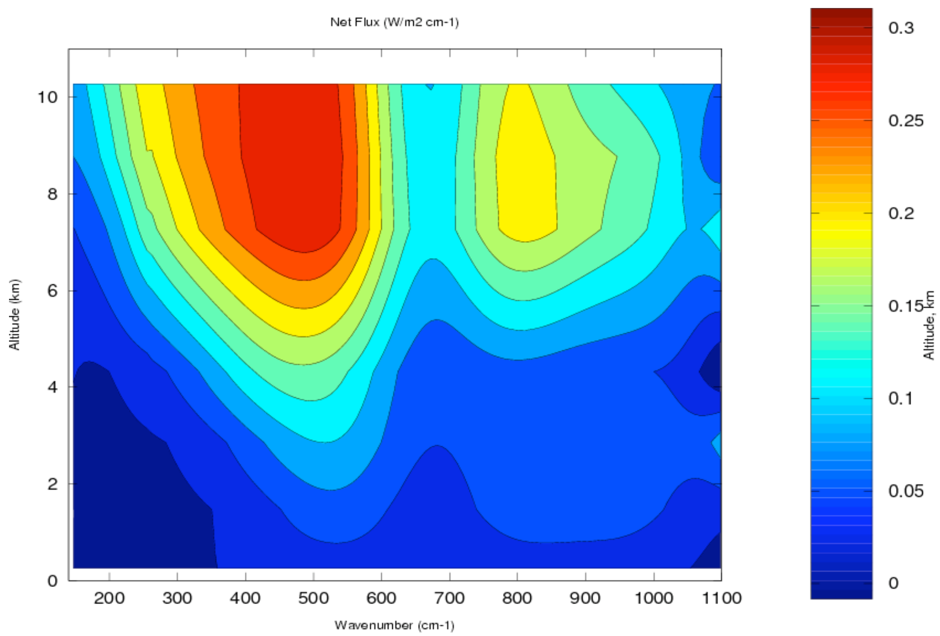
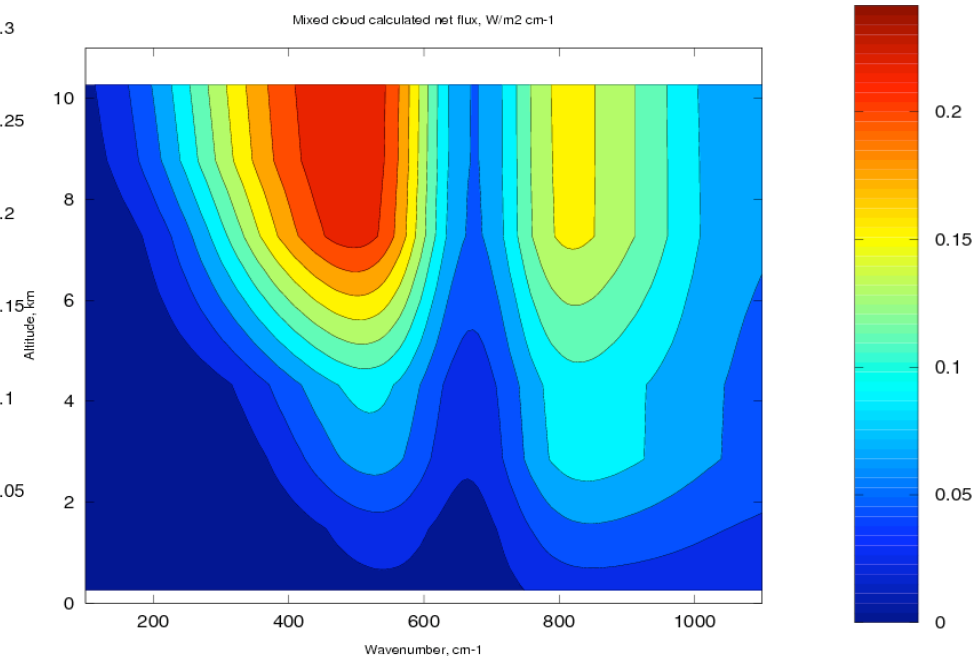


Measured LW Net Flux

1/5/2010



Calculated LW Net Flux

1/52010

INFLAME Derived LW Cooling Rates

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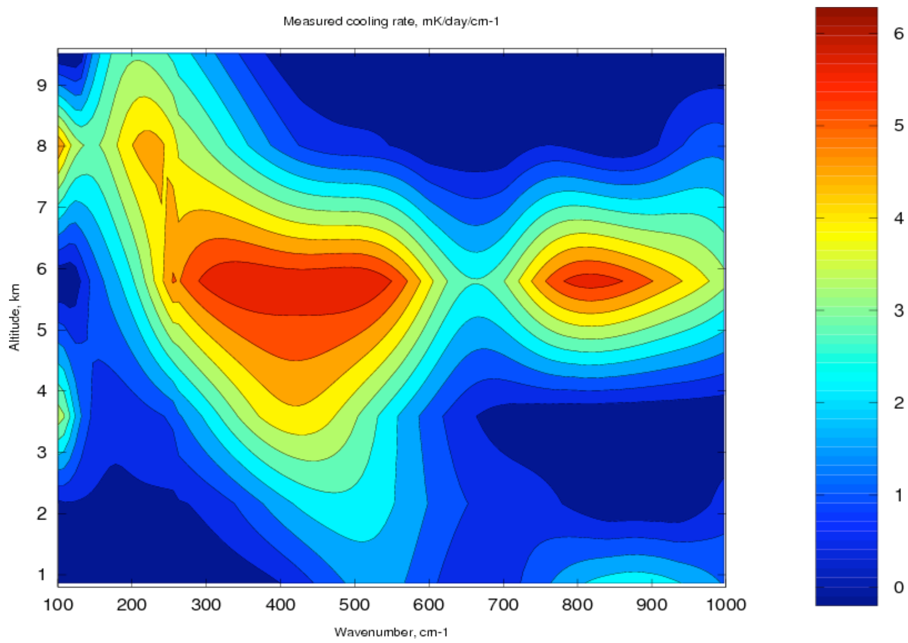
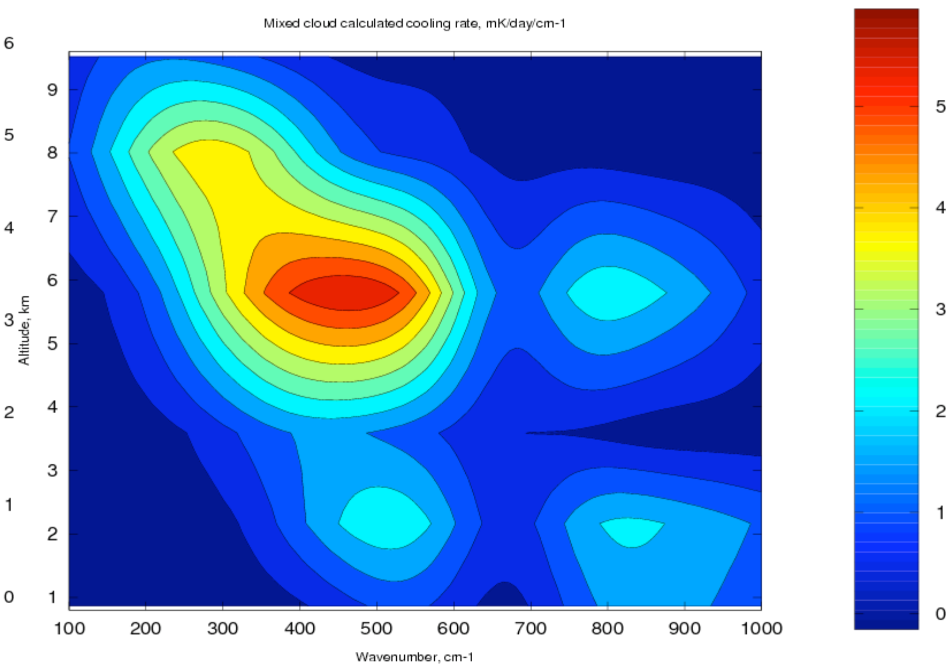


Measured LW Cooling mK/Day/cm^{-1}

1/5/2010 flight.



Calculated LW Cooling mK/Day/cm^{-1}

1/5/2010 flight

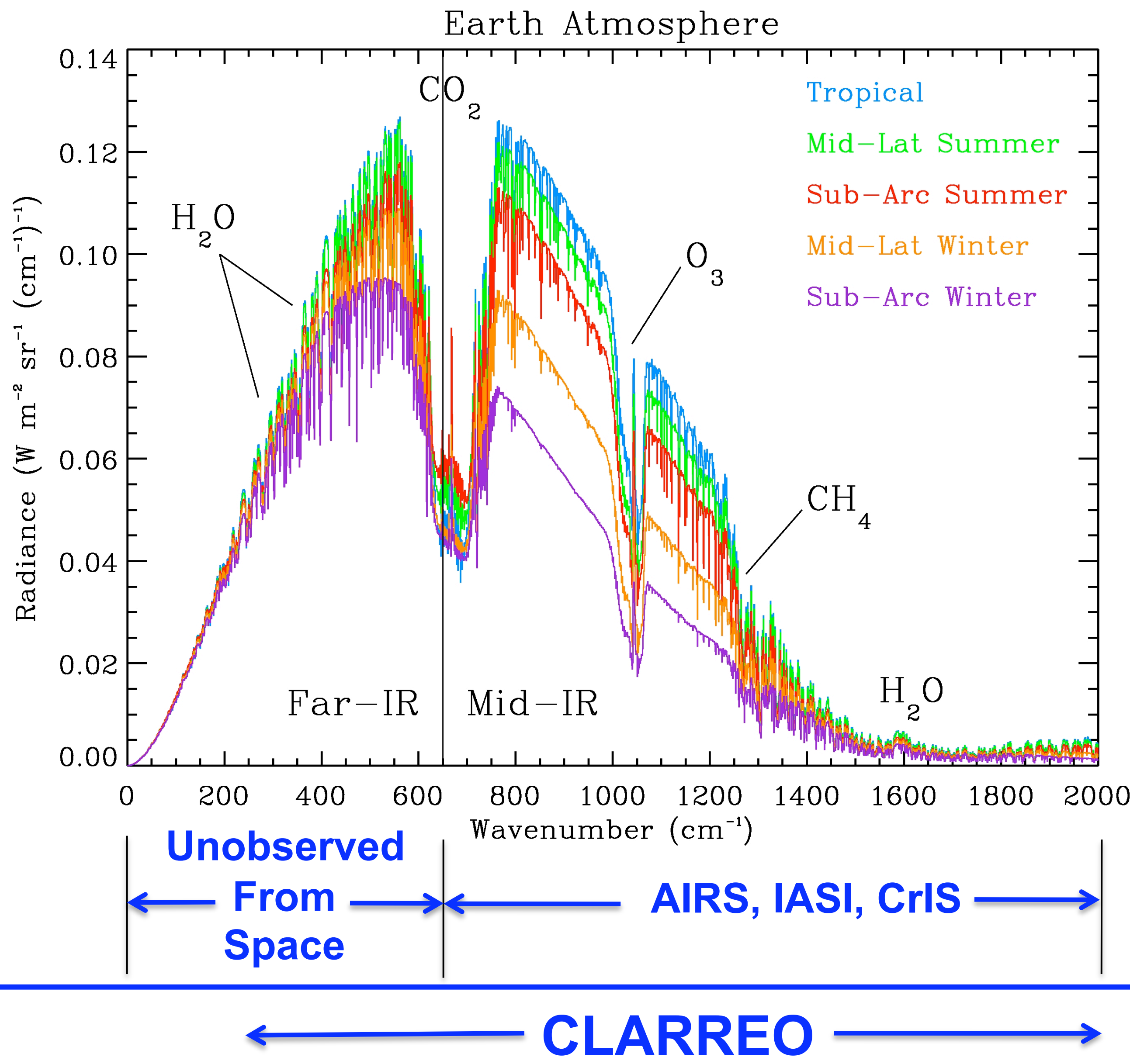
INFLAME Flight Results

Summary

- IR FTS (LW) Successfully demonstrated during flight
  - First direct measurement of net fluxes and cooling rates within the atmosphere
  - Analysis is ongoing

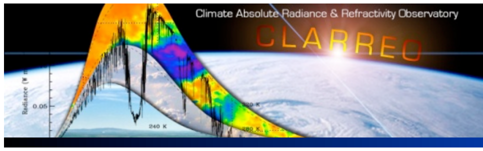
- UV-NIR FTS (SW): No useful flight spectra obtained.
  - Commercial controller failed due to excessive drift with temperature before takeoff.

Earth's Outgoing Longwave Radiation



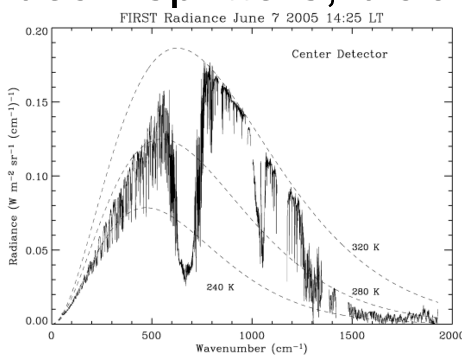
CORSAIR – Langley's Current IIP

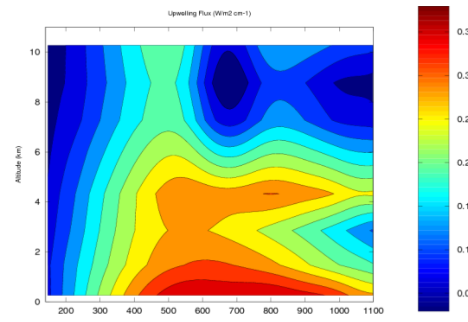
- FIRST, INFLAME demonstrate numerous technologies for FTS
- Some CLARREO – specific technologies remain
- CORSAIR IIP Project addresses:
  - Broad bandpass beamsplitters: ITT
  - Warm high sensitivity detectors: RVS
  - Blackbody radiance sources: SDL
- CORSAIR presently in year 2 of 3



Technology Development Heritage

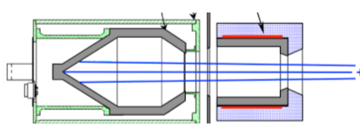
- LaRC has been developing technology for CLARREO for nearly one decade
  - FIRST and INFLAME FTS instruments developed and flown
  - CORSAIR and FIREBIB projects in progress
    - Detectors, beamsplitters, blackbodies in development



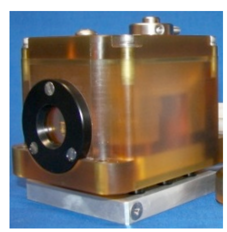


- UW/Harvard also developing CLARREO Technology
  - Verification system elements in development

Blackbodies
Emissivity Monitoring

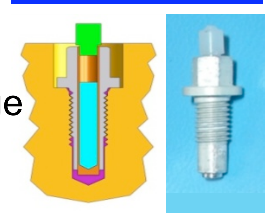


QCL



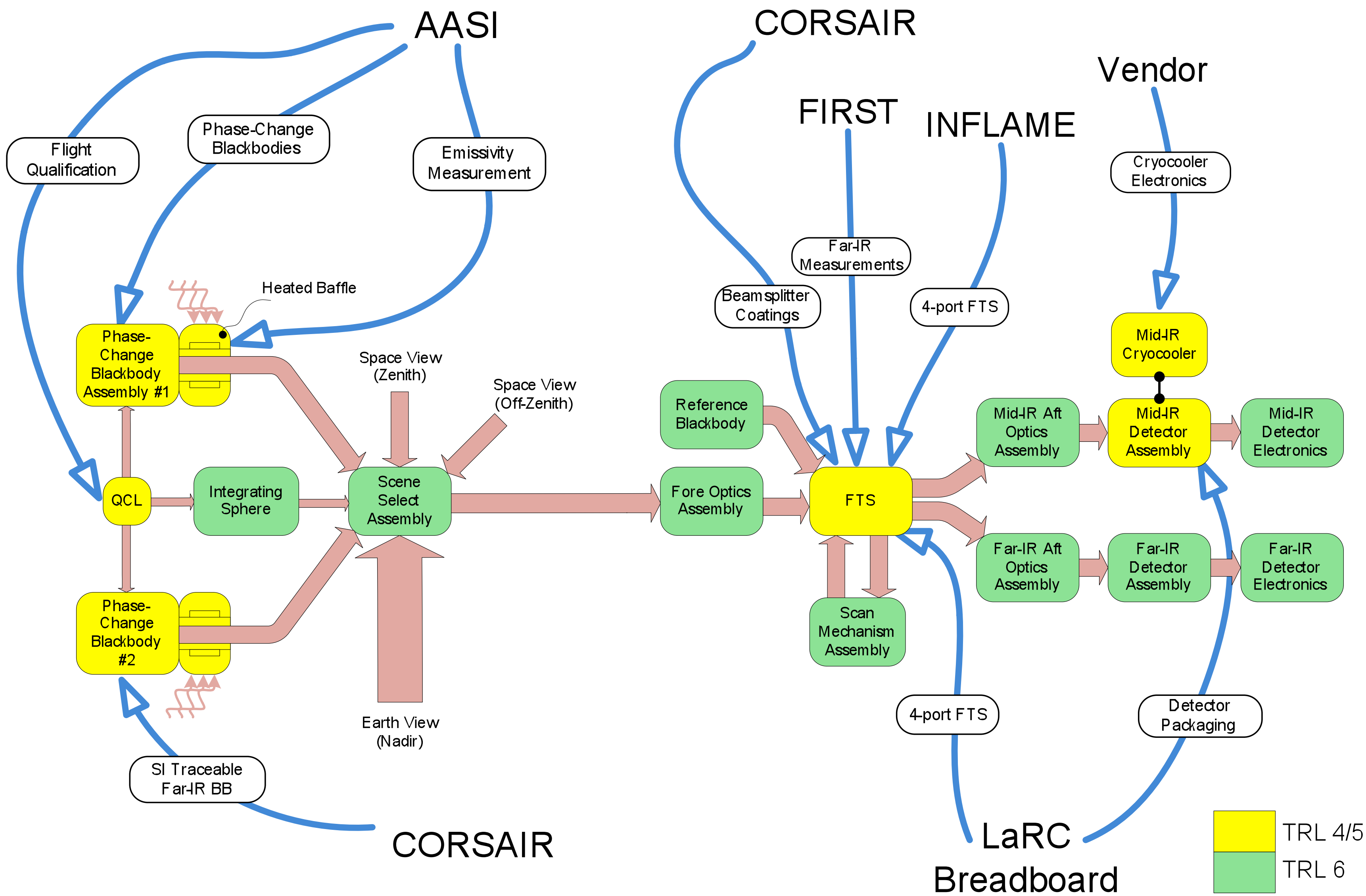
Phase Change Cells

Melt Material



Key CLARREO technologies in development to TRL 6

Technology Development Plan Leverages Hardware Matured Through Breadboard and IIP Programs



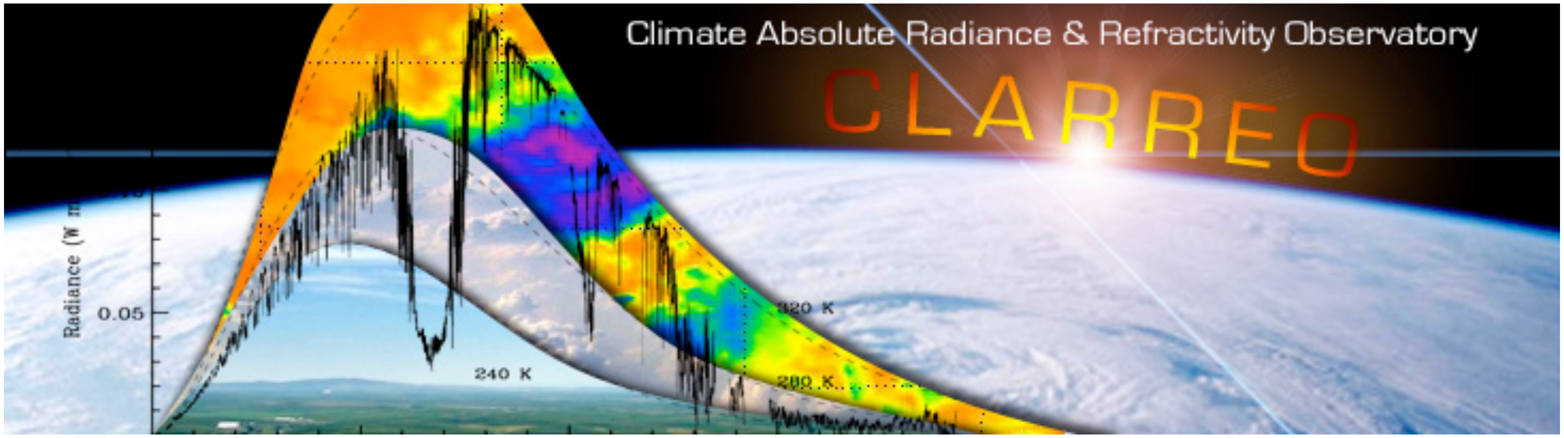
IIPs and breadboard provide early risk reduction

Summary – Incubator to Orbit

- FIRST instrument successfully developed and demonstrated and transitioned to operational scientific instrument in FORGE campaign
-
- INFLAME instrument successfully developed and demonstrated – awaiting opportunity for science campaign
- CORSAIR Project developing and demonstrating component technologies specific to CLARREO Mission
- Additional CLARREO-specific technologies being developed by U. Wisconsin and Harvard
- These ESTO-IIP efforts are paving the way to CLARREO via science and instrument technology

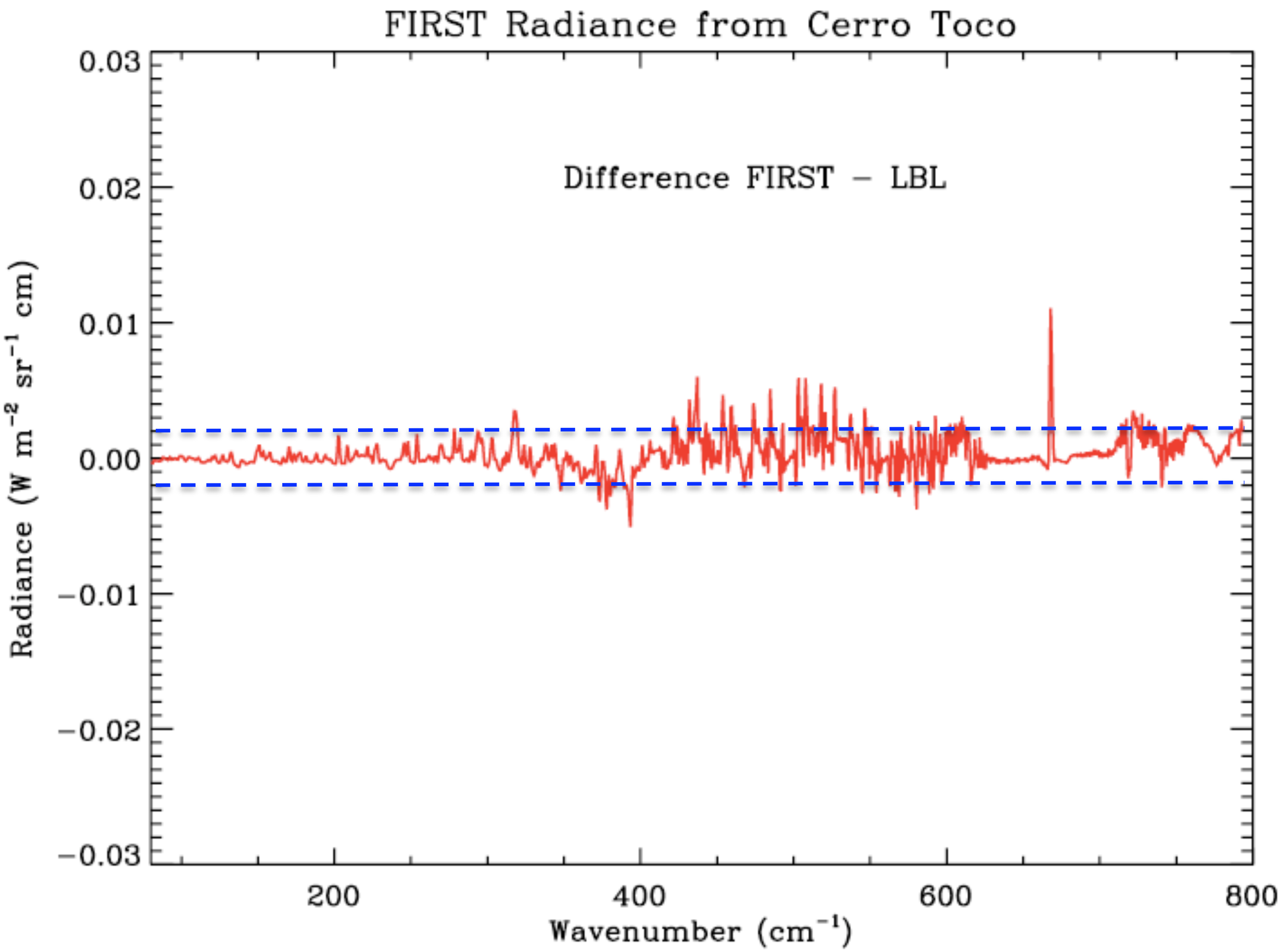
Backup Slides

Onto the Future – The CLARREO Mission

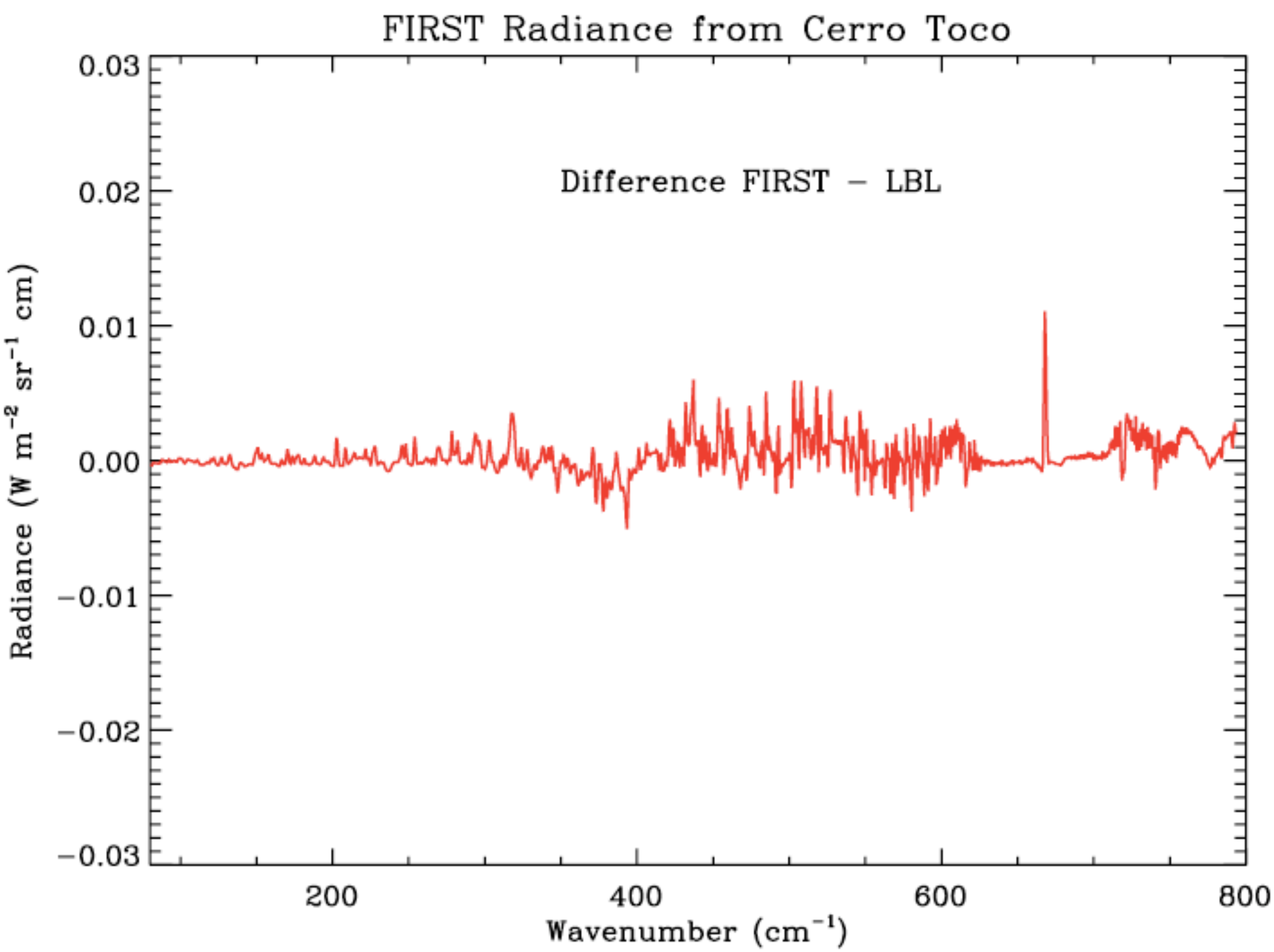


- FIRST, INFLAME demonstrate FTS instrument technology
- CORSAIR is developing CLARREO-specific component technology
- Advancing calibration and climate system measurement knowledge
- Enabling development of CLARREO IR FTS instrument

Radiance Difference – 09/05/2009



Radiance Difference – 09/05/2009



Instrument Overview

- We use two instruments to cover the required spectral range:
  - LW instrument covers thermal IR, 100 μm to 3 μm.
  - SW instrument covers solar, 3 μm to 0.3 μm.
- Main differences between LW and SW are the calibration sources, optical coatings, and detectors.

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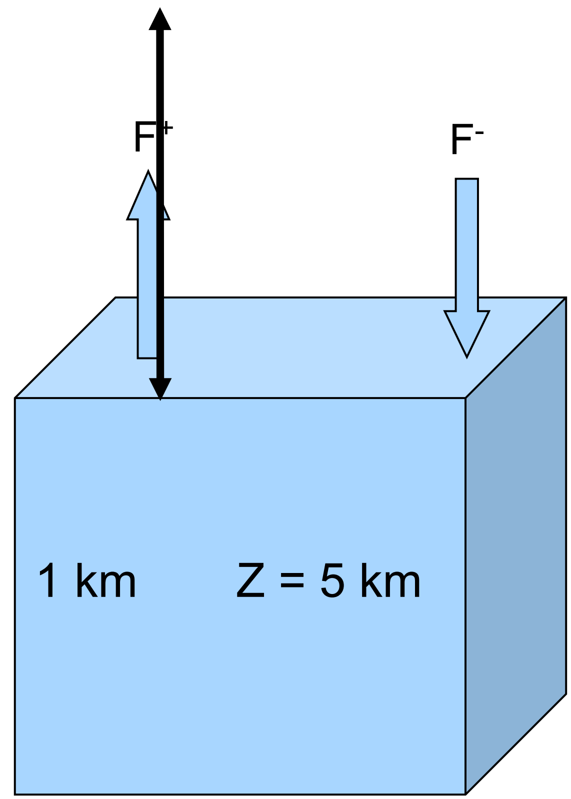
Measurement Overview

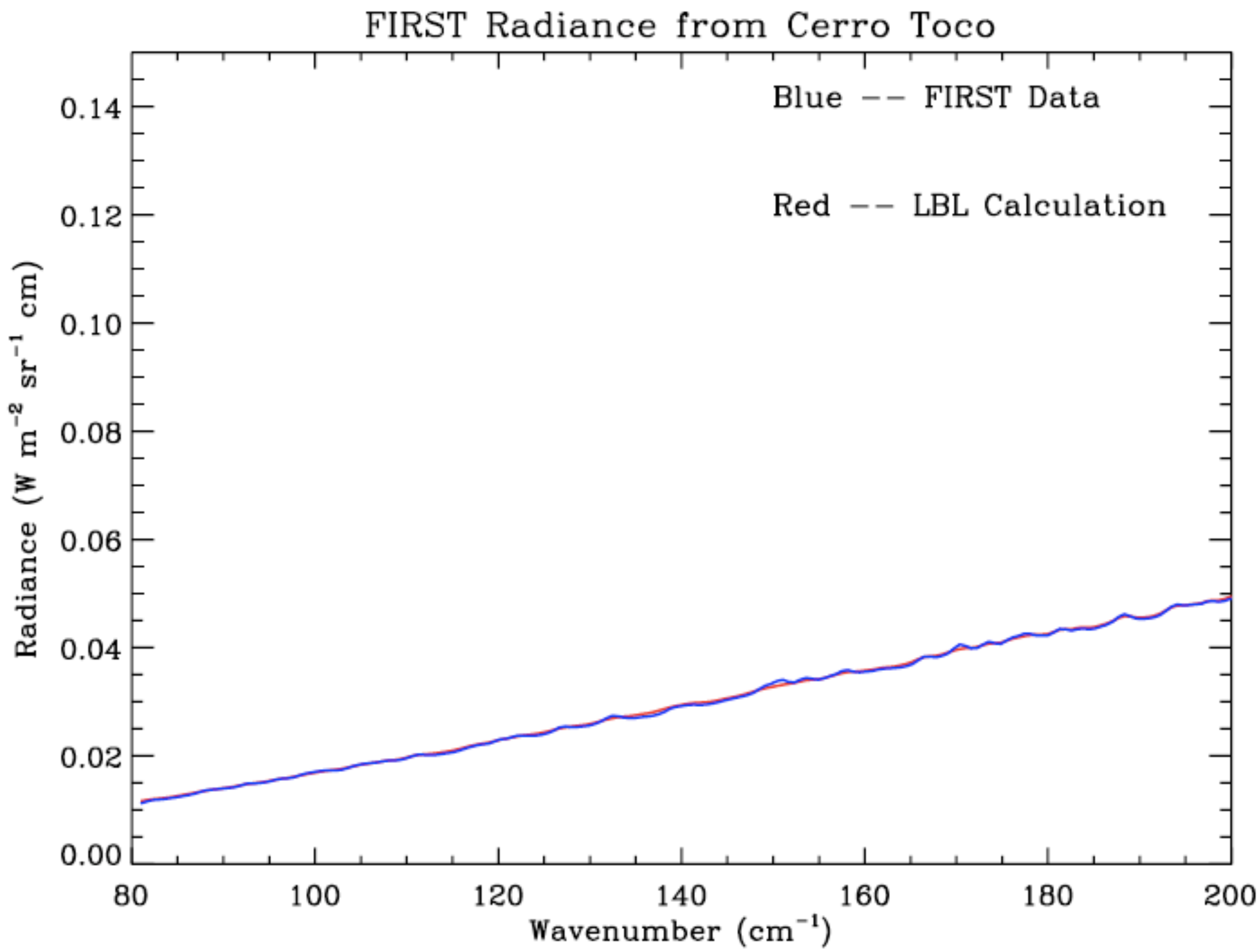
- **Consider a unit cube in the terrestrial atmosphere:**
  - Spectral flux is the energy per unit frequency interval flowing through one face (F^+ or F^-);
  - Net Flux is the difference in energy flowing through one face in opposite directions:

$$Fz = F^+ - F^-$$

  - Flux divergence is given by dFz/dz;
    - Assume dFx/dx and dFy/dy are small.
- **Radiative heating rate is estimated from the measured flux divergence:**



September 5 2009 – PWV = 0.75 mm



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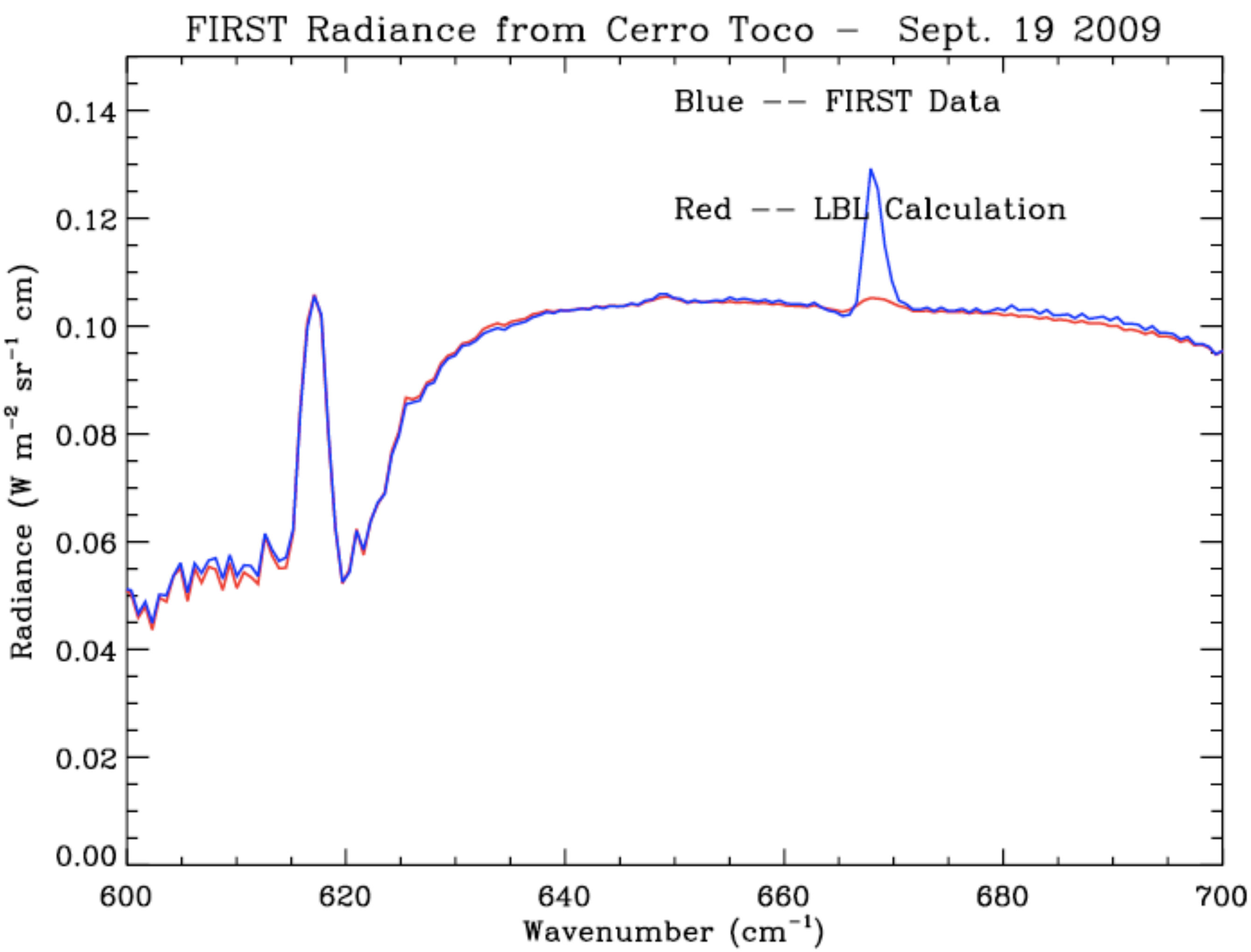

INFLAME Objective

- Measure the spectral dependence of radiative heating rates in the troposphere.
  - Flight demonstration goal is to measure net flux with sufficient stability to estimate radiative heating rates from the net flux divergence in 1 km layers of the troposphere with an accuracy of 10%

- Milestones:
  - Proposed: 11/2004
  - Funded: 11/2005
  - Calibration: 7/2009
  - Test flight: 1/5/2010

Measurement Challenge

- What if we use uplooking and downlooking instruments to measure fluxes as functions of altitude, subtract to get net flux, and take the derivative to get flux divergence?
  - Need to measure small changes in the difference of large numbers:

	F+, W/m2	F-, W/m2	Fz, W/m2	dFz/dz, W/m2 km
Thermal IR	344	263	81	16.1
Solar	80	768	-688	-13.6

- Small systematic errors in measured F+ and F- can easily be as large as $dF_{net}(z)/dz$.

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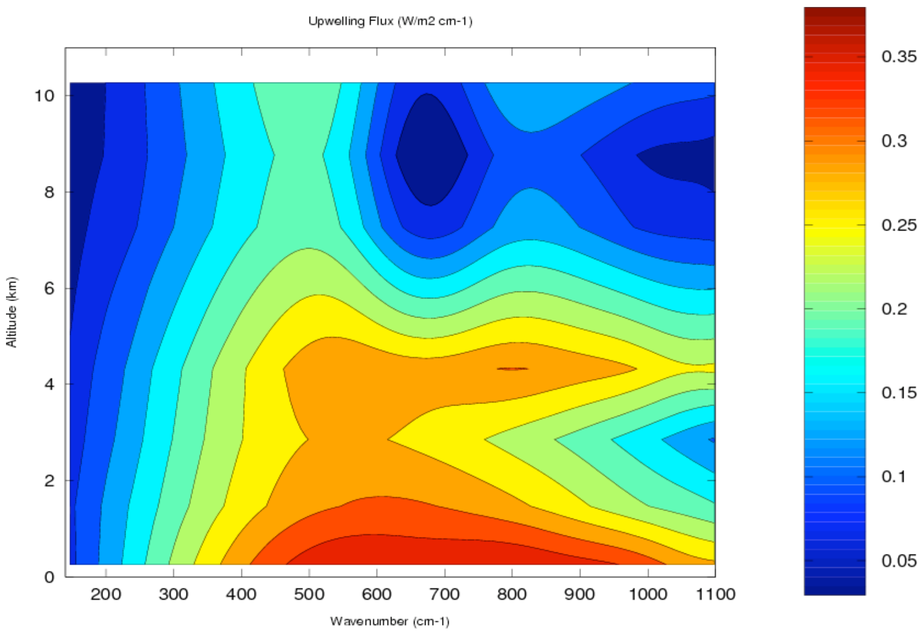
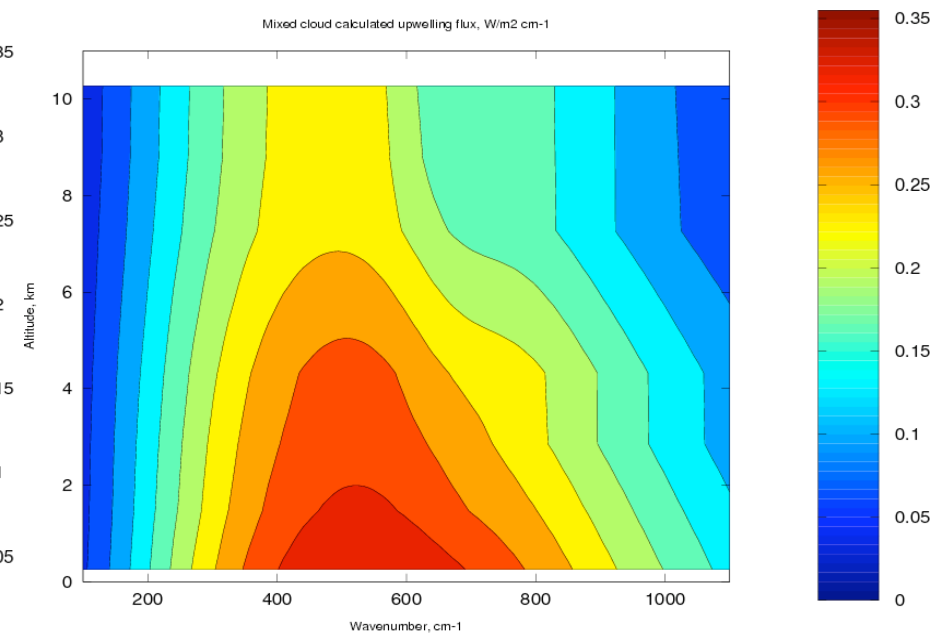
INFLAME LW Upwelling Flux





Measured Upwelling IR Flux

Calculated Upwelling IR Flux

1/5/2010

INFLAME LW Downwelling Flux

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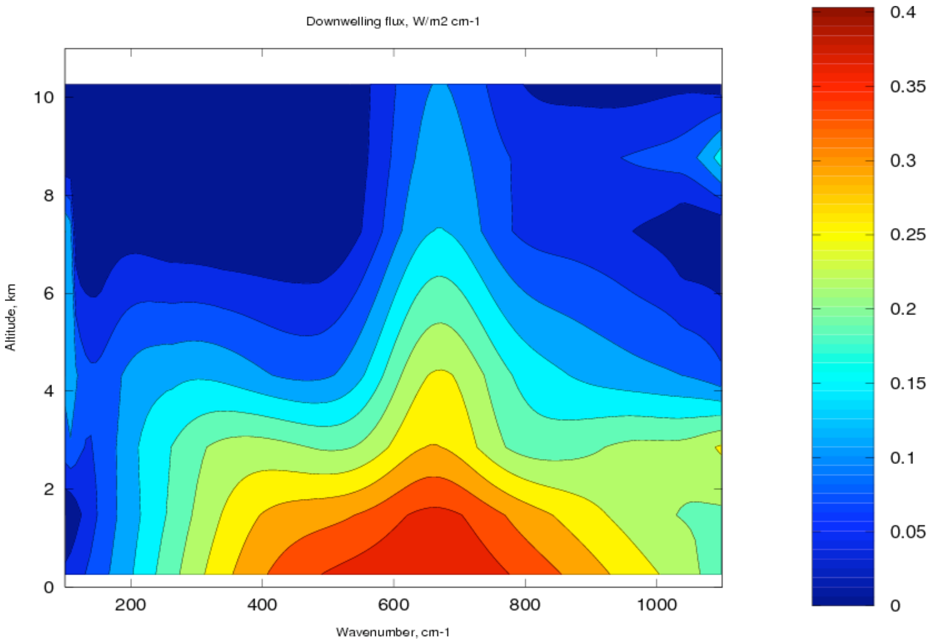
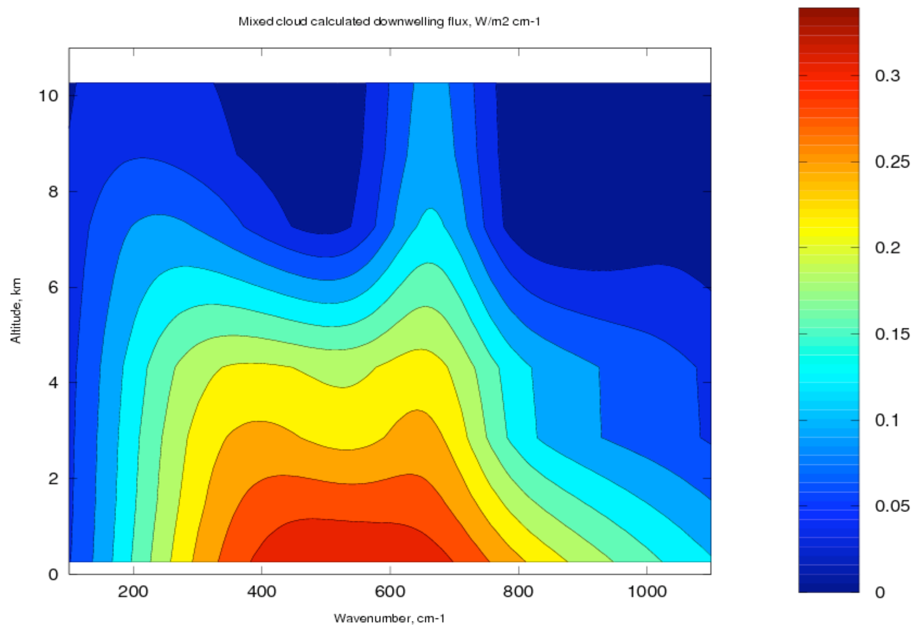


Measured LW Downwelling Flux

1/5/2010



Calculated LW Downwelling Flux