The CubeSat Infrared Atmospheric Sounder (CIRAS)

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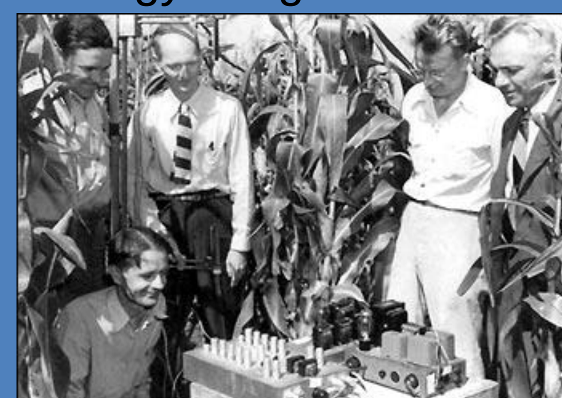
13 Oct 1959-Feb 1960 Explorer 7

The 1st meteorological satellite instrument to observe the Earth

- Radiometer designed by Verner Suomi & Robert Parent
- Omni-directional spheres

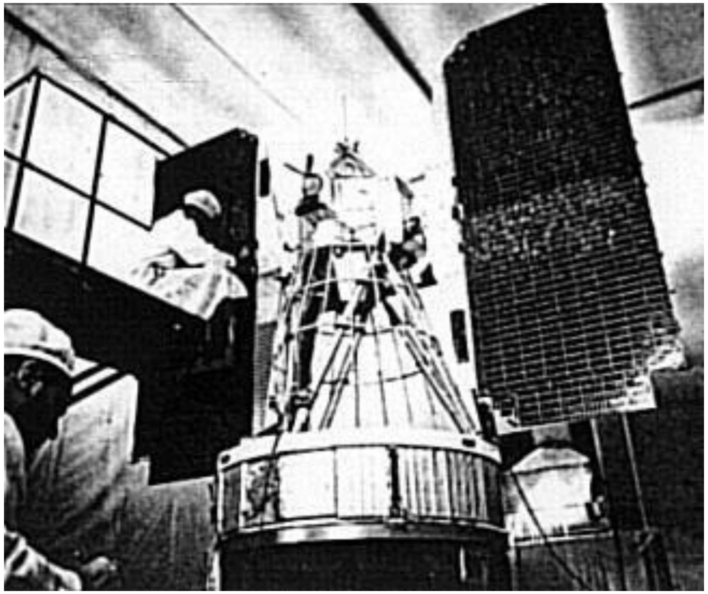
Spectrally integrated obs continue today today

An outgrowth of measuring the energy budget of a corn field



NASA just in its 2nd year

Nimbus Satellites of 1960s-1980s
Operationalized Weather Imaging and Sounding



http://www.astronautix.com/craft/nimbus.htm

Satellite	Launch Date	Decay Date
Nimbus 1	1964-08-28	1974-05-16
Nimbus 2	1966-05-15	1969-01-17
Nimbus 3	1969-04-14	1972-01-22
Nimbus 4	1970-04-08	1980-09-30
Nimbus 5	1972-12-11	
Nimbus 6	1975-06-12	
Nimbus 7	1978-10-24	

Visible Imaging

Acronyms	Instruments	Satellites
AVCS	Advanced Vidicon Camera System	Nimbus 1 and 2
IDCS	Image Dissector Camera System	Nimbus 3 and 4

Infrared Imaging

Acronyms	Instruments	Satellites
HRIR	High Resolution Infrared Radiometer	Nimbus 1, 2, 3
MRIR	Medium Resolution Infrared Radiometer	Nimbus 2 and 3
THIR	Temp.-Humidity Infrared Radiometer	Nimbus 4 – 7

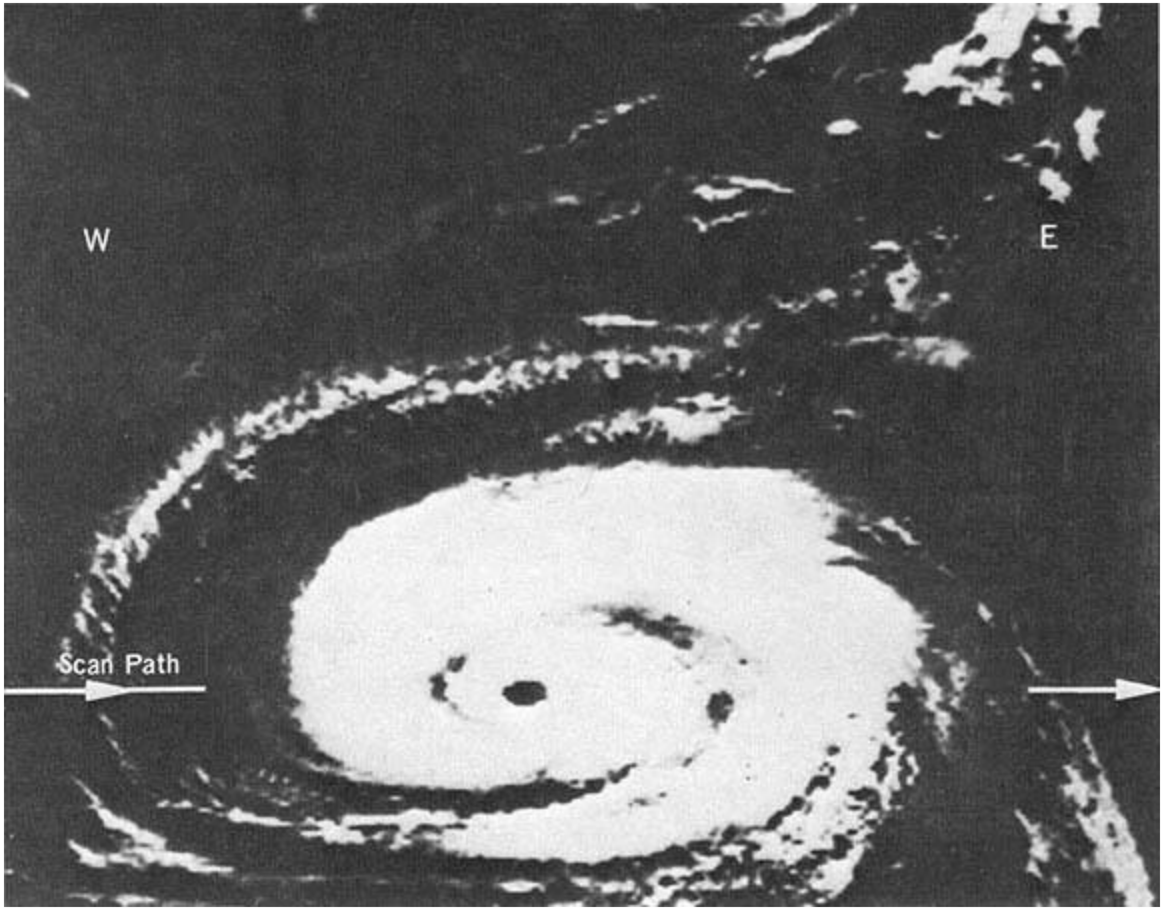
Microwave Imaging

Acronyms	Instruments	Satellites
ESMR	Electronic Scanning Microwave Radiometer	Nimbus 5 & 6
SMMR	Scanning Multispectral Microwave Radiometer	Nimbus 7

Sounding

Acronyms	Instruments	Satellites
HIRS	High Resolution Infrared Sounder	Nimbus 6
IRIS	Infrared Interferometer Spectrometer	Nimbus 3 and 4
LIMS	Limb Infrared Monitor of the Stratosphere	Nimbus 7
LRIR	Limb Radiance Inversion Radiometer	Nimbus 6
NEMS	Nimbus E Microwave Spectrometer	Nimbus 5
PMR	Pressure Modulated Radiometer	Nimbus 6
SAMS	Stratospheric and Mesospheric Sounder	Nimbus 7
SCAMS	Scanning Microwave Spectrometer	Nimbus 6
SCR	Selective Chopper Radiometer	Nimbus 4 and 5
SIRS	Satellite Infrared Spectrometer	Nimbus 3 and 4

Early Nimbus Image of Hurricane Gladys



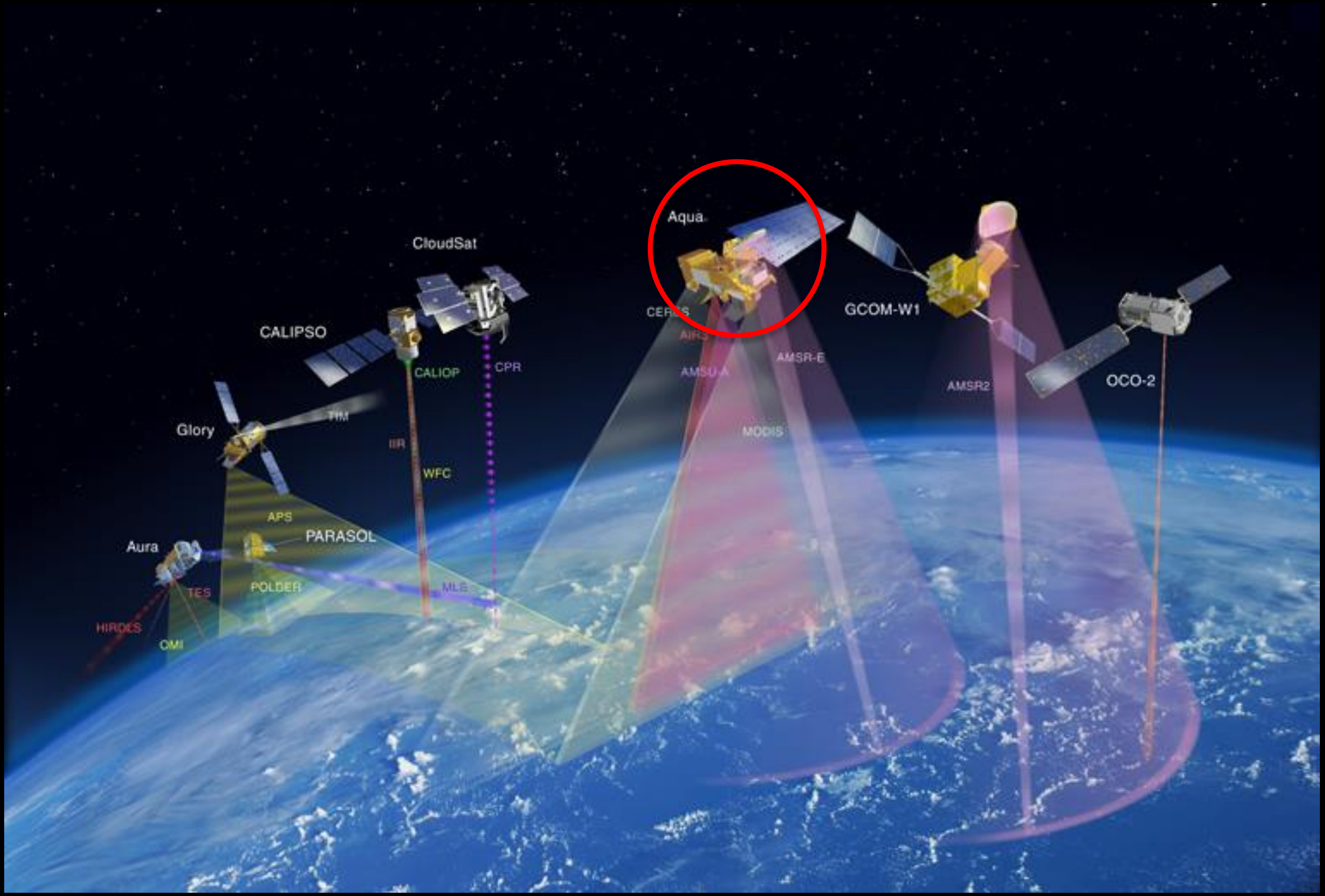
Hurricane Gladys, as seen by NASA's Nimbus 1 satellite in September 1964. Hurricane Gladys traveled over the U.S. East Coast, Bermuda and Canada. Credits: NASA

Currently Flying NASA Earth Science Satellites
May 1, 2013

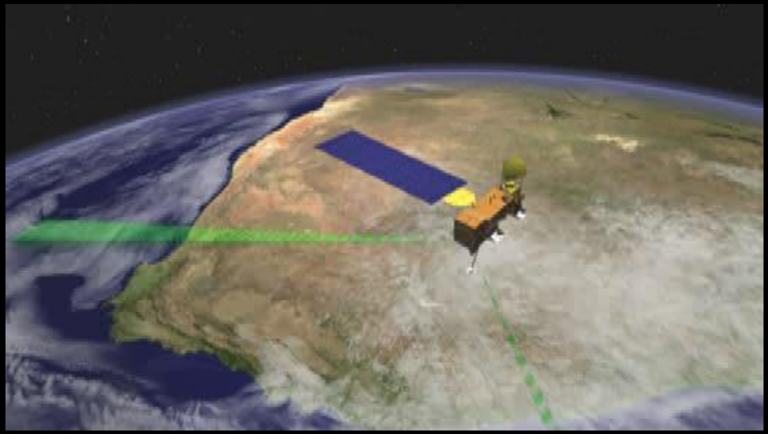
Aqua Launched May 4, 2002 from Vandenberg Air Force Base

Aqua was first in the "A-Train"

Aqua Launched On a Delta 2



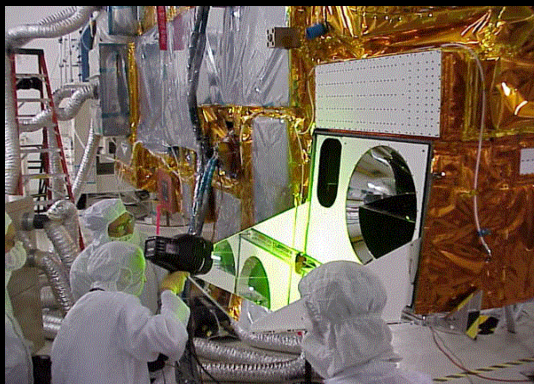
Aqua Instruments Provide Global Daily Coverage of the Earth Surface and Atmosphere



The Aqua Spacecraft

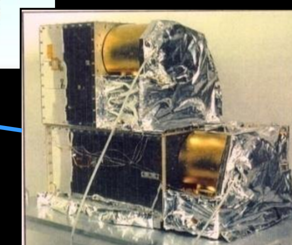
Launched May 4, 2002

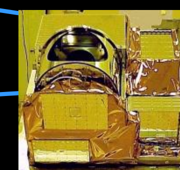
Advanced Microwave Scanning Radiometer (AMSR-E)
MSFC/JAXA



Moderate Resolution Imaging Spectroradiometer (MODIS)
GSFC/Raytheon

Advanced Microwave Sounding Units (AMSU-A/B)
JPL/Aerojet





Humidity Sounder from Brazil (HSB)
JPL/Aerojet

Atmospheric Infrared Sounder (AIRS)
JPL/BAE SYSTEMS

AQUA Spacecraft
GSFC/NGST

Clouds and Earth Radiant Energy System (CERES)
LaRC/NGST

AIRS on Aqua uses Hyperspectral IR to Measure Atmospheric Greenhouse Gases

Atmospheric Infrared Sounder (AIRS)

Characteristics

Aqua Spacecraft

Launched: May 4, 2002

Orbit: 705 km, 1:30pm

IFOV : 13.5 km

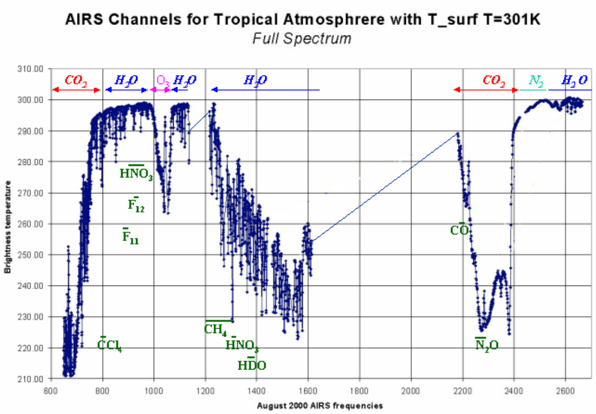
Global Daily Coverage

Spectral Range: 3.5-15.4 µm

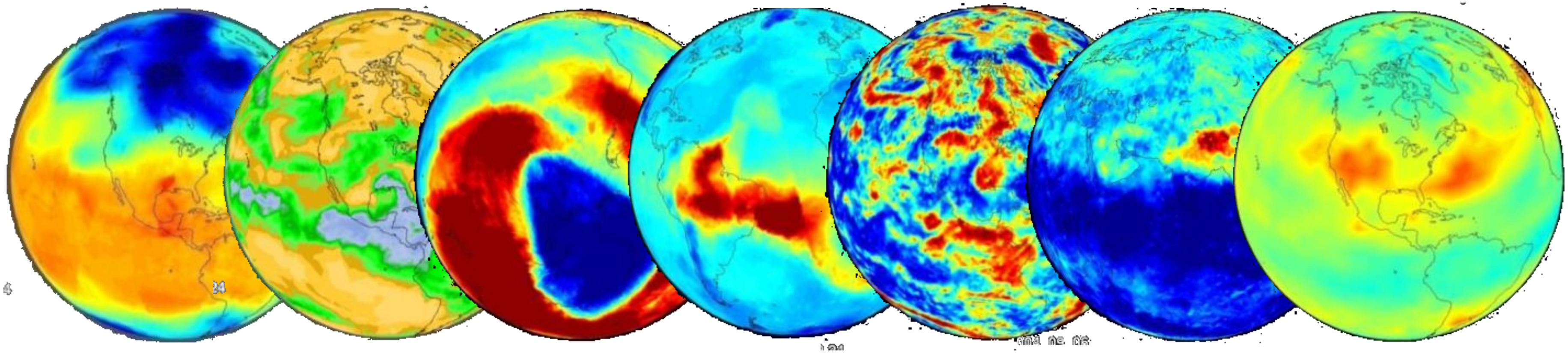
No. Channels: 2378

Climate Quality Accuracy and Stability

AIRS Hyperspectral Infrared Spectrum



AIRS Measures Key Greenhouse Gases with Global Daily Coverage



Temperature | Water Vapor | Ozone | Carbon Monoxide | Cloud Properties | Methane | Carbon Dioxide

Infrared Sounders Measure the 3D Distribution of Temperature and Water Vapor

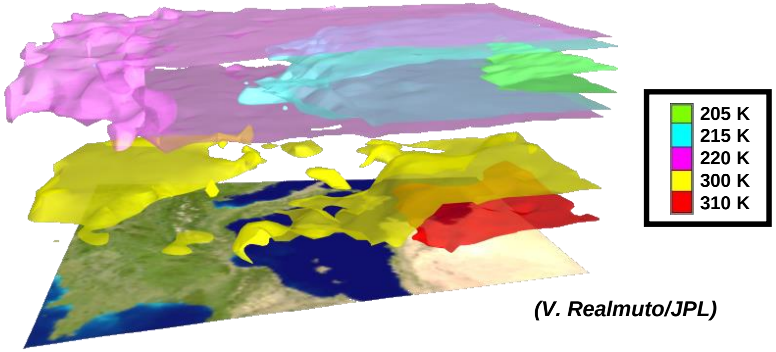
Imagers measure the 2D Distribution
Of Radiance with Global Daily Coverage

AVHRR, MODIS, VIIRS, GOES

VIIRS on JPSS

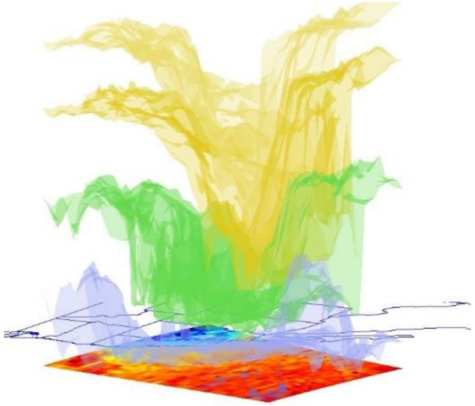
Sounders measure the 3D Distribution
HIRS, AIRS, CrIS

AIRS Temperature Isosurface



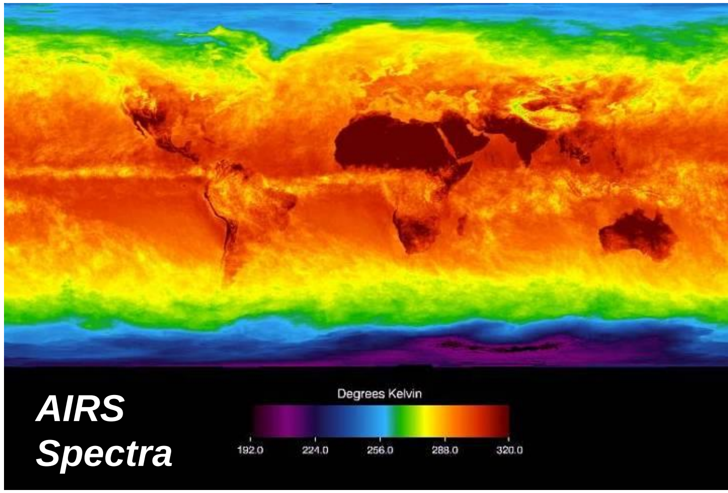
(V. Realmuto/JPL)

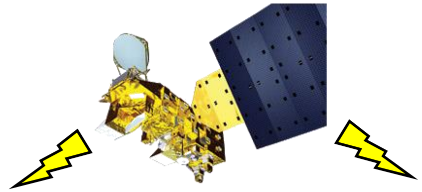
AIRS Water Vapor Isosurface



(T. Pagano/JPL)

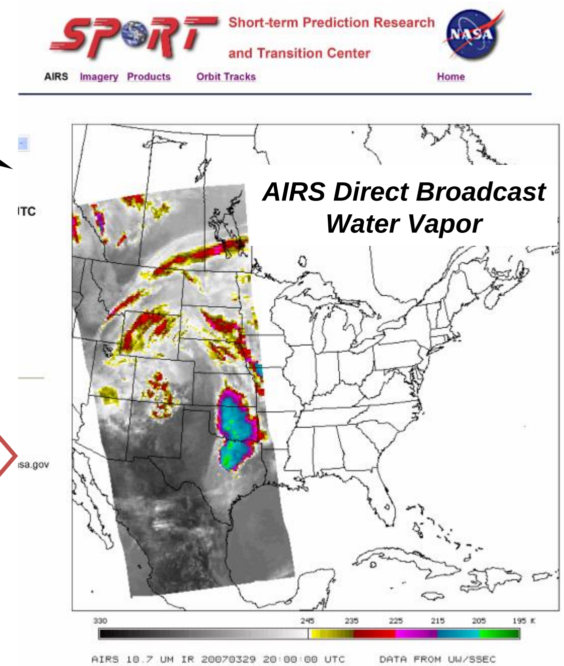
AIRS Part of Operational Weather Forecast System





***NASA* Groundstations**

Direct Broadcast



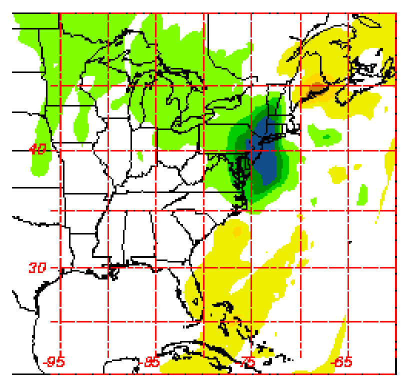
GES/ DISC

Near Real Time Assimilation

Near Real Time Product Generation

NCEP, ECMWF, and UKMet
Operational Forecasts

6 Hrs on 5 Day Improvement on Operational NCEP Forecast



AIRS - NOAIRS

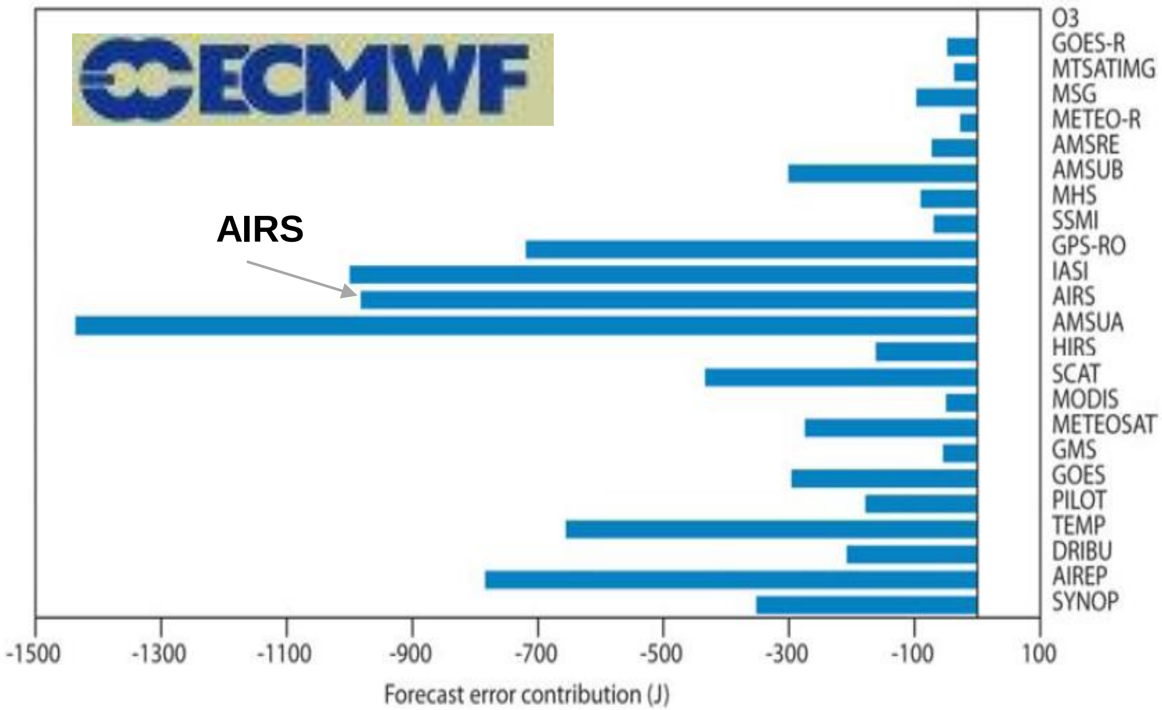
Over 4 hPa Improvement in Regional Model Forecast

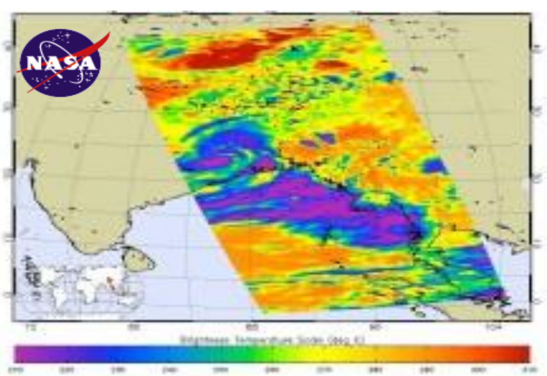
AIRS Improves Weather Forecasts

JPL/
GSFC

NOAA
NESDIS/NCEP

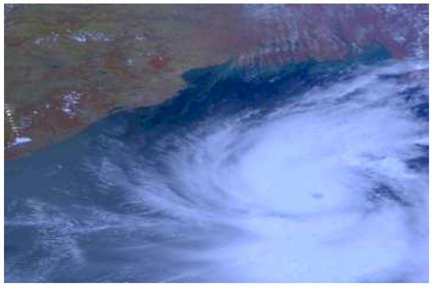
JCSDA



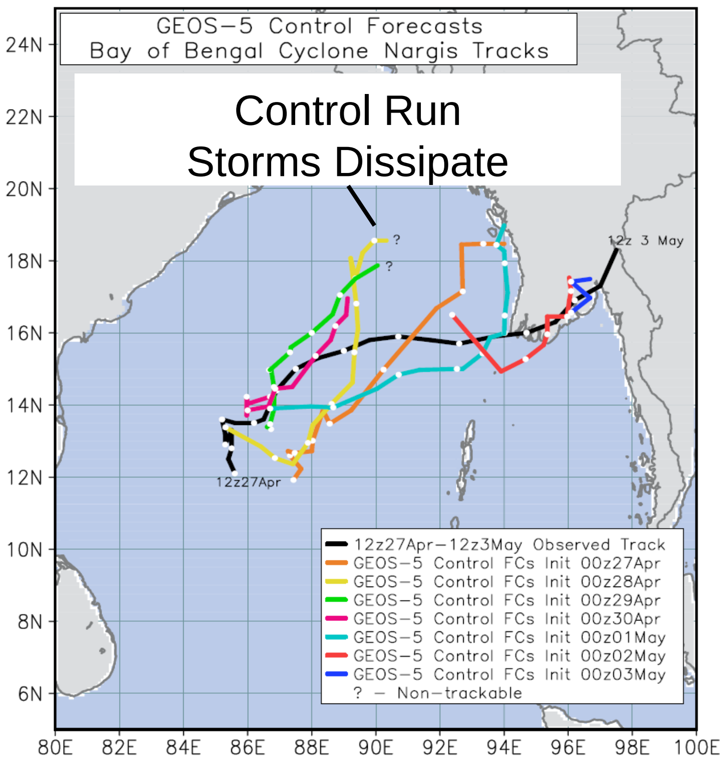


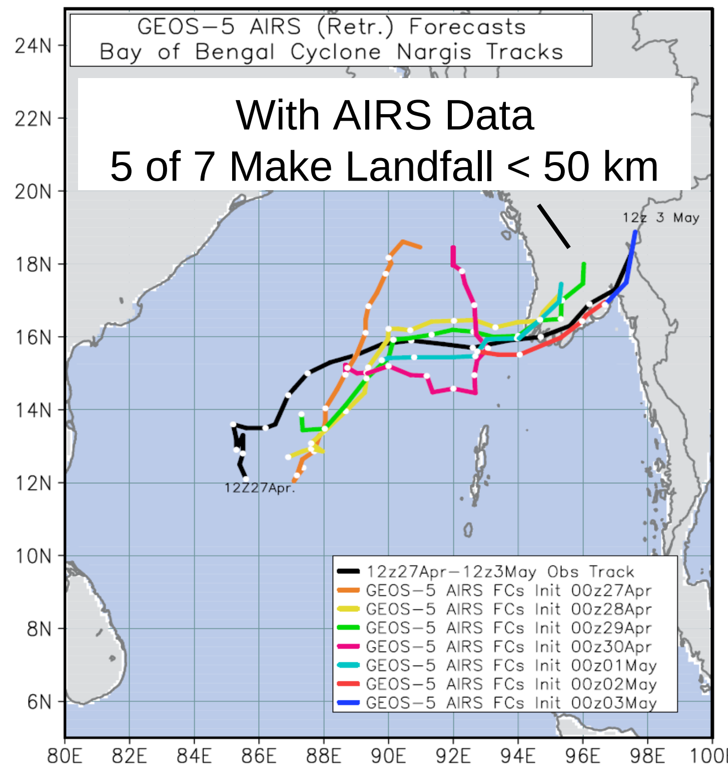
- Third Highest Impact to Forecasts
  - AMSU has 4 Instruments
  - IASI is also an IR Sounder
  - (Cardinali, ECMWF Tech. Memo. 599, 2009)

AIRS Data Improves Prediction of Hurricanes



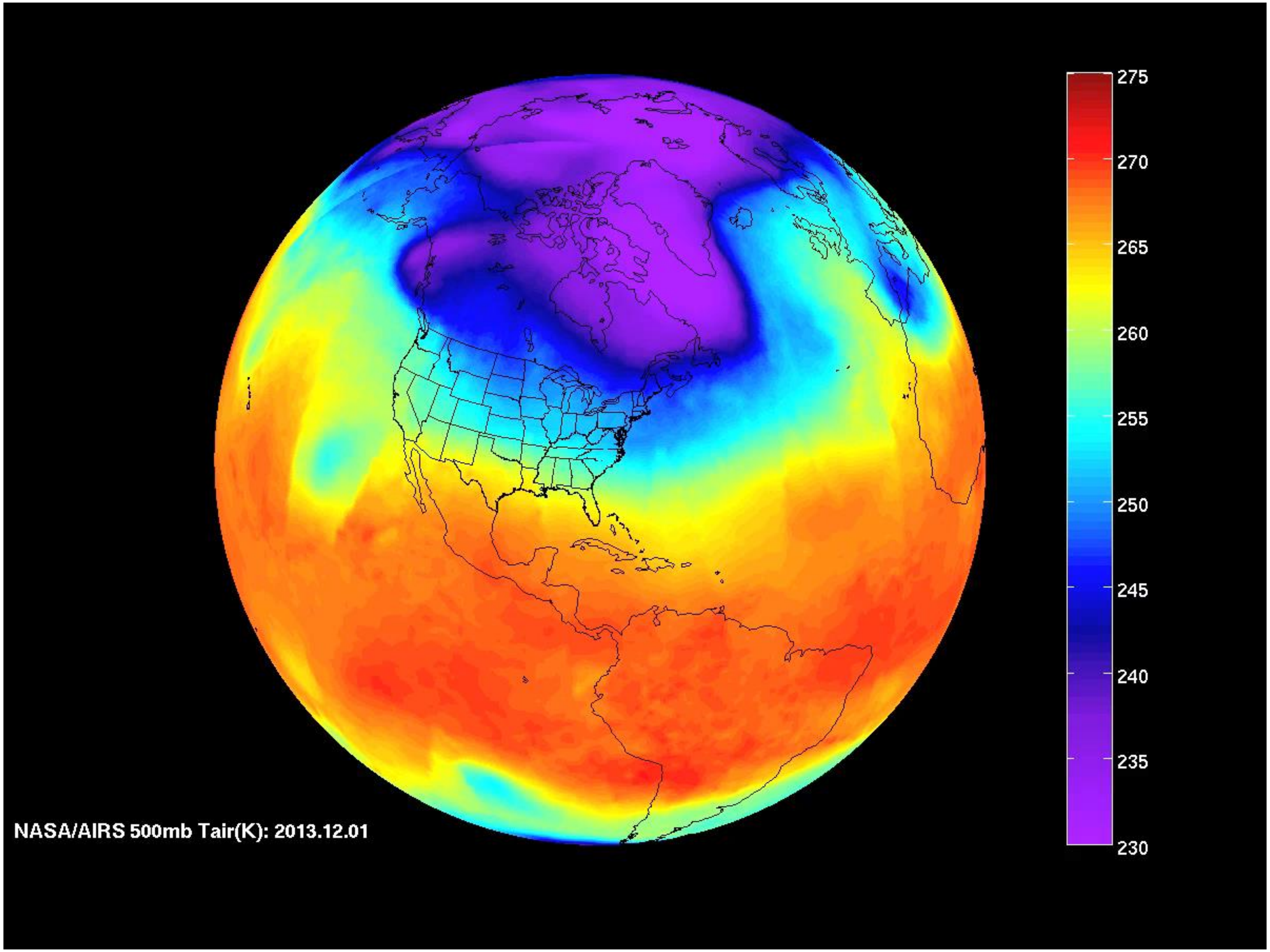
- Tropical Cyclone Nargis
- Killed over 140,000 People
- Worst Natural Disaster in history of Burma`
- O. Reale, GSFC, 2008





Reale, O., W. K. Lau, J. Susskind, E. Brin, E. Liu, L. P. Riishojgaard, M. Fuentes, and R. Rosenberg (2009), AIRS impact on the analysis and forecast track of tropical cyclone Nargis in a global data assimilation and forecasting system, Geophys. Res. Lett., 36, L06812, doi:10.1029/2008GL037122. http://www.agu.org/journals/gl/gl0906/2008GL037122/

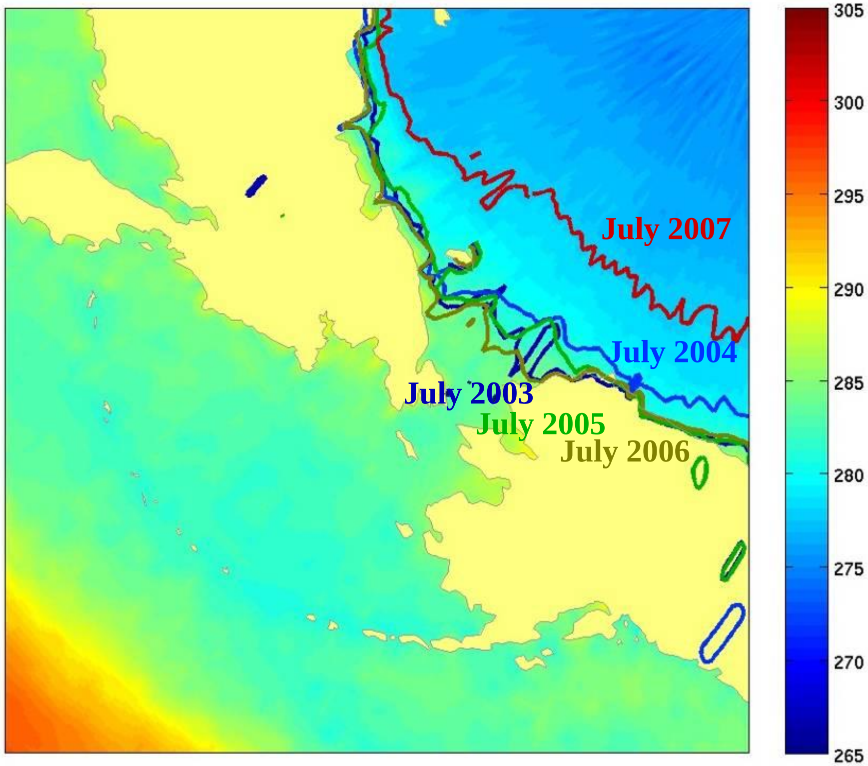
IR Sounders Capture Severe Weather Events (Polar Vortex of 2013/2014)



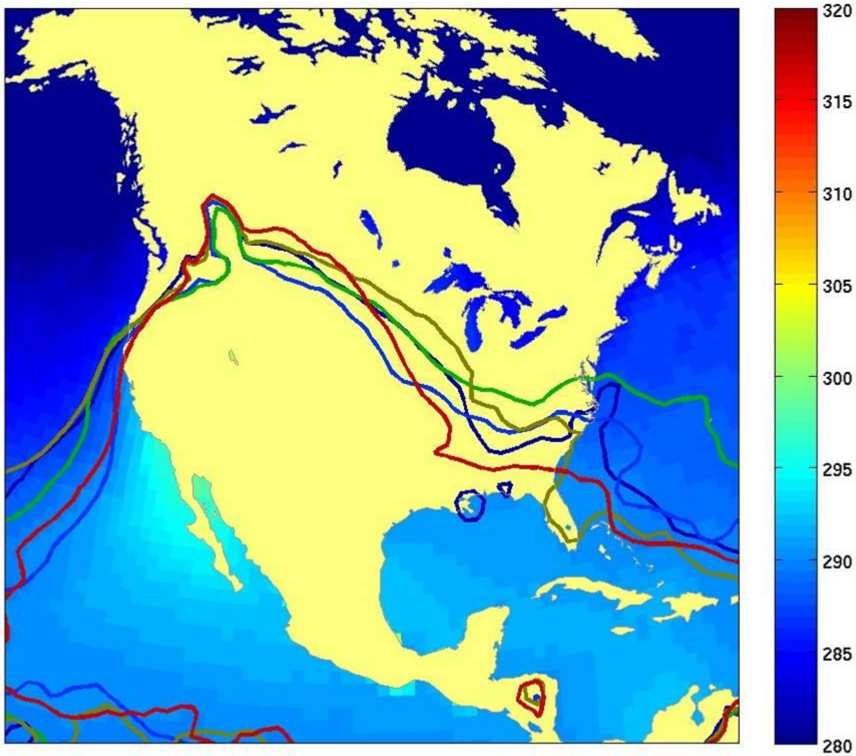
Dec 4, 2013: Denver weather: Temperature hits minus 13 — record low for the date
Dec 24, 2013: Record Low Tied at Cedar Rapids This Morning | Iowa Weather Blog
Jan 6, 2014: Chicago Record Low Temperature: City Hits -16 Mark To Kick Off ...
Jan 29, 2014: Atlanta, Georgia, historic weather for the past week

AIRS First Look at 5 Year Trends

278K Isotherms at 1000 mb

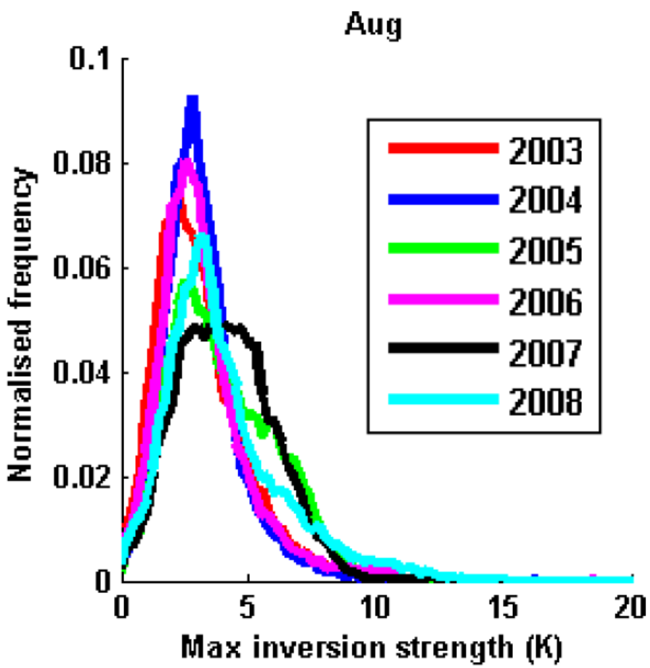


290K Isotherms at 850 mb



Swedish Study uses AIRS data to Study Temperature Inversions in Arctic Region

- Arctic Region warming at twice the rate of the rest of the world
- Temperature inversions play a crucial role in mass and moisture flux
- AIRS data used to study frequency and strength of inversions
- Inversions of 2007 stronger than other years. Warming seen to 400mb



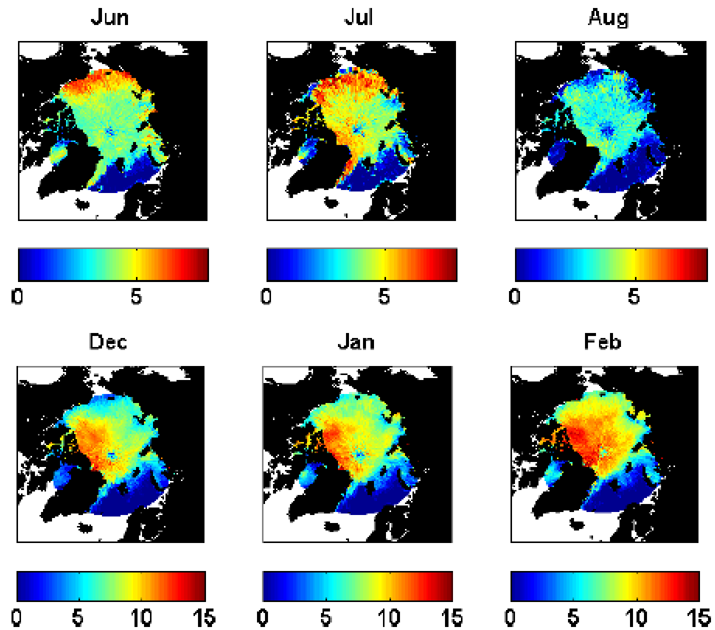
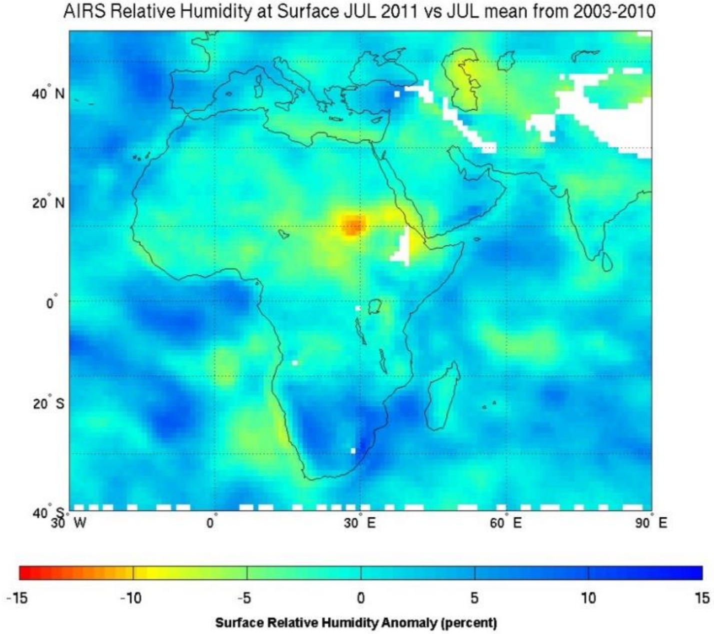


Fig. 5. The spatial pattern of inversion strength (in K) averaged over 2003–2008 for summer (top row) and winter (bottom row) months from the ascending passes. Note that the scale for the winter months is doubled.

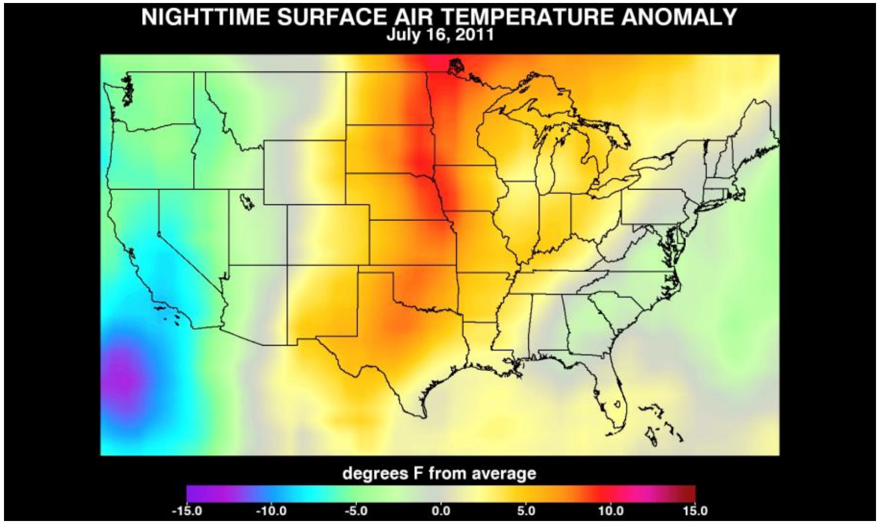
A. Devasthale, U. Will´en, K.-G. Karlsson, C. G. Jones, "Quantifying the clear-sky temperature inversion frequency and strength over the Arctic Ocean during summer and winter seasons from AIRS profiles". Atmos. Chem. Phys., 10, 5565–5572 2010

Climatologies Enable Identification of Anomalous Weather and Climate Events

Relative Humidity Anomaly
Somalia Drought of July 2011



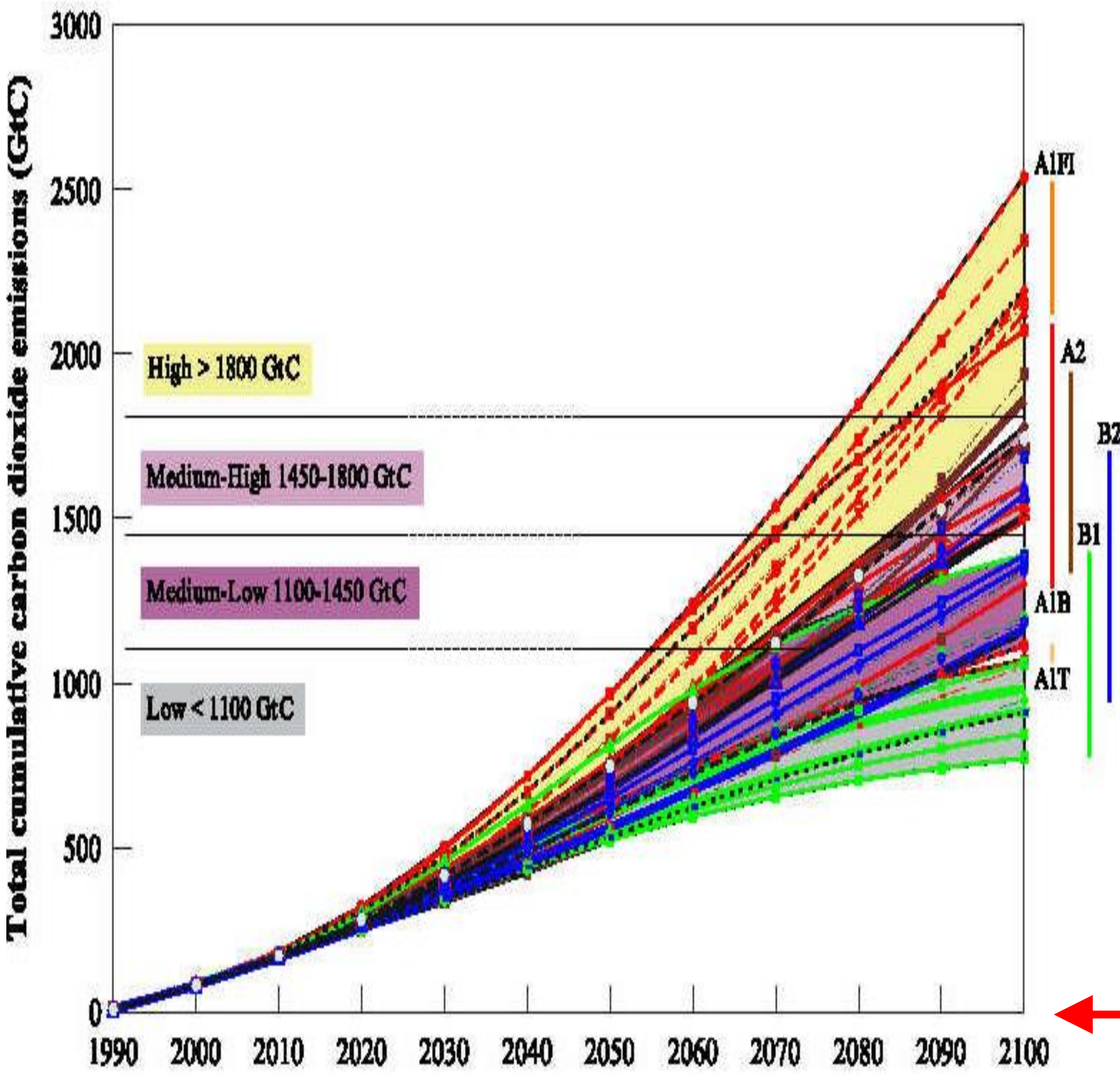
Surface Skin Temperature Anomaly
Heat Wave of July 2011



Additional Products Under Development:

- Mosquito Habitat Identification
- Temperature Inversion Identification (for Air Quality)

IPCC estimates of future warming uncertain

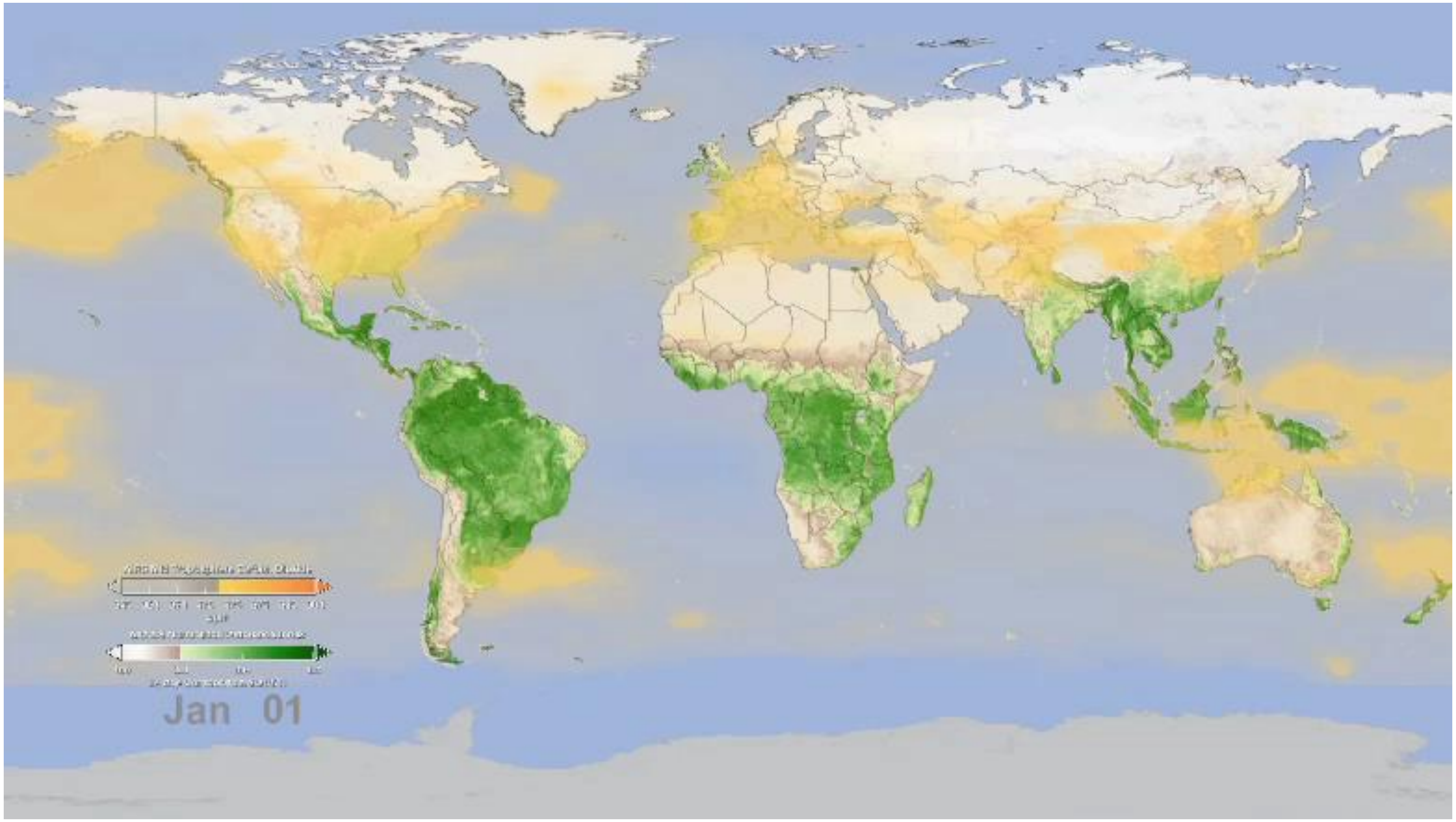


NOTE: Uncertainty in IPCC models is due to:

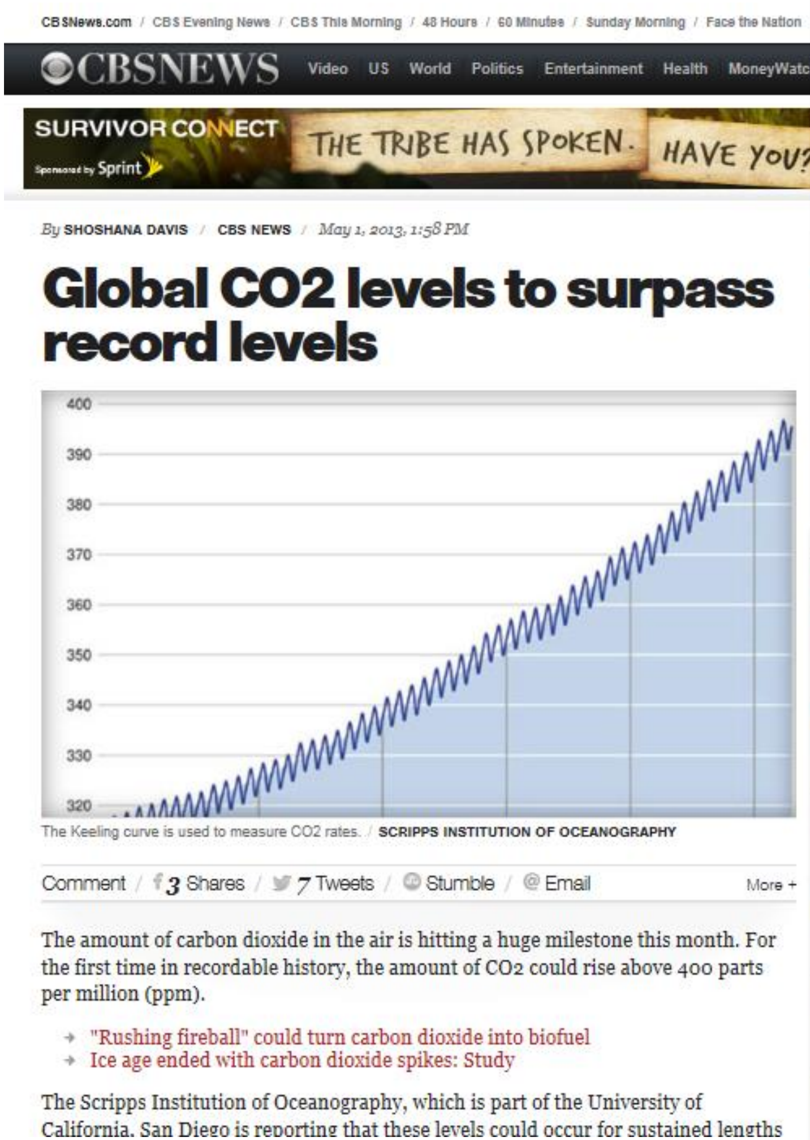
1) Population projections: "1" is continuously increasing, "2" peaks mid-century at 8 billion
2) types of economies: "A" is global, "B" is local"
3) fuel choices: "F1" is fossil intensive, "T" is high technology, "B" is balanced.

Emissions w.r.t. 1990

AIRS Mid-Trop CO_2 Drawdown Follows Regional Vegetation Cycle



CO_2 Reaches Record Levels
Public Interest is High



CBSNews.com / CBS Evening News / CBS This Morning / 48 Hours / 60 Minutes / Sunday Morning / Face the Nation

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SURVIVOR CONNECT Sponsored by Sprint THE TRIBE HAS SPOKEN. HAVE YOU?

By SHOSHANA DAVIS / CBS NEWS / May 1, 2013, 1:58 PM

Global CO2 levels to surpass record levels

The Keeling curve is used to measure CO2 rates. / SCRIPPS INSTITUTION OF OCEANOGRAPHY

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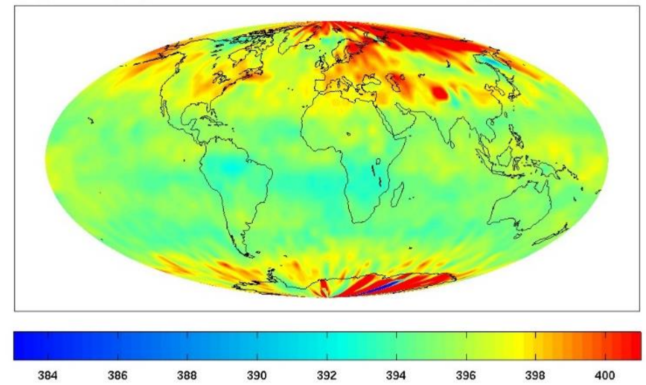
The amount of carbon dioxide in the air is hitting a huge milestone this month. For the first time in recordable history, the amount of CO2 could rise above 400 parts per million (ppm).

- "Rushing fireball" could turn carbon dioxide into biofuel
- Ice age ended with carbon dioxide spikes: Study

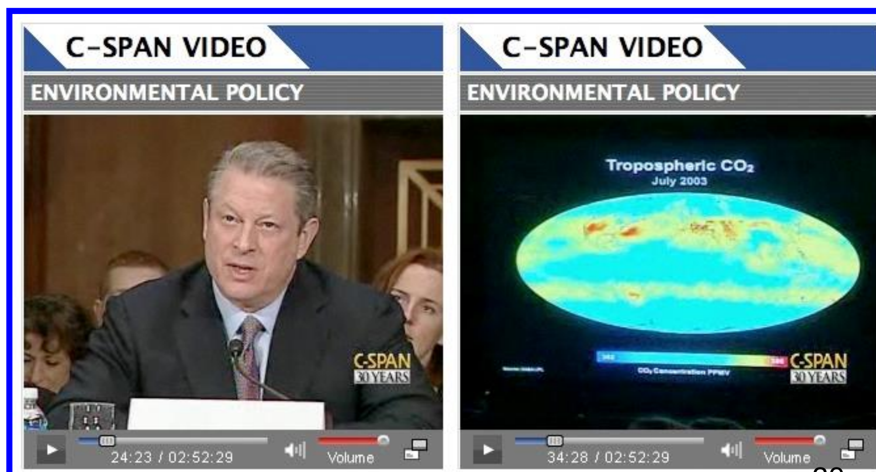
The Scripps Institution of Oceanography, which is part of the University of California, San Diego is reporting that these levels could occur for sustained lengths

Atmospheric CO_2 Levels Exceed 400 ppm

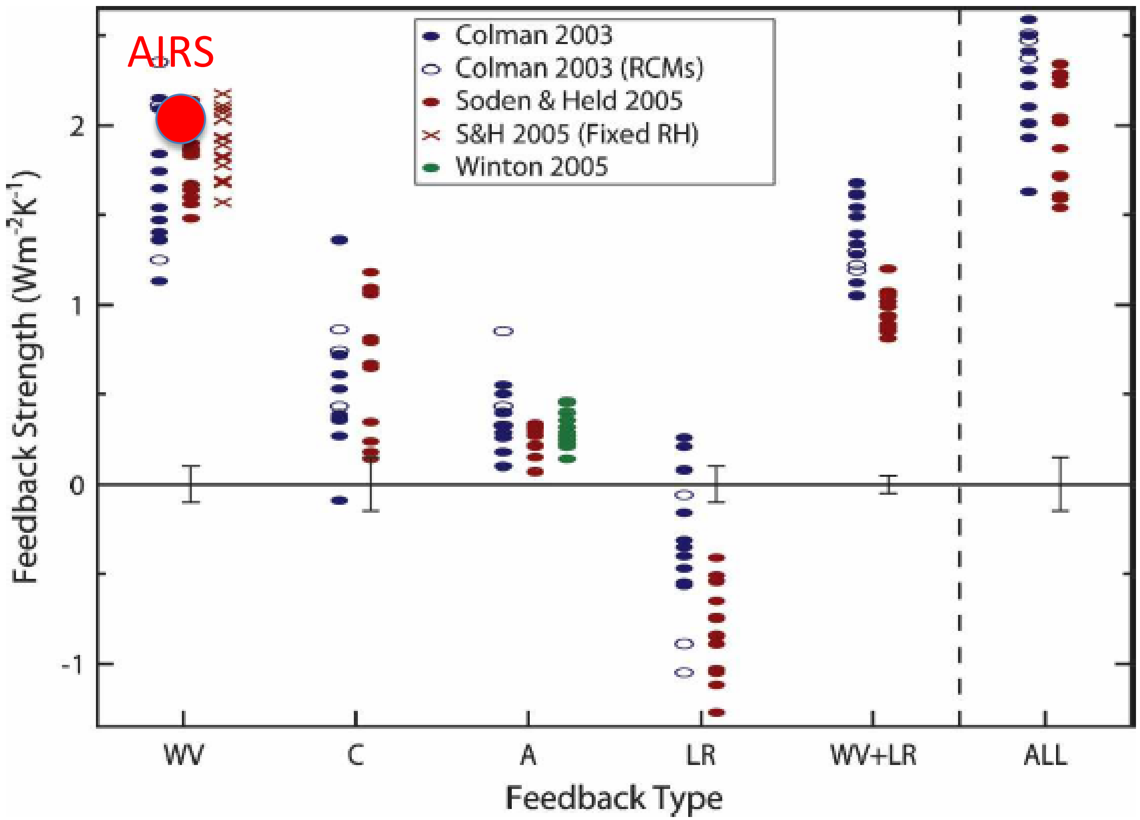
AIRS IR-Only Mid-Tropospheric CO2, March 2013, V5411 CO2std <= 2 ppm DAY&NIGHT Day 15 x 31



AIRS CO2 Images used in former Vice-President Al Gore's Testimony to the US Senate Foreign Relations Committee

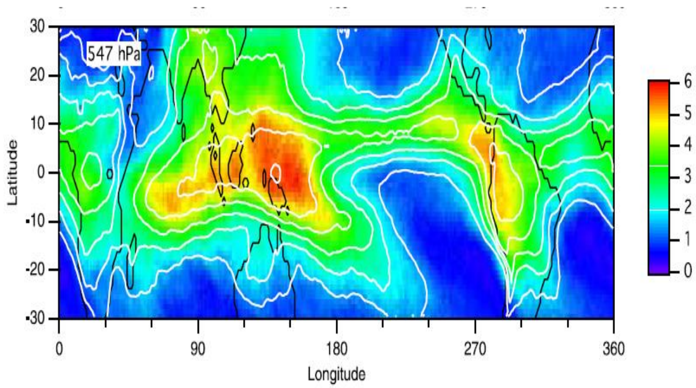


Climate Feedbacks Differ Amongst Models

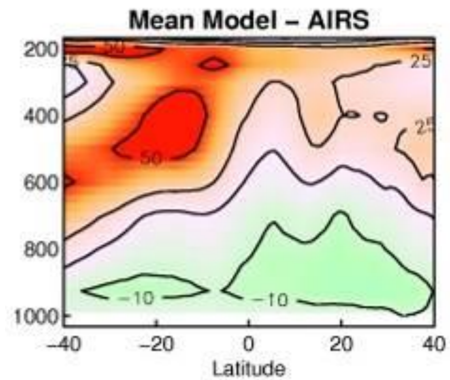


Bony, S., et al., “How Well Do We Understand and Evaluate Climate Change Feedback Processes?”, Journal of Climate, Vol 19, p 3445-3482.

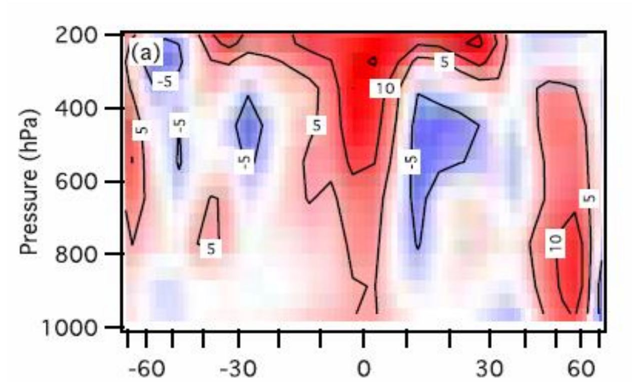
IR Sounders Support
Climate Research and Model Validation



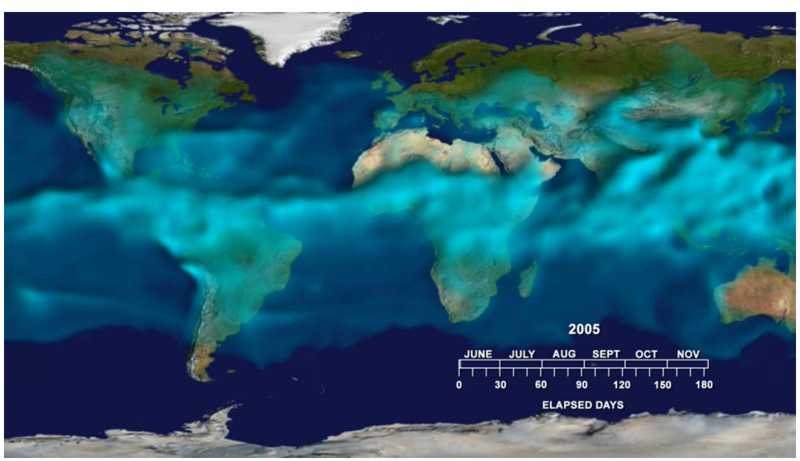
Water Vapor Transport
(Dessler, Texas A&M, 2007)



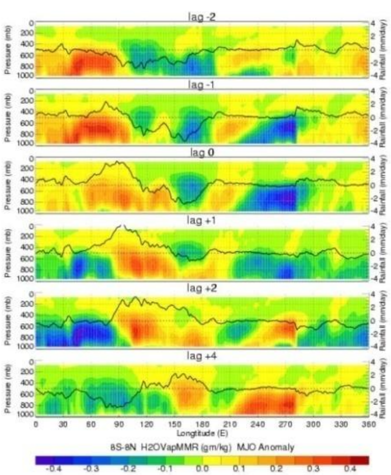
Water Vapor Climatology
(Pierce, Scripps, 2006)



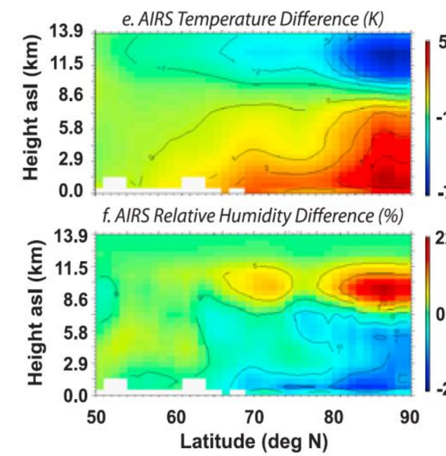
Water Vapor Feedback
(Dessler, Texas A&M, 2008)



AIRS Water Vapor Isosurface (5kg H2O /kg Dry Air)
V. Realmuto, C. Thompson, T. Pagano, S. Ray NASA/JPL



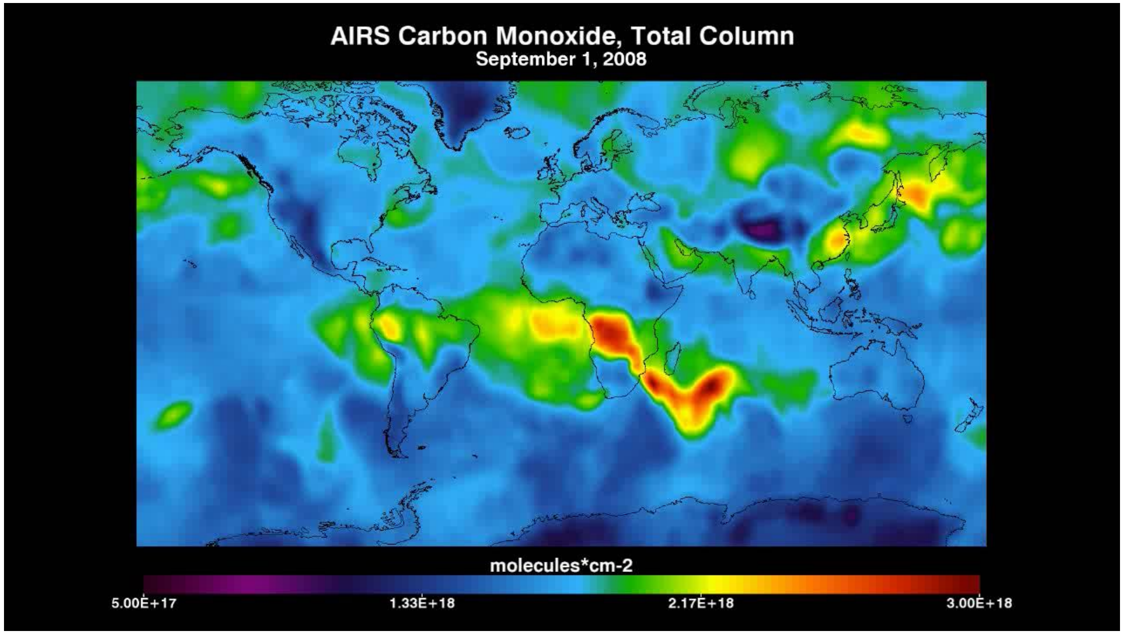
Madden Julian Oscillation
(Tian, JPL, 2006)



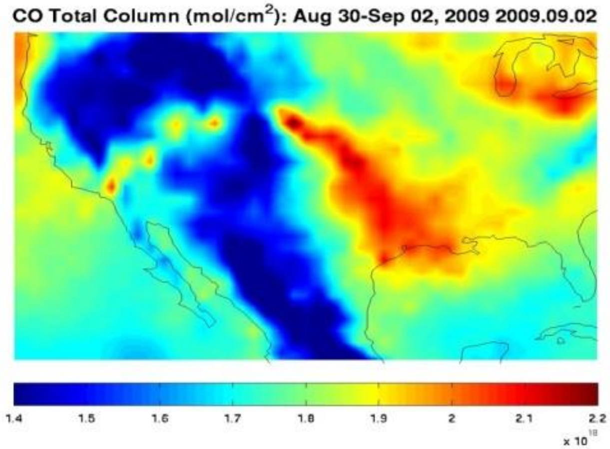
Polar Warming/Drying 2007
(Kay, J. E., 2008)

AIRS Views Carbon Monoxide from Fires

Global Carbon Monoxide Transport 2008



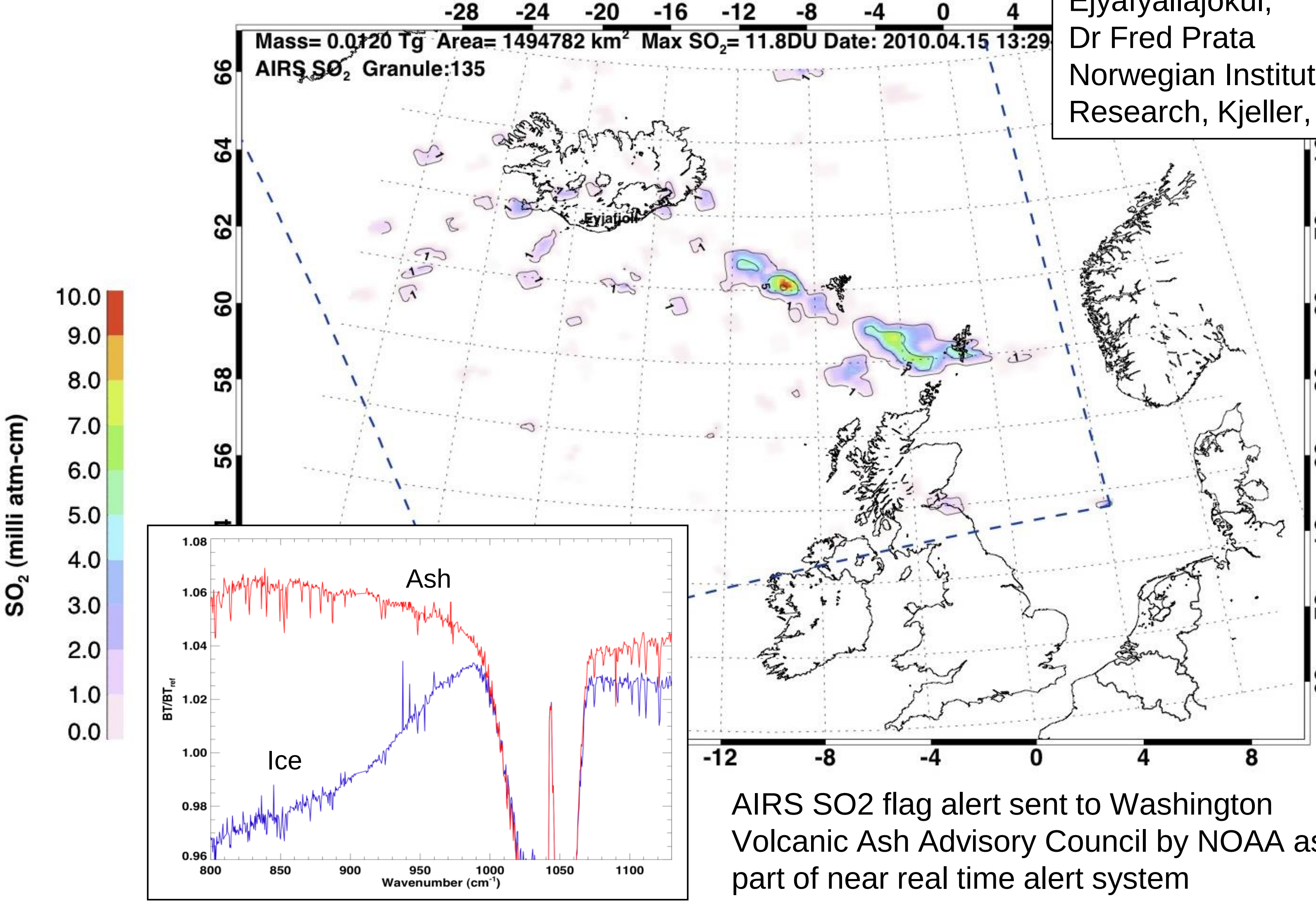
California Station Fire 2009



Carbon Monoxide Leads to Poor Air Quality Downwind

AIRS Supports Volcanic Emission Alerts

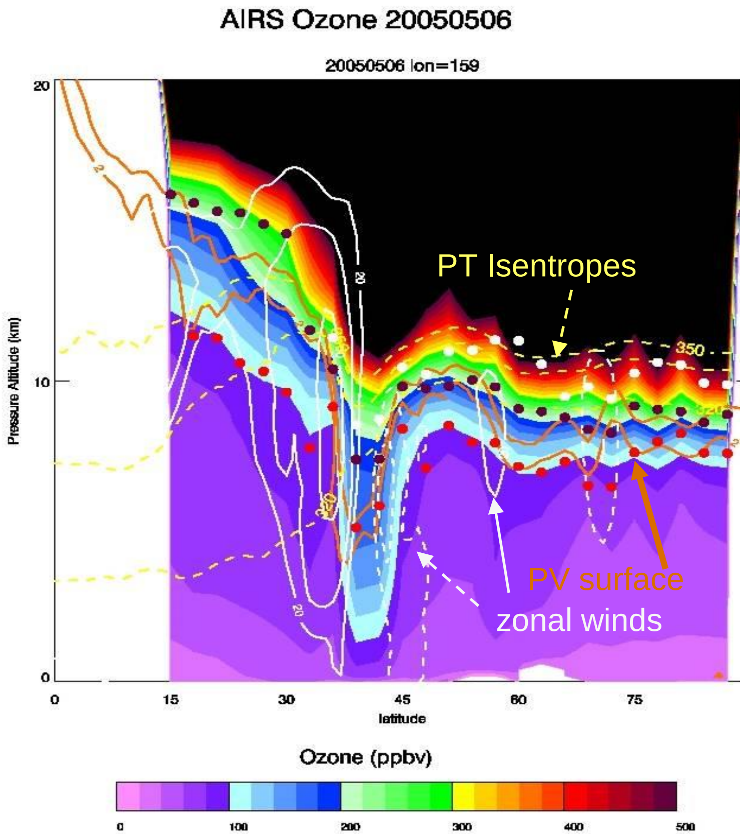
Ejyafyallajokul,
Dr Fred Prata
Norwegian Institute for Air Research, Kjeller, Norway



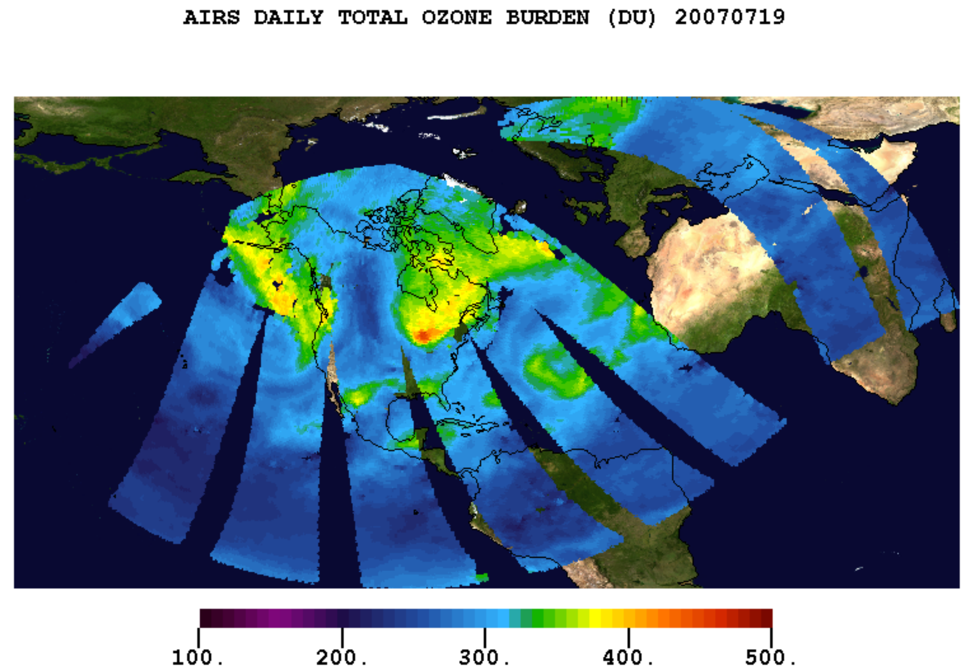
AIRS SO2 flag alert sent to Washington Volcanic Ash Advisory Council by NOAA as part of near real time alert system

AIRS Monitors Upper/Tropospheric-Stratospheric Ozone

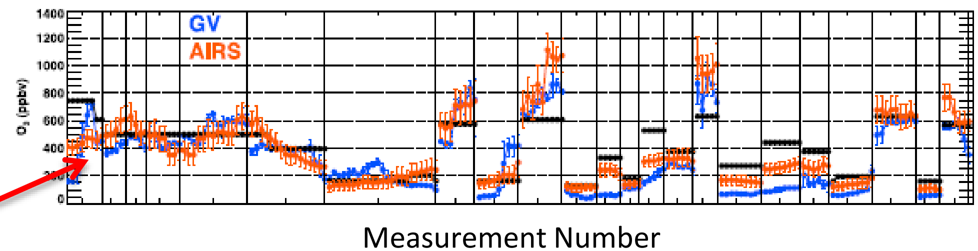
AIRS Identifies Stratospheric Ozone Intrusion, May 6, 2005 (Wei, 2008)



AIRS Ozone Daily Global Imagery Enables Early Warning of Possible Poor Air Quality



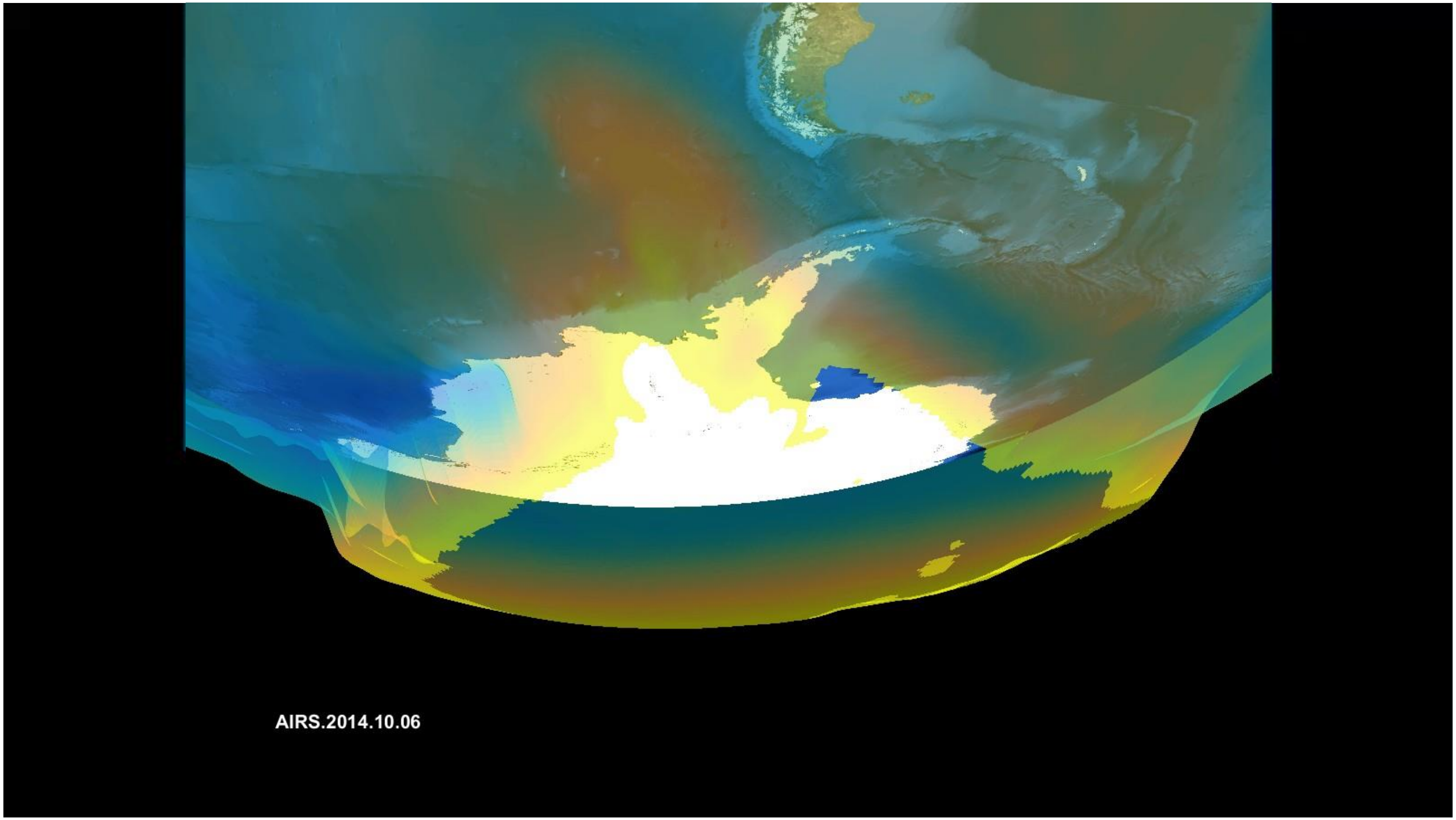
AIRS data compare well with ground and aircraft based ozone measurements



Pittman, J. V., L. L. Pan, J. C. Wei, F. W. Irion, X. Liu, E. S. Maddy, C. D. Barnet, K. Chance, and R.-S. Gao (2009), Evaluation of AIRS, IASI, and OMI ozone profile retrievals in the extratropical tropopause region using in situ aircraft measurements, J. Geophys. Res., 114, D24109, doi:10.1029/2009JD012493

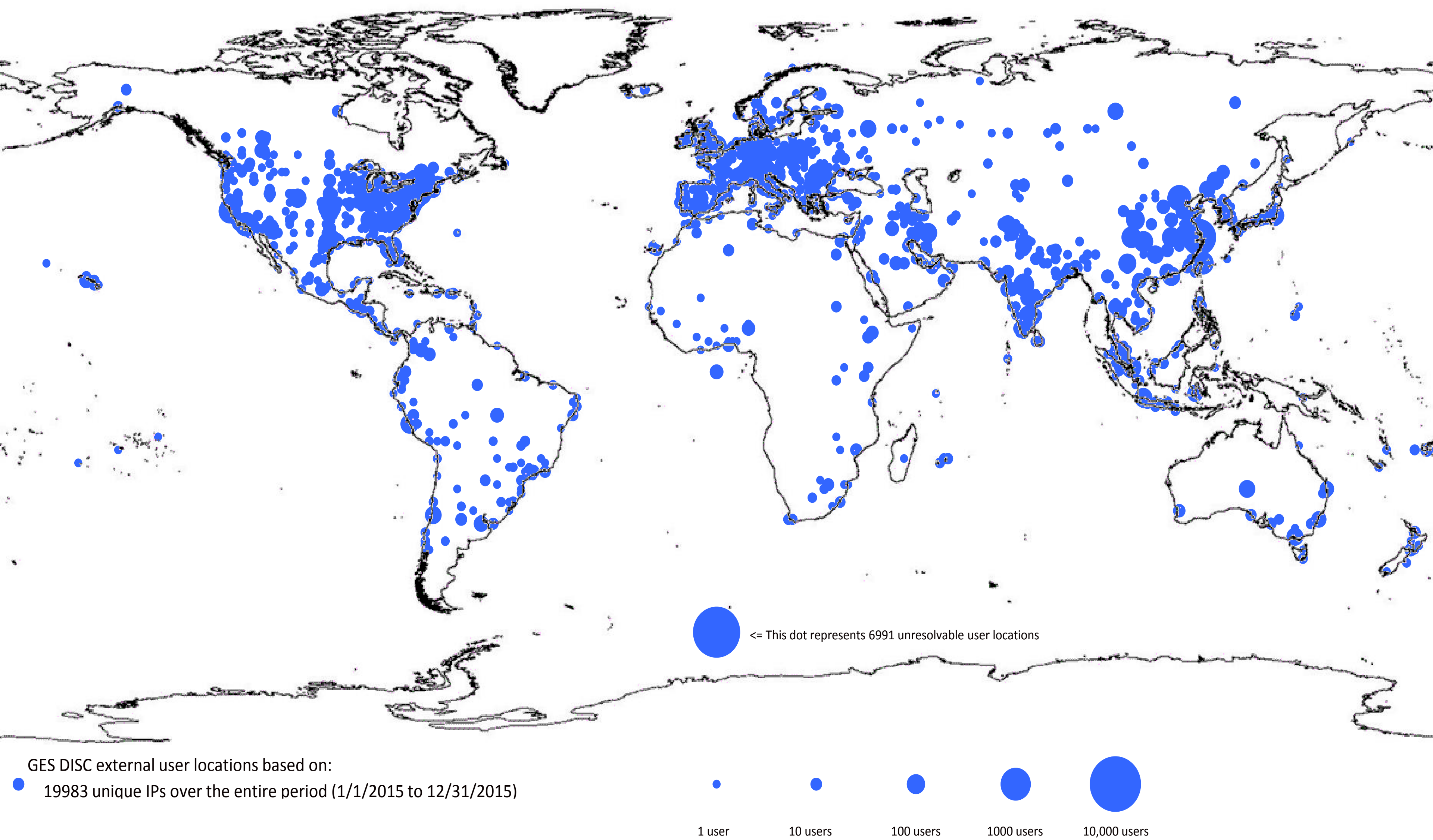
AIRS 3D O_3 12 Hr Over Poles Demonstrates Value of Improved Timeliness. EON-IR will enable trace gases.

AIRS O_3 Isosurface, Sept, 2014



AIRS O3_VMR, 2014. Isosurface at 5 x 10^{-7} ppmv. Altitude Scale: 100, Altitude Offset: 10 km, Max Altitude (above which transparent): 18 km

Users Over the World Access AIRS Data in 2015



GES DISC external user locations based on:

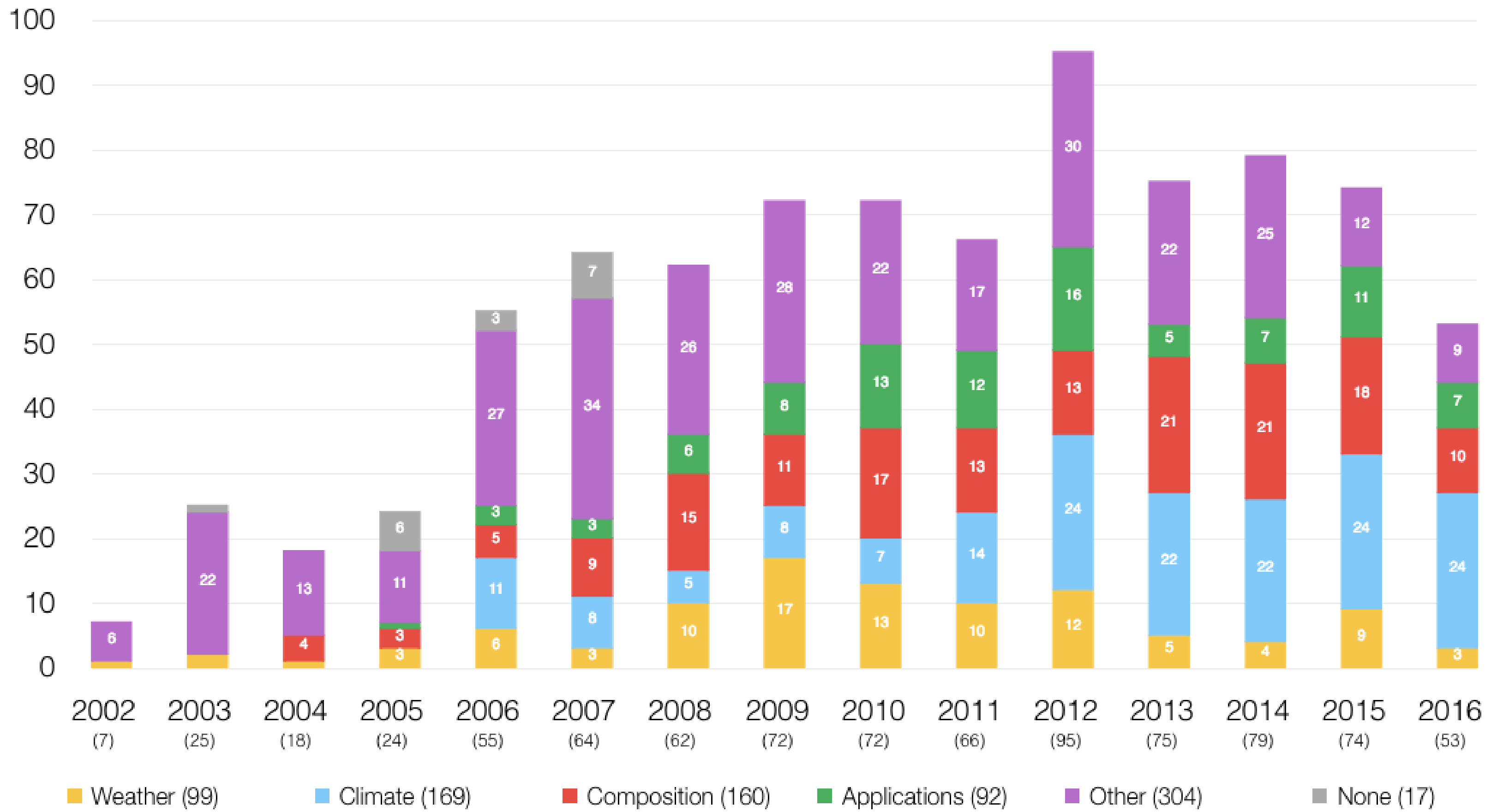
19983 unique IPs over the entire period (1/1/2015 to 12/31/2015)

Feng Ding (GSFC)

Over 70 Peer Reviewed Pubs / Year since 2012

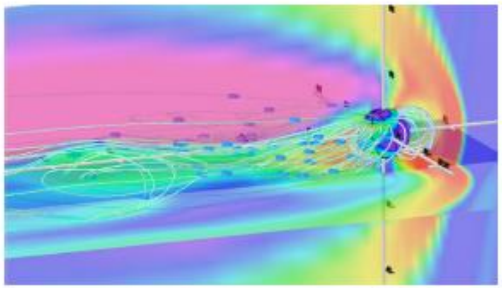
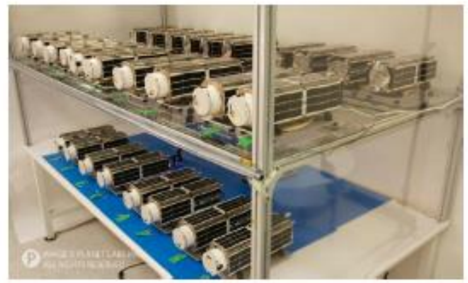
AIRS Peer Reviewed Publications

January 2002 to August 2016



Space Studies Board of the NAS recommends NASA take advantage of CubeSats

Constellations and Swarms


Recommendation: Constellations of 10-100 science spacecraft have the potential to enable critical measurements for space science and related space weather, weather and climate, as well as some for astrophysics and planetary science topics. Therefore, NASA should develop the capability to implement large-scale constellation missions taking advantage of CubeSats or CubeSat-derived technology and a philosophy of evolutionary development.

Zurbuchen, 2016

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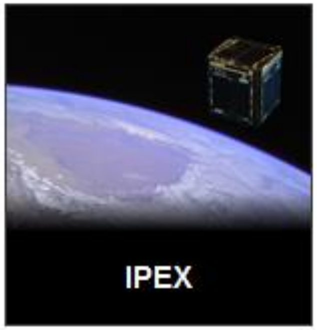
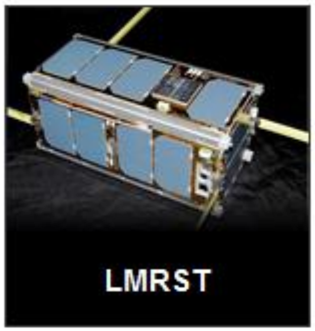
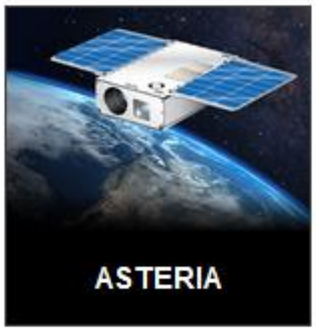
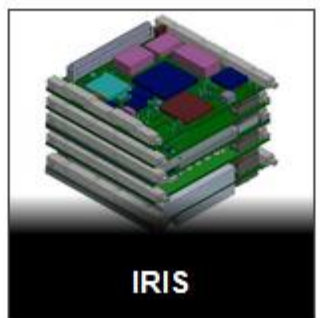
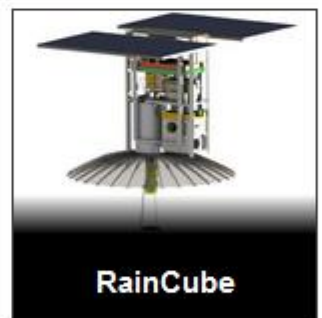
CubeSat Missions at JPL
http://www.jpl.nasa.gov/cubesat/missions/







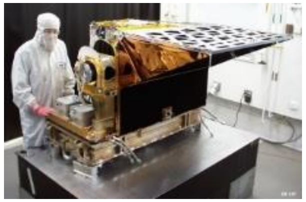




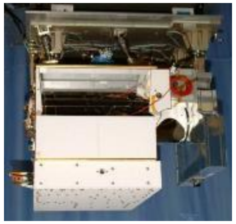
CIRAS Builds on the Success of Legacy Infrared Sounders; Prepares for Future Operational Use

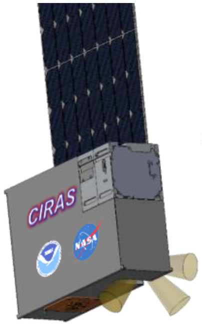
- Atmospheric Infrared Sounder (AIRS)
  - Launched May 4, 2002 on the EOS Aqua Spacecraft
  - Grating Spectrometer, Active Cryocoolers, HgCdTe
  - Highest Forecast Impact of Any Single Instrument (tied with European IASI)
  - Leading Data Set downloaded in Obs4MIPS for CMIP5 to Validate Climate Models
  - AIRS expected to be fully operational beyond 2022
- Crosstrack Infrared Sounder (CrIS)
  - CrIS on NPP and JPSS-1 and JPSS-2
  - Similar Performance to AIRS
- CubeSat Infrared Atmospheric Sounder (CIRAS)
  - NASA tech. demo. for IR sounding in a CubeSat (~$6M)
  - Meets sounding requirements in the lower troposphere
- Future Concept: Earth Observation Nano-Satellite Infrared (EON-IR)
  - Reduce the cost of operational sounding (~$15M vs ~$200M)
  - Gap mitigation in the event of a loss of CrIS on JPSS
  - Could be used to add satellite soundings at new times
  - Constellation compatible for improved timeliness
  - Extended spectral range to meet upper troposphere and/or atmospheric composition (12U)
  - Operational Quality (>2 year mission life).

JPL/BAE AIRS



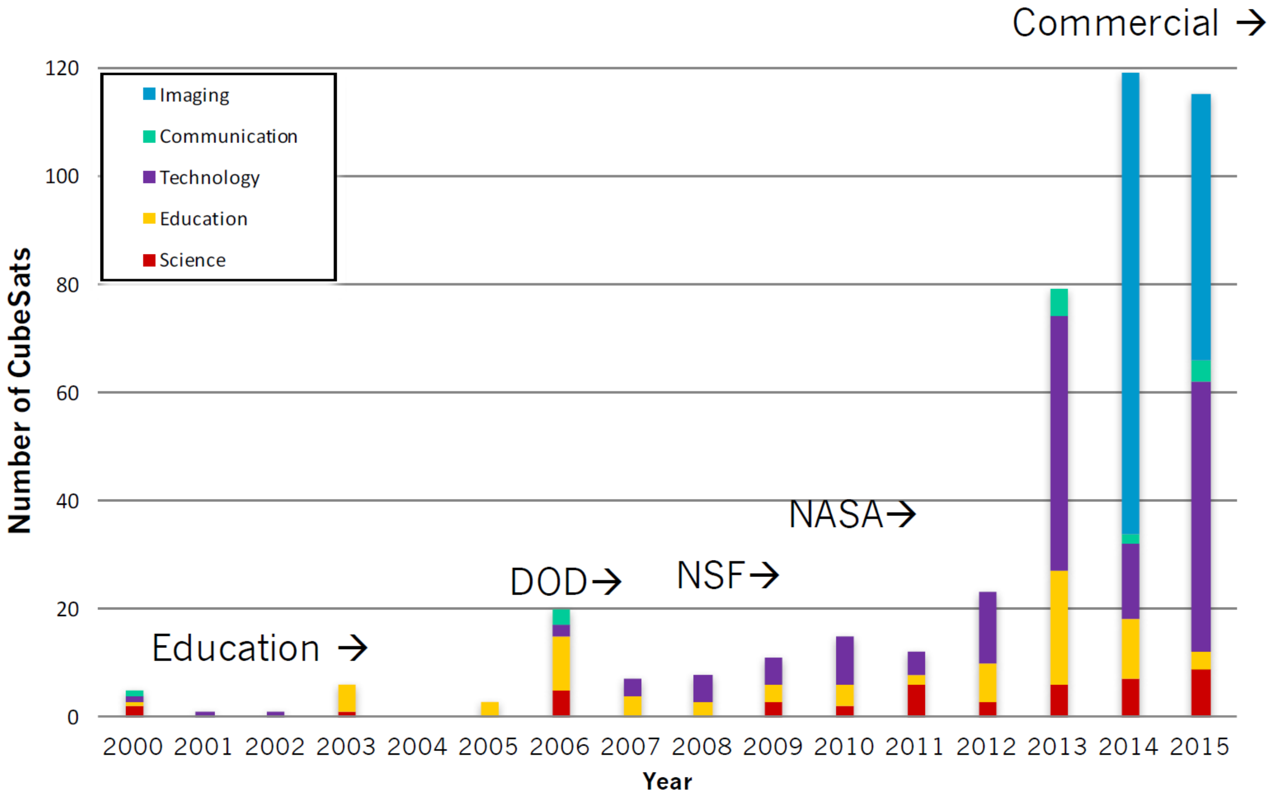
CrIS on JPSS





Hundreds of CubeSats Flown and the Number is Increasing

US CubeSats Launched – by Mission Type



* Only CubeSat in the Public Domain are shown

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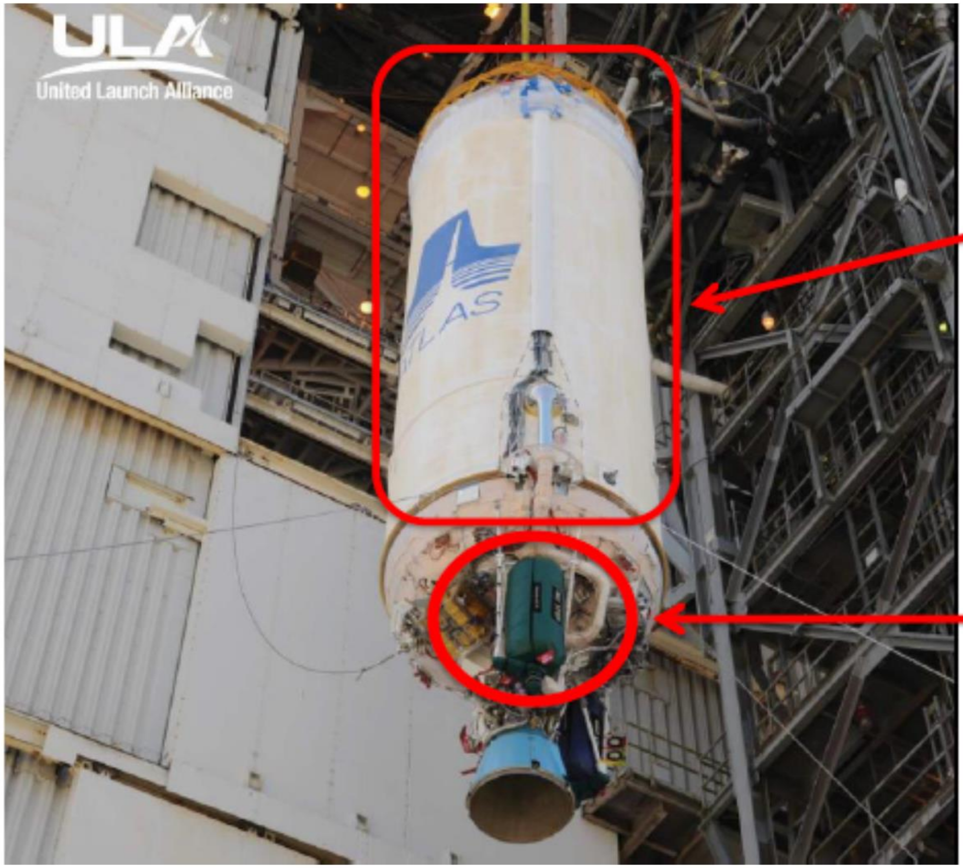
Zurbuchen, 2016

CubeSat Launch Costs Low as Secondary Payload

Launch Canister on Atlas



Main payload

$200M

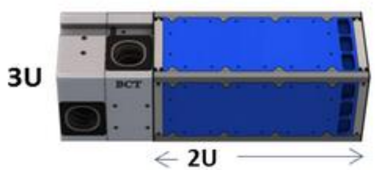
Cubesats
$250K

7

3U, 6U, 12U CubeSat Systems Now Available Commercially

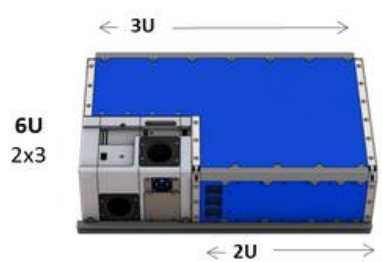
3U XB1 Spacecraft

2U Available Payload Volume



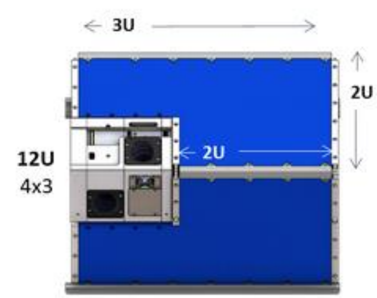
6U XB1 Spacecraft

5U Available Payload Volume



12U XB1 Spacecraft

11U Available Payload Volume



Micro-Sat XB1 Spacecraft

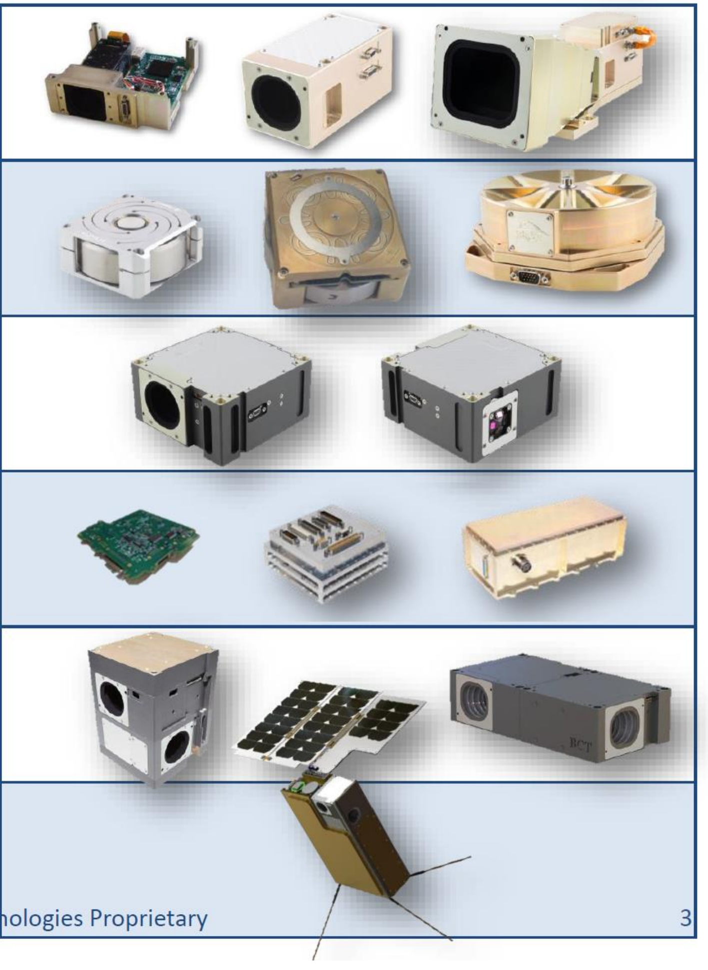
Leverages the XB1 Avionics and the FleXcore Attitude Control to maximize performance and available Payload Volume

BLUE CANYON TECHNOLOGIES

Spacecraft Subsystems Commercially Available

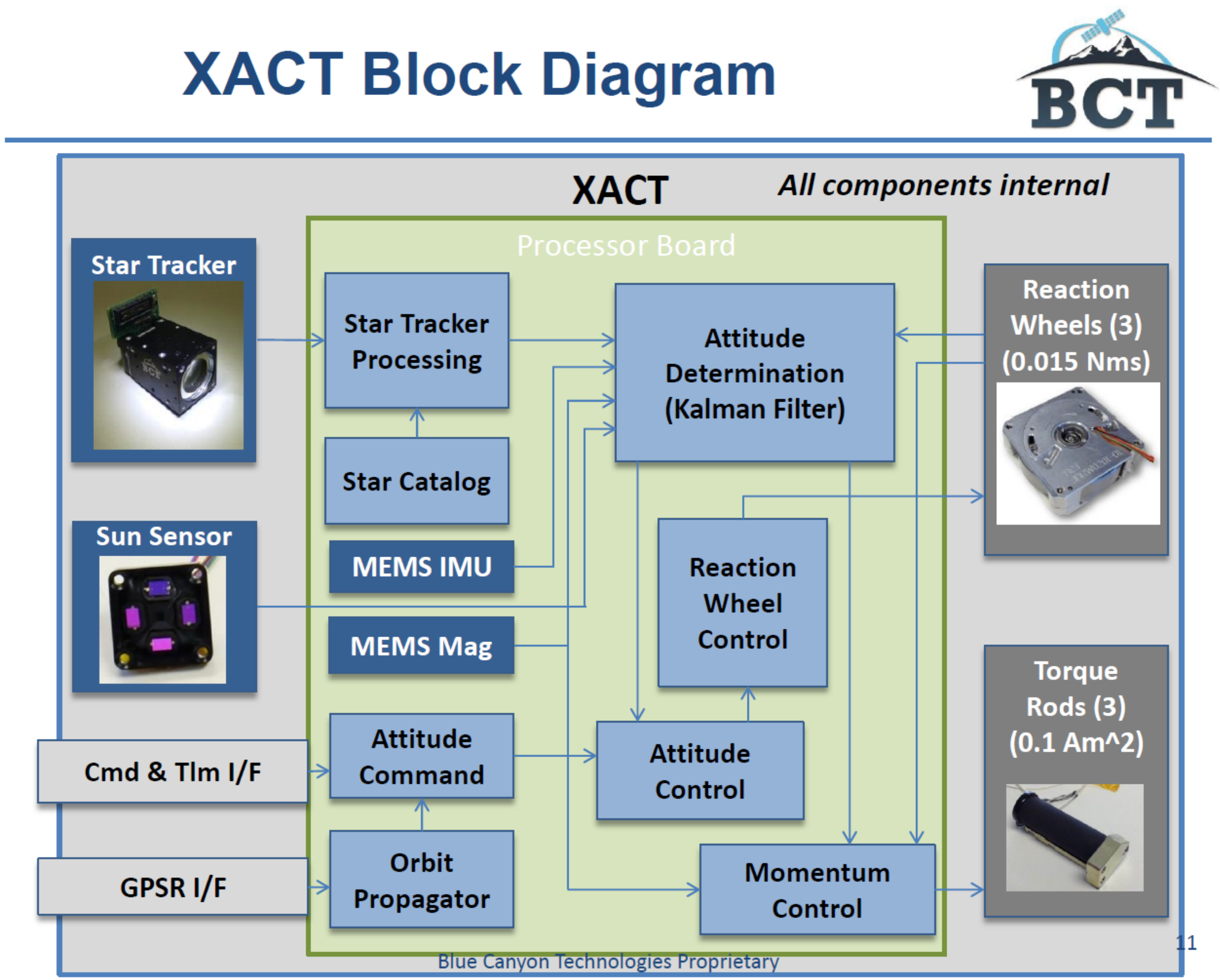
BCT High-Performance Products

Nano Star Trackers High-performance, ultra-small size & power	
Reaction Wheels Nanosat, CubeSat, and Microsat sized wheels	
XACT - Attitude Control Systems Precision GN&C Systems	
Electrical Power Systems Batteries, solar panels, power control and distribution	
XB1 - 1U NanoSat System Integrated Nanosat system (ADCS, EPS, C&DH, GPS, RF Comm)	
XB1 Spacecraft Bus Complete Nanosat Spacecraft Bus Solution	



Blue Canyon Technologies Proprietary 3

Spacecraft Attitude Control System



Complete Spacecraft Avionics in 1U

XB1 – 1U Nanosat System

XACT-Based 1U Integrated CubeSat System

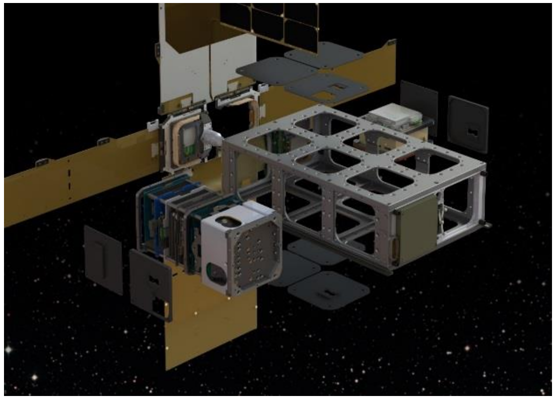
BCT

- Highest-available pointing performance from *Dual* Micro-Star Trackers
- Bus functionality for GN&C, EPS, Thermal, C&DH, SSR, option for RF Comm
- Interfaces and control provided for Payload, Propulsion, and Solar Arrays
- Supports configurations up to 27U
- Side by Side or Stacked Configurations available

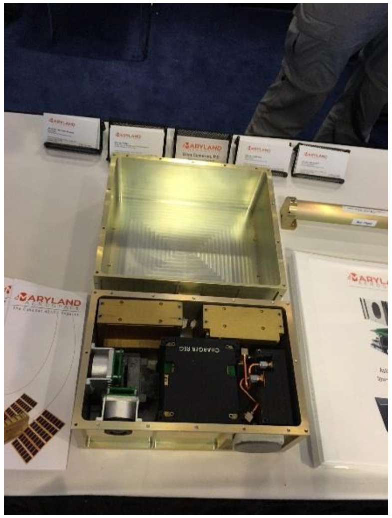
	XB1 Parameter	Value/Notes
GN&C	Pointing Accuracy	±0.002° (1-sigma), 3 axes, 2 Trackers
	Pointing Stability	1 arc-sec/sec
	Maneuver rate	10 deg/sec (typical 3U CubeSat)
	Orbit knowledge	4m, 0.05m/s
CDH	Data Interfaces	Serial: LVDS, I2C, or SPI available
	Onboard Data Processing	Configurable via user loadable software
	Telemetry Acquisition	6 12bit Analog, 6 discrete inputs
	Commands	Real-time, stored, macro
	Onboard Data Storage	32 Gbytes
EPS	System Bus Voltage	10 – 20 V (battery and array dependent)
	Energy Storage	Standard: 25Whr, expandable
	Solar Panels	Customer or BCT Provided Solar Panels (Details available per request)
	High Current Capability	Unregulated up to 60W
	Payload Power Feeds	QTY 6 (12, 5, 3.3V or Bus voltage)
Comm	Frequency	UHF or Sband (X Band option available)
	Uplink	CCSDS, USB, SGLS
	Downlink	250 kbps / 5 Mbps (Other options available)
	Encryption	AES 256
	Solid State Recorder Capacity	4 Gbytes
Prop	Heater Controllers	Up to 6 independently controlled zones
	Propulsion System Drive	Or up to 6 Thruster drivers or Latch Valves Drivers
	Telem. Interfaces	2 Temperatures, 4 voltages, 6 discrete IO
	Mass / Volume	1.5 kg / 10 cm x 10 cm x 10 cm
	XACT-Bus Nominal Power	< 6.3W
	Orbit Altitude / Orbit Lifetime	LEO 3 year

2/1/2016 13

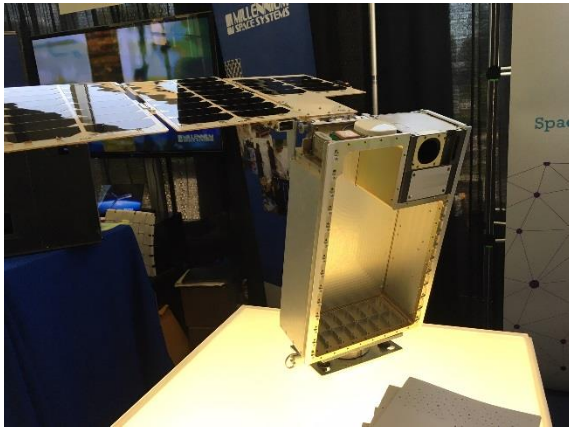
Payload is Modular in Most Designs



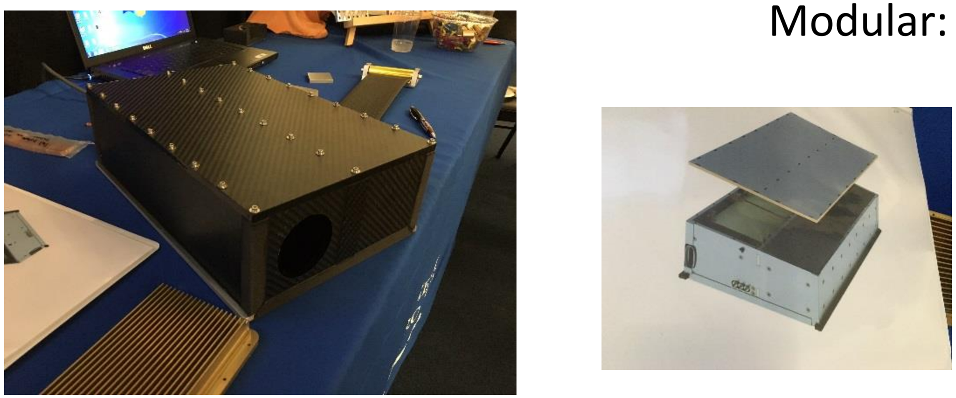
Bolt-In Pumpkin



Modular: MAI



Panel: BCT

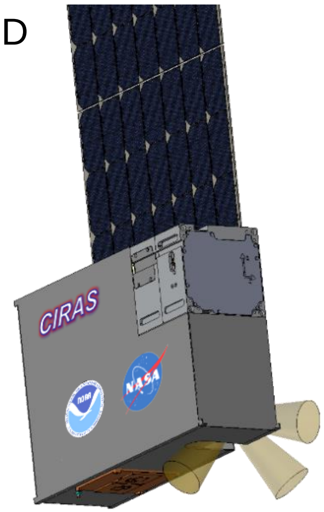


Isothermal CubeSat Structure

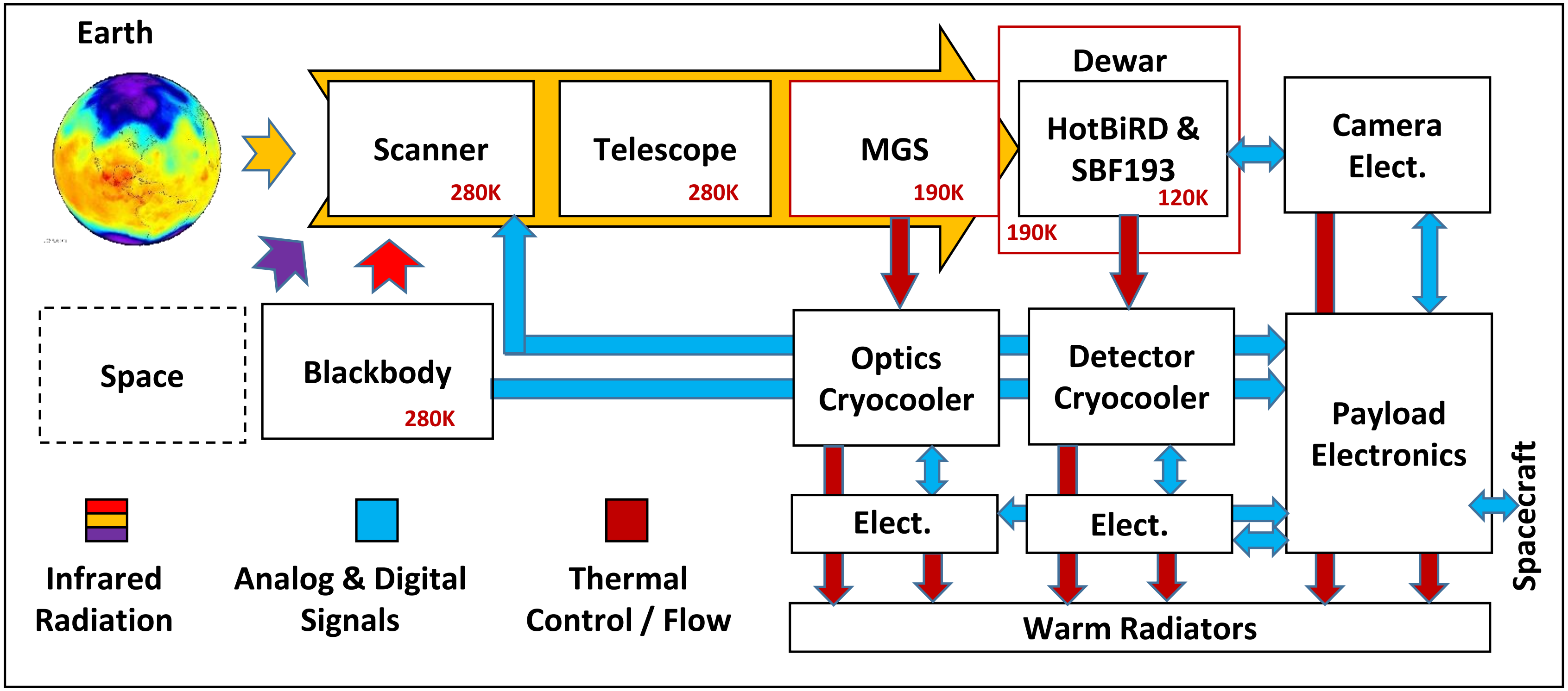
CIRAS Mission Overview

CIRAS is a ***technology demonstration*** mission to enable hyperspectral infrared atmospheric sounding on a CubeSat

- **Mission Objectives**
  - In-Space Technology demonstration for key infrared subsystems: JPL HOT-BIRD IR Detectors, JPL Grism Spectrometer, Black Silicon Blackbody
  - Demonstration of Mid-wavelength Infrared (MWIR) temperature and water vapor sounding. Limited to mid to lower troposphere.
  - All technologies will be advanced to TRL 7 at the end of experiment
- **Implementation Summary**
  - 6U CubeSat (approx. 30 x 20 x 10 cm, <14 kg)
  - LEO Sun Synchronous Morning Orbit (400 km – 850km)
  - Minimum Mission Duration: 3 months
  - JPL Payload Development, Ball Optics, Commercial Spacecraft
  - CubeSat Launch Initiative for Launch Services
  - Sponsored by NASA Earth Science Technology Office (ESTO) In-flight Validation of Earth Science Technologies (InVEST) Program, Awarded 2015
  - Design performed in collaboration with the NOAA Office of Projects, Planning, and Analysis (OPPA)
  - Selected on 2/18/16 for a launch opportunity by the NASA CubeSat Launch Initiative . Launch No Earlier Than June 2018.



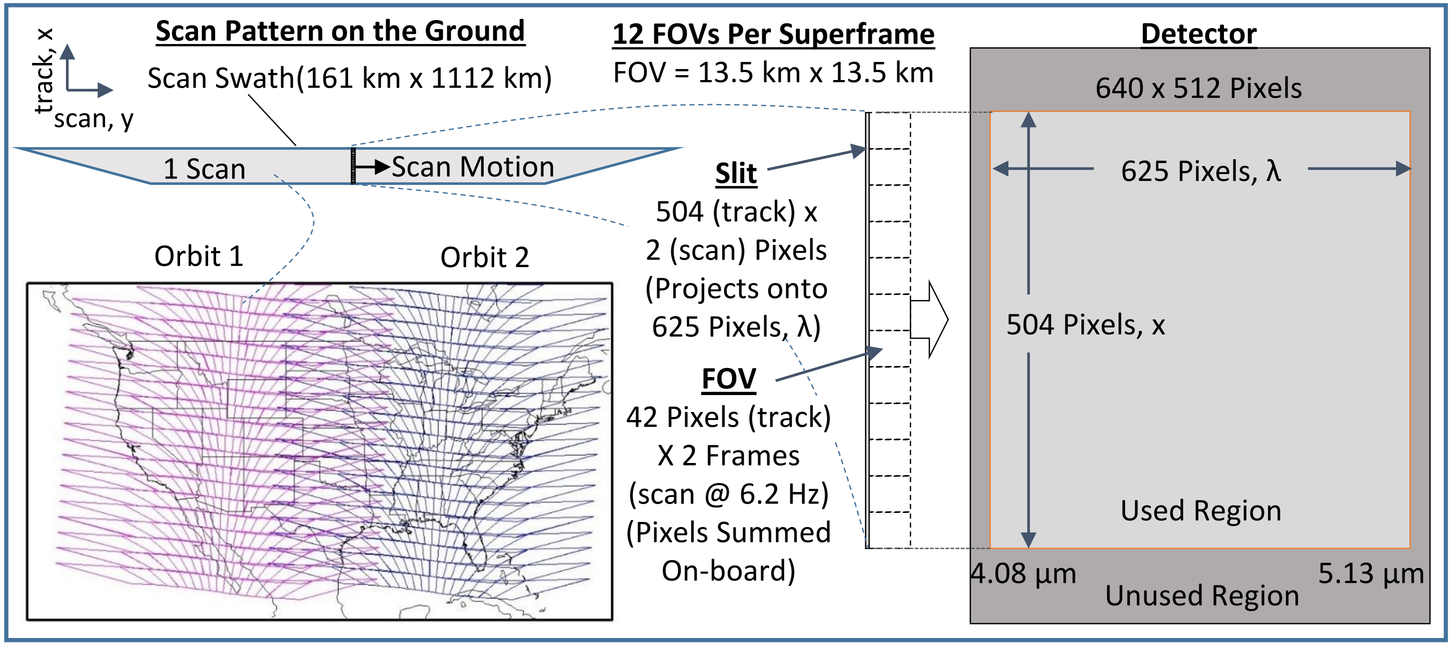
CIRAS Payload Block Diagram



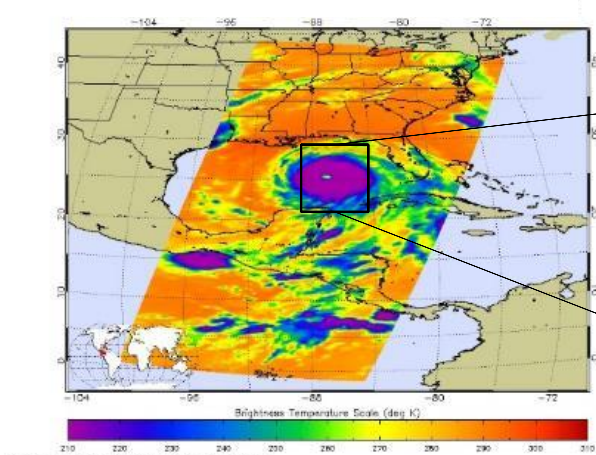
CIRAS Spatial Requirements comparable to AIRS, CrIS + Zoom

- Programmable Pixel Binning and Scan Rate Allow Global and Zoom Modes

CIRAS Binning Scheme (600 km Orbit)



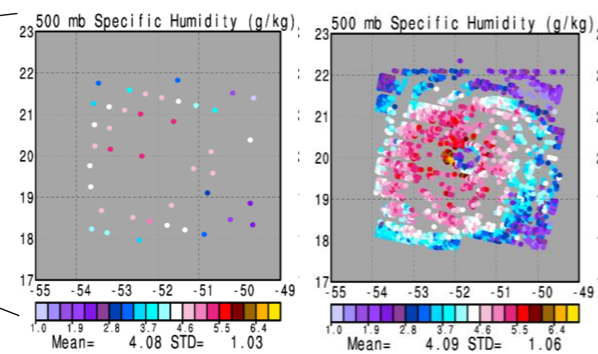
AIRS Global Mode



Simulated Sounder Yield

Global Mode 14 km GSD

Zoom Mode 3 km GSD

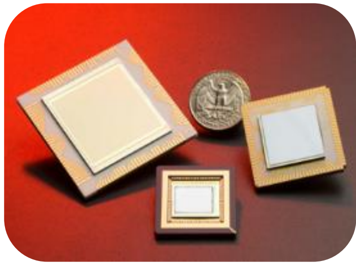


Technologies relevant to Infrared Sounders

- Scanners
- Telescopes
- Spectrometers
  - Grating, FTS, Etalon, Prism, Grism,…
- Dichroic Beamsplitters
- Camera or Aft-Optics
- Stripe Filters
- Detectors
  - MWIR, LWIR, Far IR
- Readout Integrated Circuits (ROICs)
  - Sets dynamic range and drives cooling
- Camera Electronics
- Payload Electronics
- Optical Bench
- Mainframe or Payload Structure
- Thermal Radiators, Heat Pipes
- Dewar
- Cryocooler
- Satellite
  - Power system
  - Communications
  - Attitude Sensing and Control
  - Navigation
  - Structure and Thermal

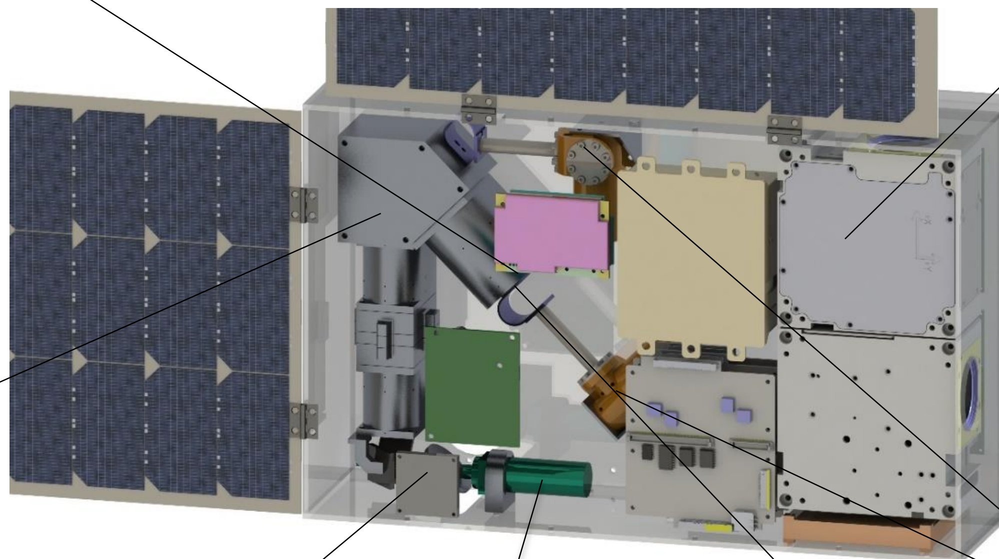
CIRAS Instrument Uses Latest HSIR Technologies

Size	6U Cubesat
Mass	8.5 kg
Power	37.5W
Data Rate	2 Mbps

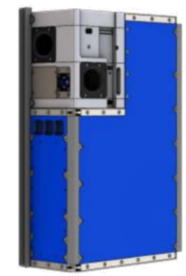


JPL
HOTBIRD
Detectors

JPL/BALL
Midwave Infrared
Spectrometer



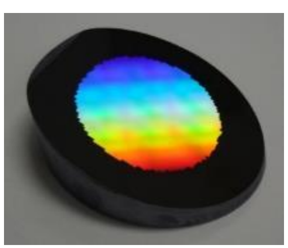
Commercial
Spacecraft



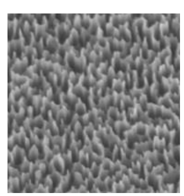
IR Cameras
SBF193 Electronics

JPL MDL Technologies

Immersion Grating

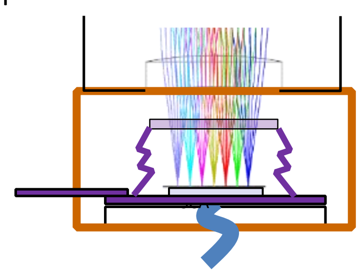


Black Si.
Blackbody & Slit



Scan Mirror Assy
Commercial Stepper
Motor + Elex

Custom Detector
and Cold Filter
Mount

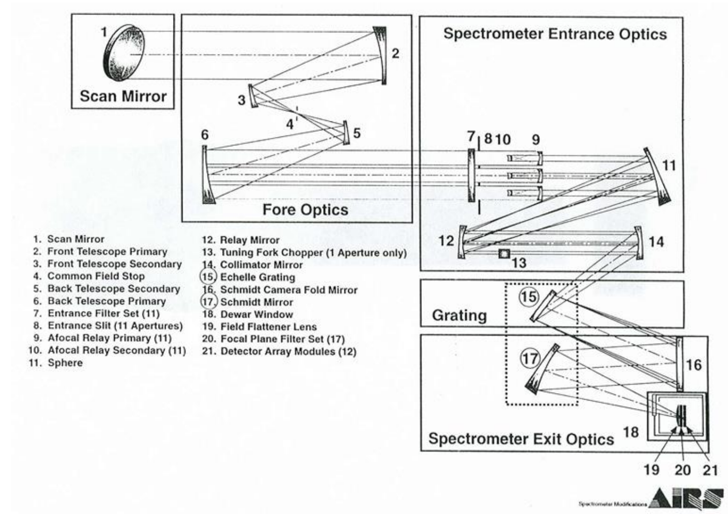


Ricor K562S
Cryocoolers + Elex

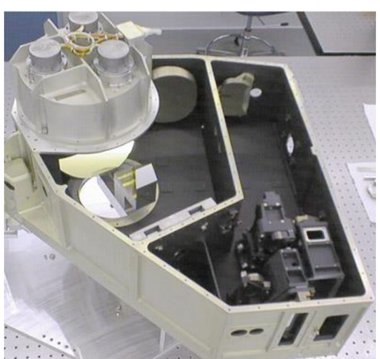
AIRS Demonstrated Advancement in Hyperspectral IR Technology

AIRS Requirements

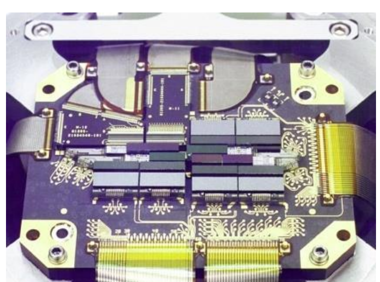
- Spatial
  - IFOV : 1.1° x 0.6° (13.5 km x 7.4 km)
  - Scan Range: ±49.5°
- Spectral
  - 2378 Channels
  - 3.74-4.61 µm, 6.2-8.22 µm, 8.8-15.4 µm
  - $\lambda/\Delta\lambda \approx 1200$
- Radiometric
  - Accuracy: < 0.2K
  - Stability: < 10 mK/year
- Mass: 177Kg
- Power: 256 Watts
- Life: 5 years (7 years goal)



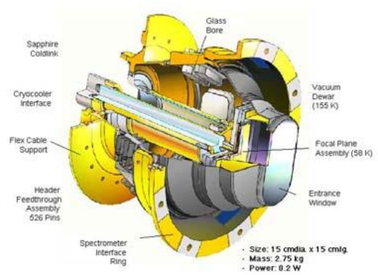
•IR Grating Spectrometer
•155K Operation



•FPAs: PV HgCdTe to 13.7 µm, PC HgCdTe to 15.4 µm



• Cryogenic Dewar Technology

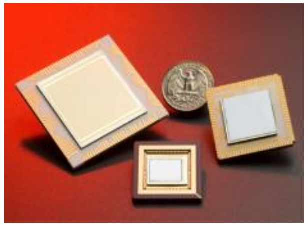


•Focal Plane Cooling using Stirling Pulse Tube

CIRAS Key Technologies to Demonstrate

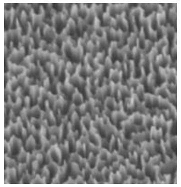
- CIRAS Demonstrates In-Space Key Technologies Required for Hyperspectral Infrared Measurements
  - **HOT-BIRD Detectors (TRL 6):** The new High Operating Temperature Barrier Infrared Detector (HOT-BIRD) detector materials developed at JPL provide superior uniformity and operability, higher operating temperature, and lower 1/f noise with comparable performance as HgCdTe at these wavelengths, and can be made at a significantly reduced cost.
  - **MWIR Grating Spectrometer (MGS) (TRL 5):** The CIRAS MGS is a high dispersion immersion grating spectrometer enabling IR remote sensing of hyperspectral radiances with no moving parts, at low cost, in a CubeSat package. To be built by Ball Aerospace.
  - **Black Silicon IR Blackbody (TRL 5):** A cryo-etched silicon surface that exhibits less than 0.2% reflectance across a broad spectral band
- Extensive use of commercial technologies
  - Camera electronics, scan motor and controller, cryocoolers, cryocooler electronics, and spacecraft
- All technologies will be advanced to TRL 7 at the end of the spaceflight mission

JPL HOT-BIRD Detector



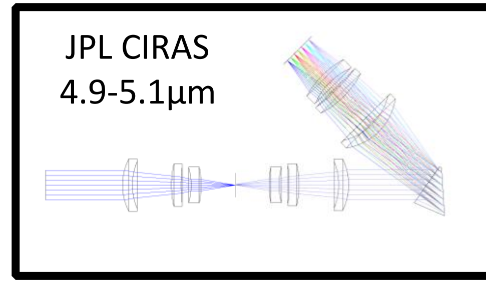
CIRAS optics based on SIRAS developed in IIP 2000 and 2007

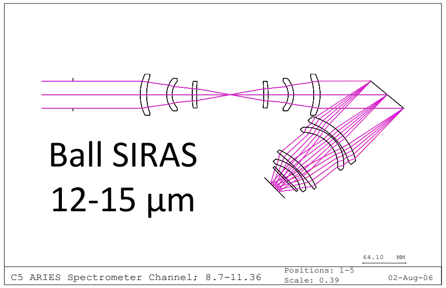
Black Si. Blackbody & Slit

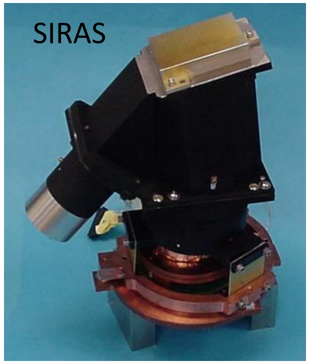


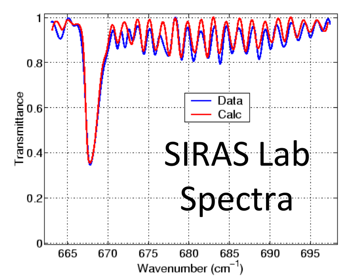
CIRAS Optics Based on NASA IIP Technologies

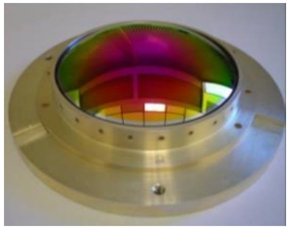
- Wide Field of View: Allows wide swath for slow scan
- All refractive optics with multiple surfaces enable good image quality across the field and high spectral resolution
- High degree of commonality. Telescope uses same optics as collimator
- JPL Immersion grating: Reduces size of spectrometer and reduces distortion
- JPL Black silicon slit: Low stray light
- Ball has history of development of wide field refractive IR spectrometers for JPL, ESTO and NOAA
  - SIRAS ESTO IIP-1 (JPL Lead)
  - SIRAS-G ESTO IIP-3
  - Wavelengths: 12-15 µm, 3-5 µm

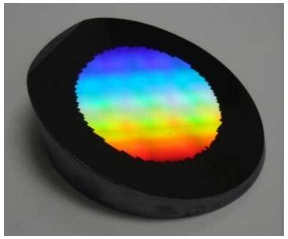








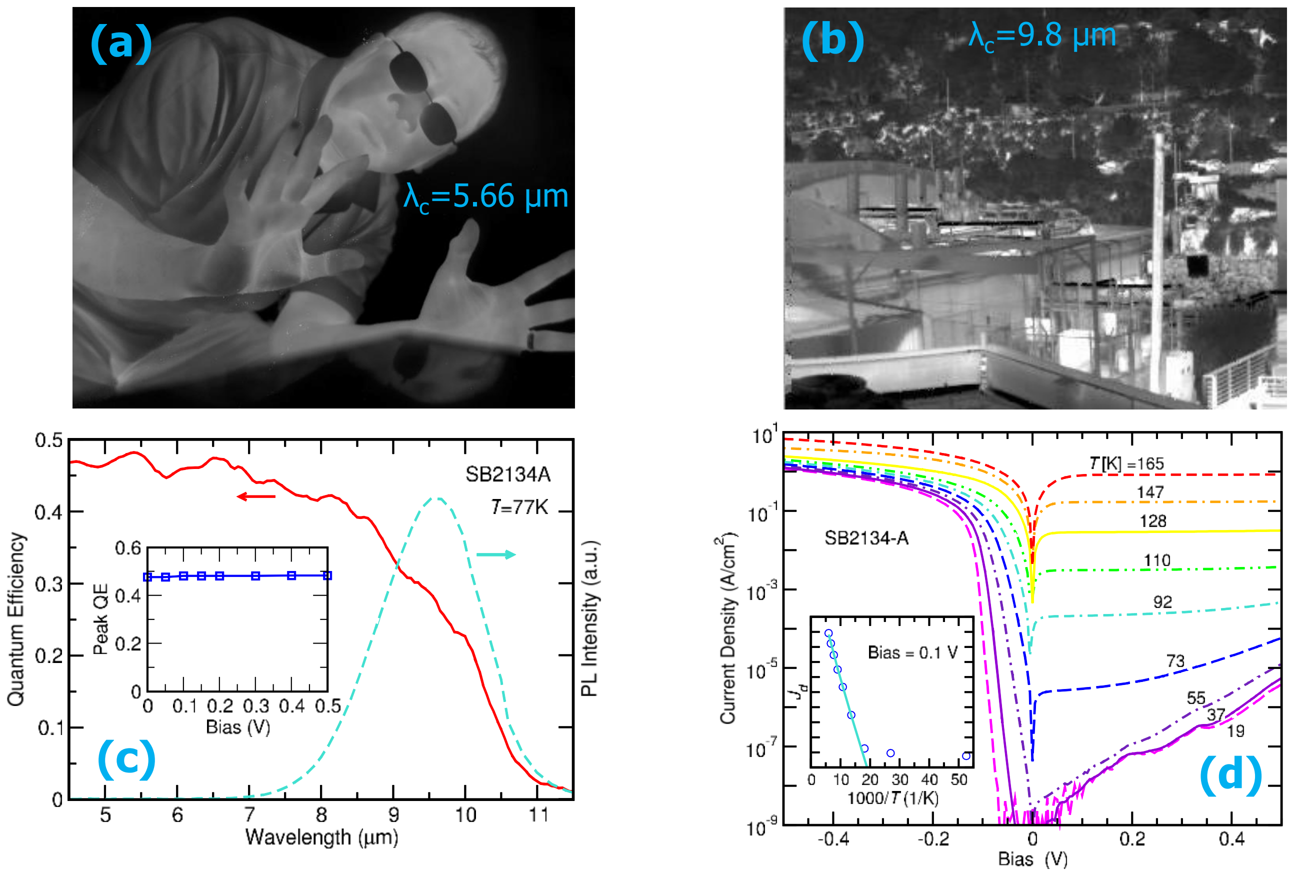




JPL Immersion Grating

CIRAS Uses JPL High Operating Temperature (HOT) Barrier IR Detector (BIRD) Technology

High performance Barrier IR detectors (BIRD) with continuously adjustable cutoff wavelengths have been developed at JPL. Affordable HOT-BIRD-based MWIR (3-5μm) and LWIR (8-14 μm) FPAs routinely achieve high operability and uniformity.

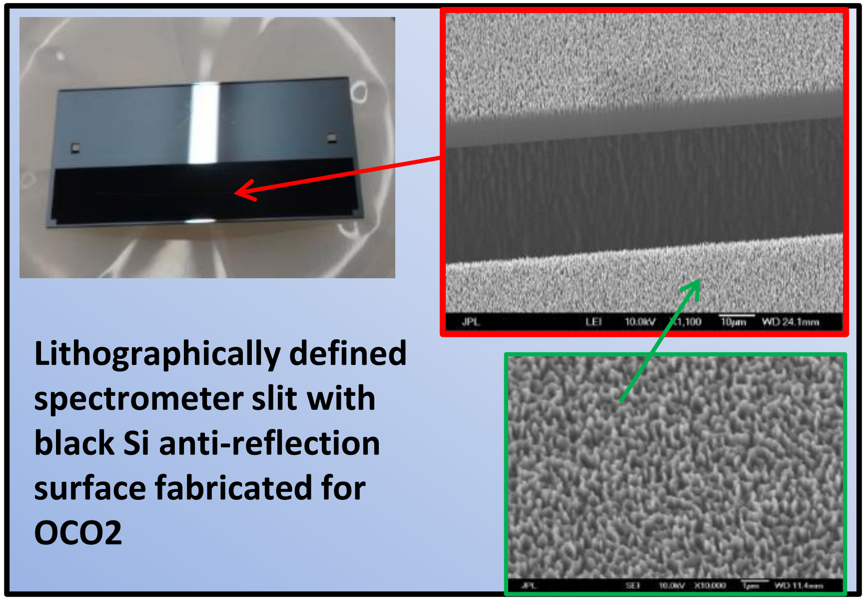


(a) Image taken by an MWIR FPA made from the BIRD material.
(b) Image taken by an LWIR FPA made from the BIRD material.
(c) Spectral quantum efficiency (no anti-reflection coating), photoluminescence, and QE vs bias (inset) of the BIRD material used for the LWIR FPA
(d) Dark current characteristics of the BIRD material used for the LWIR FPA.

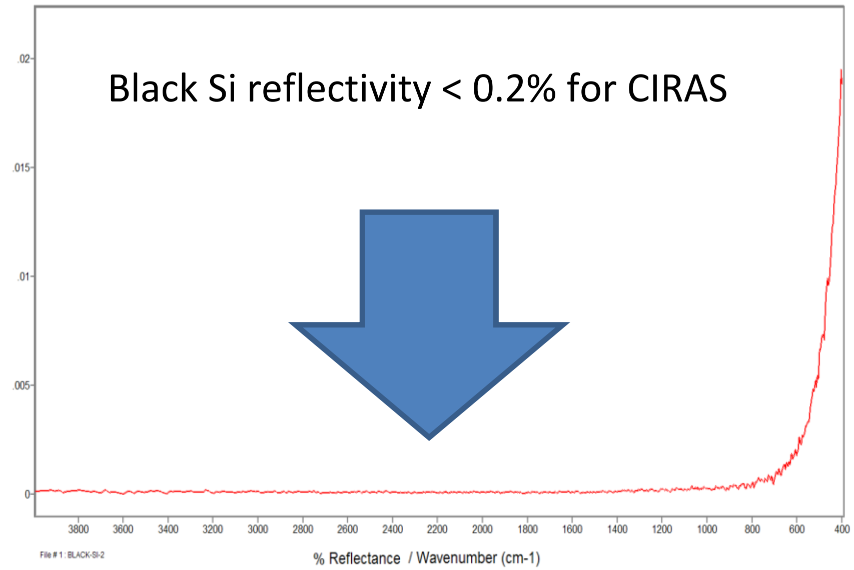
CIRAS will demonstrate an IR Blackbody using Black Silicon in space

Black Silicon Uses for CIRAS:

- Blackbody Surface
  - <2” Diameter (Max target size manufacturable is ~5.5” diameter wafer)
  - Surface is robust under shock / vibration, and is compatible with liquid cleaning
- Entrance Slit
  - Lithographically defined, precision micro machined slit with smooth sidewalls
  - Knife edge geometry with black silicon anti-reflection surface texturing for reduction of stray light
  - Flight heritage: JPL instruments utilizing slits of this type include: HyTES, AVARIS, UCIS, HyspIRI, MaRS2, PRISM, NEON

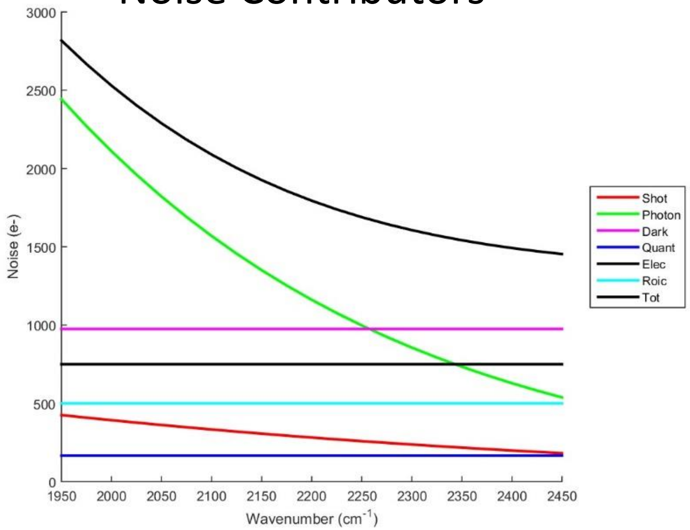


Lithographically defined spectrometer slit with black Si anti-reflection surface fabricated for OCO2

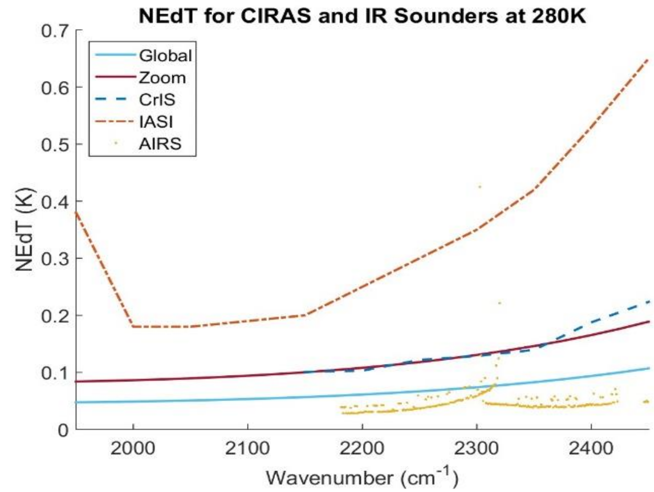


Spectral and Radiometric Models Predict Good Performance for CIRAS

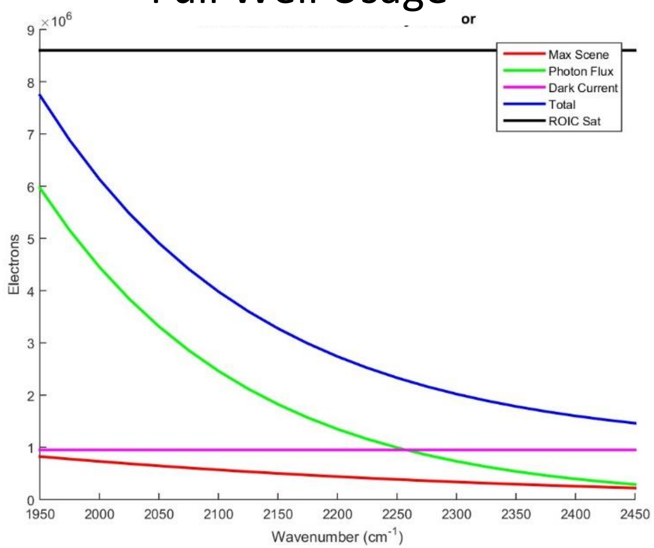
Noise Contributors



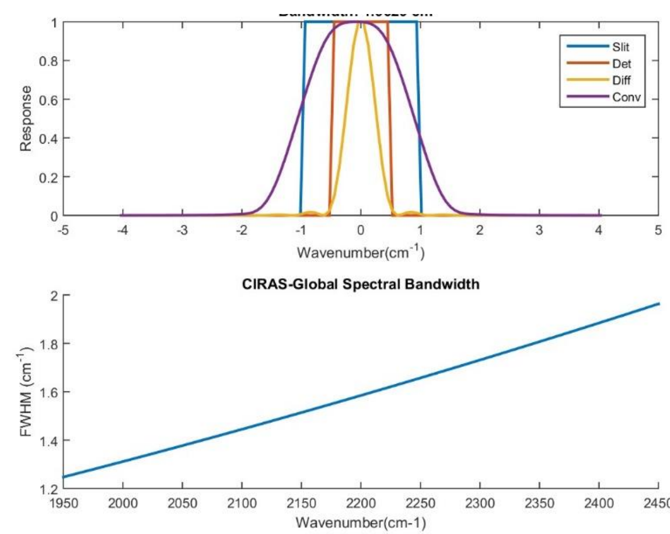
Noise Equivalent Temperature



Full Well Usage



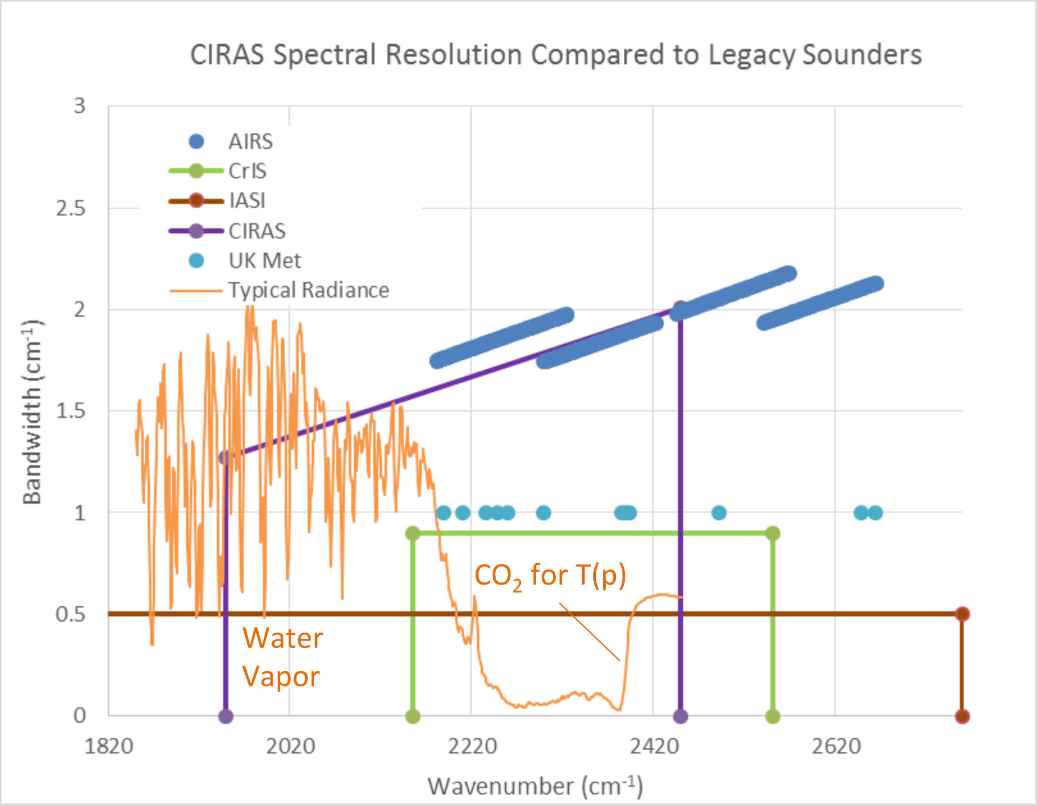
Spectral Response and Resolution

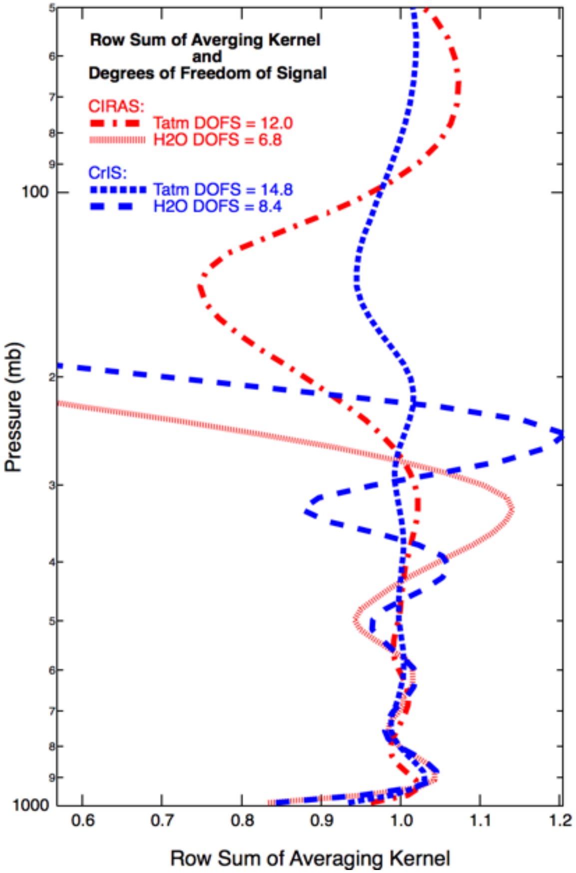


CIRAS Spectral performance comparable to AIRS in MWIR

CIRAS Spectral like AIRS but Extends into Water Band
1950 cm^{-1} – 2450 cm^{-1}
$\Delta\nu = 1.6\ cm^{-1}$, $N_{ch} = 625$

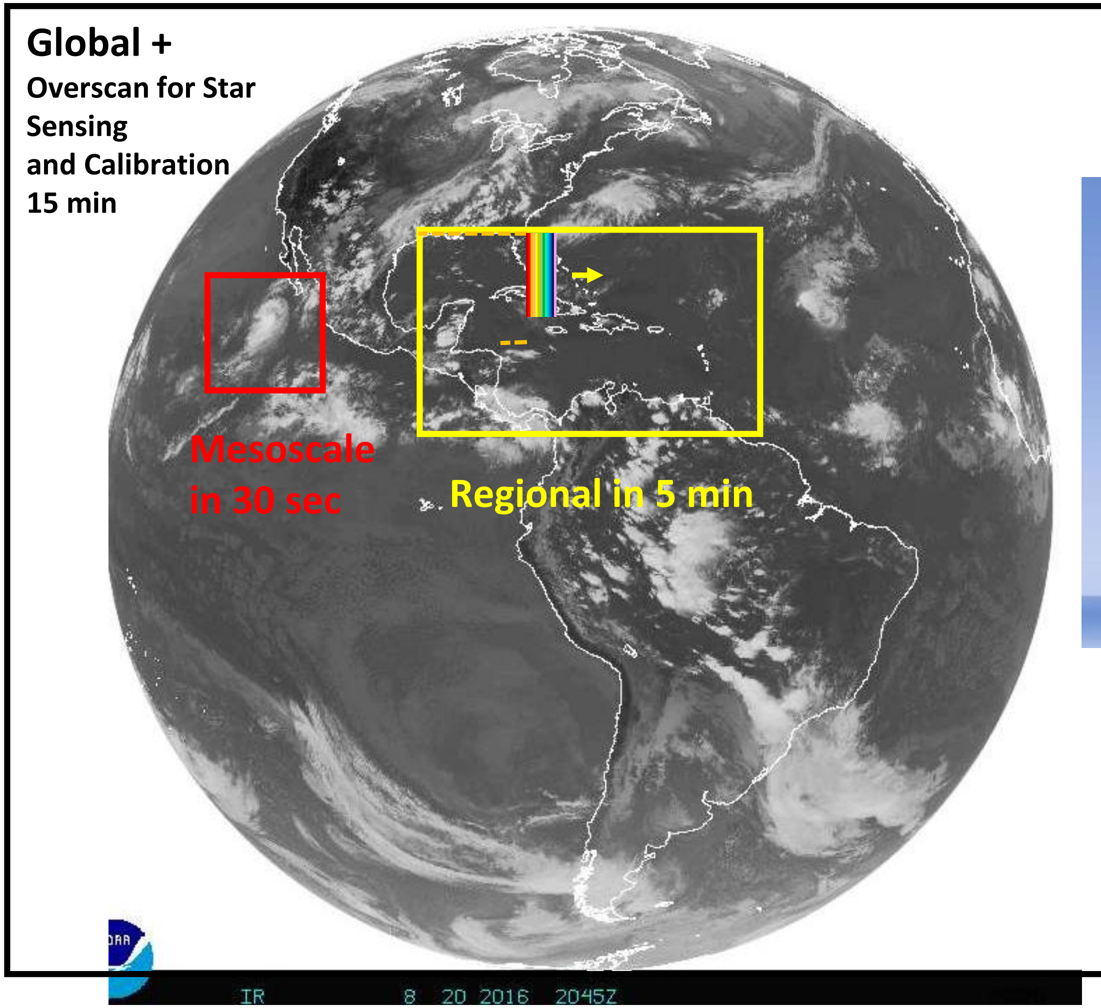
CIRAS Information Content Extends from Surface to 300 mb





Improved Timeliness Important for Storm Development: Model Clouds Shown Below

Imagers work in GEO. Hyperspectral IR Sounders Not Yet Flown in GEO



"BlueMarble-2001-2002". Licensed under Public domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:BlueMarble-2001-2002.jpg#mediaviewer/File:BlueMarble-2001-2002.jpg

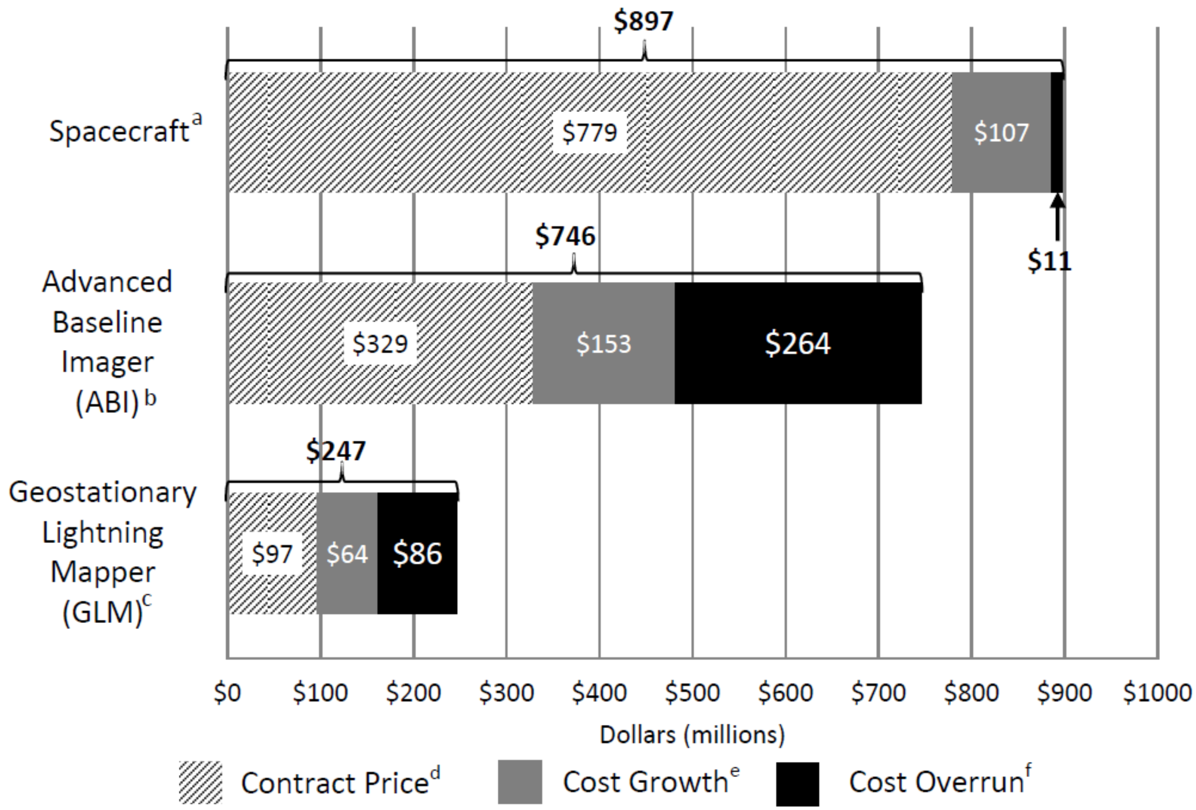
GOES-R Advanced Baseline Imager
Developer: Exelis

Size	1.6x1.5x1.4 m^3
Volume	3.28 m^3
Mass	275 kg
Power	450 W

EUMETSAT to Launch First GEO Infrared Sounder (IRS) on MTG in 2022 Timeframe

High Cost of GEO Payloads Motivates CubeSat Constellations for IR Sounders

Figure 3. Costs of Spacecraft, ABI, and GLM, as of December 2012



Source: Adapted from GOES-R program and NASA contract documentation
[a] Includes the spacecraft for the GOES-R and -S flight models; [b] includes instruments for GOES-R and -S flight models; [c] includes instruments for GOES-R, -S, and -T flight models; [d] the contract price (base cost + award fee) at award including exercised contract options; [e] costs negotiated and added to the contract for decisions made by program management (e.g., requirements changes, additional testing, and schedule adjustments); [f] contractor incurred and planned costs that exceed the expected costs of their negotiated contracts.

Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats

MIT Lincoln Laboratory (proposing organization)

William J. Blackwell, Principal Investigator, Scott Braun (NASA GSFC), Project Scientist

TROPICS

- PI: William J. Blackwell. MIT Lincoln Laboratory
- Sponsor: NASA Earth Science Directorate
- Program: Earth Venture-Instruments. 2016 Award
- Instruments: 3U CubeSat Microwave Sounders
- Orbits: 12 CubeSats, 4 in each of 3 orbital planes
- Measurement: Temperature, Moisture, Microwave Imaging
- Frequencies: 12 Channels at 90, 118, and 206 GHz
- Launch: 2019/2020

https://tropics.ll.mit.edu

Summary and Conclusions

- Infrared atmospheric sounders measure hyperspectral infrared radiances with high precision and accuracy
- IR sounder radiances provide high impact to operational forecast
- IR sounders provide valuable information for climate science
- CIRAS provides IR sounding using the MWIR with sensitivity to temperature and water vapor profiles in the lower troposphere
- CIRAS can be used to mitigate a loss of operational IR sounders, add orbit times and improve timeliness
- CIRAS will demonstrate higher spatial resolution IR sounding (3 km vs legacy capability of 14 km)
- CIRAS to be built at JPL with Ball optics, and commercial technologies
- CIRAS to procure a commercial spacecraft
- CIRAS scheduled for launch in mid 2018 to early 2019 timeframe
- CIRAS is a pathfinder to a future operational mission, EON-IR enabling legacy capability at 1/10th the cost of today's IR sounders

Backup

Signal to Noise Ratio (SNR) and Noise Equivalent Temperature Differential (NEΔT)

$$SNR = \frac{S}{\sqrt{N_{photon}{}^2 + N_{det/amp}{}^2 + N_{quant}{}^2 + N_{other}{}^2}}$$

$$NE\Delta T = \frac{NE\Delta L}{dL/dT} = \frac{[L/SNR]}{dL/dT} \quad ,$$

NEΔT	=	noise equivalent temperature difference [K]
SNR	=	signal-to-noise ratio
NEΔL	=	noise equivalent spectral radiance [W/m^2-sr-μm]
L	=	Planck blackbody spectral radiance [W/m^2-sr-μm]
T	=	scene temperature [K]

Detector/Pre-Amp noise terms not included in this talk, and equations are often proprietary.

Signal Depends on Instrument Design Parameters and Scene Radiance

The number of signal electrons of interest collected by a detector or group of detectors for a single spectral band in the MODIS is given by

$$S = L \cdot \Delta\lambda \cdot \frac{\lambda}{h\,c} \cdot \Omega_o \cdot d_x d_y \cdot \tau_o \cdot T_i \cdot \eta \cdot N_{sum},$$

where

S	=	integrated sensor signal electrons
L	=	spectral radiance [W/m^2-sr-µm]
λ	=	wavelength [µm]
$\Delta\lambda$	=	bandwidth of spectral channel [µm]
$\frac{\lambda}{h\,c}$	=	number of photons (with wavelength λ) per unit energy $\left[\frac{\text{photons}}{W\,s}\right]$
Ω_o	=	effective optical system solid angle [sr]
τ_o	=	optical throughput
η	=	quantum efficiency [electrons/photons]
$d_{x,y}$	=	detector size in the x,y direction [cm]
T_i	=	integration time [s]
N_{sum}	=	number of signals summed in TDI or spatially aggregated

IR Systems Performance Depend on Background Flux at Detector

$$N_{phot} = \sqrt{Q_{photon} \eta d_x d_y T_i}$$

$$Q_{photon} = \frac{\lambda \Delta\lambda}{h c}\left[L_{scene}\,\Omega_{opt}\,\tau_{opt} + \sum_{i=1}^{J}\left(L_i(1-\tau_i)\Omega_{opt}\prod_{k=i+1:i\neq J}^{J}\tau_k\right) + L_{sys}\left(\Omega_{sys} - \Omega_{opt}\right)\tau_J\right]$$

where

Q_{photon}	=	photon flux at the detector [p/cm^2-s]
$\frac{\lambda}{h c}$	=	number of photons (with wavelength λ) per unit energy $\left[\frac{\text{photons}}{\text{W s}}\right]$
$\Delta\lambda$	=	bandpass filter spectral bandwidth [µm]
L_{scene}	=	scene spectral radiance [W/m^2-sr-µm]
Ω_{opt}	=	solid angle of the MODIS optical system [sr]
τ_{opt}	=	total system optical transmittance
i	=	optical element number (i=1 is the scan mirror, i=J is the filter)
J	=	number of elements in the system
L_i	=	spectral radiance of the ith element [mW/cm^2-sr-µm]
τ_i	=	transmittance of the ith element
$(1-\tau_i)$	=	effective emission and reflection off of the ith element
L_{sys}	=	internal system spectral radiance [W/m^2-sr-µm]
$\Omega_{c/s}$	=	cold stage window solid angle [sr]