Challenges And Successes In Creating Multi-instrument/Multi-platform Space-Based Earth System Data Records

Jack A. Kaye

Earth Science Division
Science Mission Directorate
NASA Headquarters

July 31, 2012

Overview

- Introduction
- The Scientific and Programmatic Challenges
- Examples and Lessons Learned
- Looking Ahead

Presentation includes inputs from many scientists and managers at NASA HQ and centers – thanks to them for sharing:

P. K. Bhartia, Paula Bontempi, David Considine, Ramesh Kakar, Eric Lindstrom, Norm Loeb, Rich McPeters, Martha Maiden, Rich Eckman, Lucia Tsaoussi, Ralph Kahn, Jeff Myers, Steve Platnick, Garik Gutman, and others who contributed to this and to earlier talks.

The Scientific Challenge

- Goal is to be able to document long-term evolution of the Earth system using satellite data
  - Longer-term variability (esp. human-caused) is superimposed on much larger natural variability occurring on a range of scales
  - The length of the record needed requires the use of multiple satellite platforms and instruments, each of which have their own particular characteristics
  - The harsh environment of space degrades instruments and requires accurate correction
- This constitutes an international research effort that may draw on both research and operational satellites from agencies around the world
  - Focus here is on those data sets for which NASA research satellites constitute a significant or primary data source
- Challenge has been described by GCOS in its Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)
  - 25 Essential Climate Variables (ECVs) have been listed for which satellite observations make a significant contribution – 9 atmosphere (over land, sea, ice), 6 oceanic, 10 terrestrial

The Scientific Challenge, cont.

- Key elements for meeting the challenge include (but aren't limited to – note similarity to "satellite" element of GCOS Monitoring Principles)
  - Overlap between successive instruments
  - Stable Orbits
  - Accurate pre-launch and on-board calibration (including lunar calibration), traceable to recognized standards
  - Validation effort over a broad range of conditions and over the lifetime of the mission(s), including coincident measurements with surface, airborne, and balloon measurements where needed, as well as vicarious calibration
  - Detailed knowledge of underlying spectroscopy, radiative transfer, and retrieval algorithms, as well as intercomparisons among them where appropriate
  - Exchange of data among participants (both lower level and retrieved products)
  - Accuracy and consistency of ancillary data
  - Detailed analysis of data and use in quantitative scientific study and in assimilation/reanalysis
  - Periodic reprocessing of data as new knowledge is gained

The Programmatic Challenge

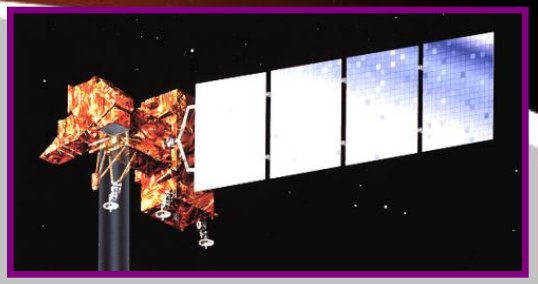
- A variety of investments are needed to support the development, maintenance, and enhancement of Earth System (climate) Data Records over multiple decades
  - The satellites that generate the data records, with significant focus on pre-launch and in-flight calibration, with gaps avoided or minimized
  - Satellite operations that “nurture” the operations to maximize duration, data collection, and data quality
  - Support for mission/instrument science teams that generate products, carry out initial validation, and make available to community, with ability to reprocess data as critical component
  - Support for ground networks, airborne capability (platforms, sensors, systems, people), and, where appropriate, “calibration offices” to support algorithm testing, calibration/validation activities, and intercomparison
  - Support for competed science teams and investigations that utilize data and develop alternative and additional products for individual missions (current and past), as well as for multi-instrument/multi-platform data records and to intercompare data from multiple providers
  - Institutional arrangements to allow for multi-agency and multi-national cooperation
  - Support for data systems to make data available, including reprocessing capability, and tools to facilitate use of data by multiple communities


NASA Earth Observing
Satellite Fleet - 2012
Launch-CY2011
Launch-CY2012
Launch-CY2013
Aquarius
OSTM/Jason 2 (NOAA)
Jason
QuikSCAT*
TRMM
EO-1
Landsat-7 (USGS)
Aqua
ACRIMSAT
Terra
SORCE
LDCM
GRACE (2)
Aura
CALIPSO
CloudSat
Suomi-NPP

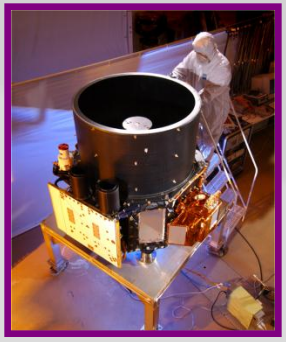
Missions in Formulation and Implementation

AQUARIUS
6/10/2011
w/CONAE; SSS

NPP
10/28/2011
w/NOAA
EOS cont., Op Met.



LDCM
1/2013
w/USGS; TIRS



ICESat-2
April 2016
Ice Dynamics

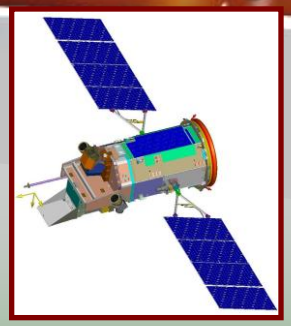
SMAP*
Oct 2014
w/CSA
Soil Moist., Frz/Thaw

GPM
Feb 2014
w/ JAXA; Precip

OCO-2
2014
Global CO_2

ESD Missions thru 2020

SAGE III
2014



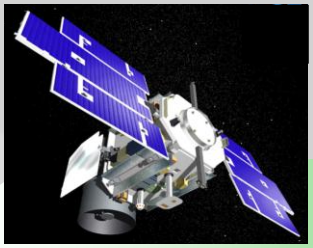
GRACE FO
2017

Phase A

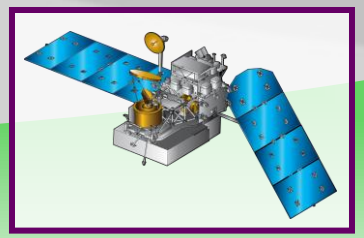
CYGNSS(EV-)2
2017

L-Band SAR
TBD

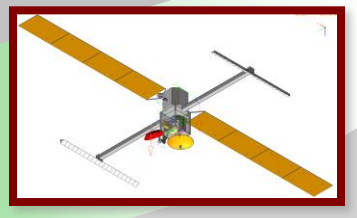
All others pre-formulation, or Pre Phase A



ASCENDS
NET 2020



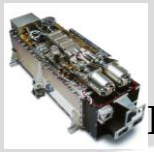
PACE
2019



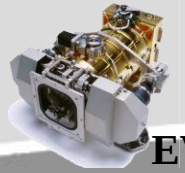
SWOT
2019

Instrument
Developments

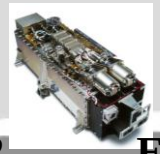
EV-I4
~2020



EV-I3
~2019



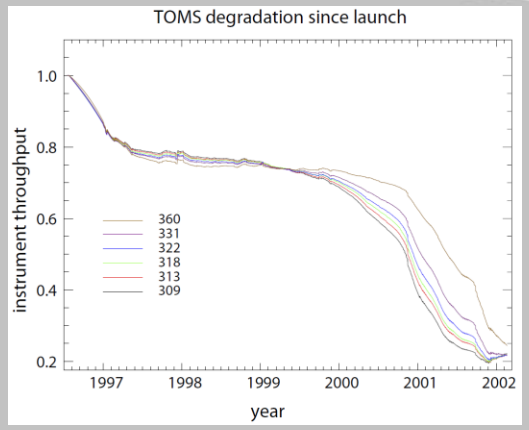
EV-I2
~2018



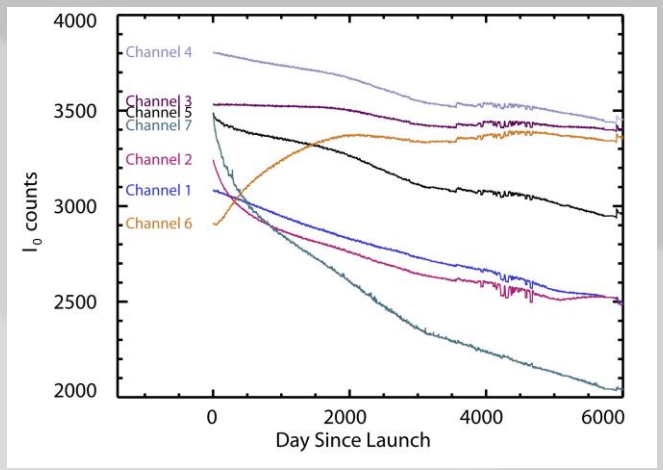
EV-I1
~2017

Instrument Calibration Challenges

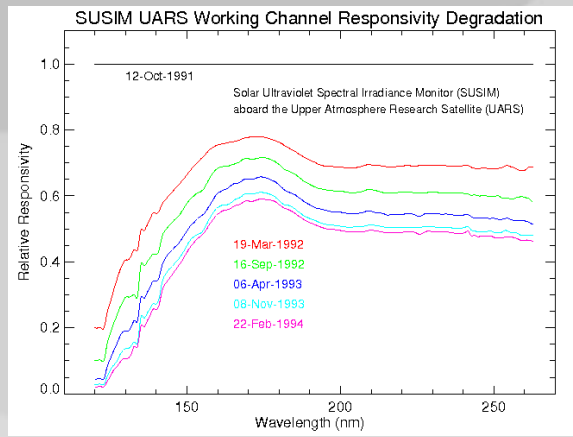
Scan mirror degradation on Earth Probe TOMS



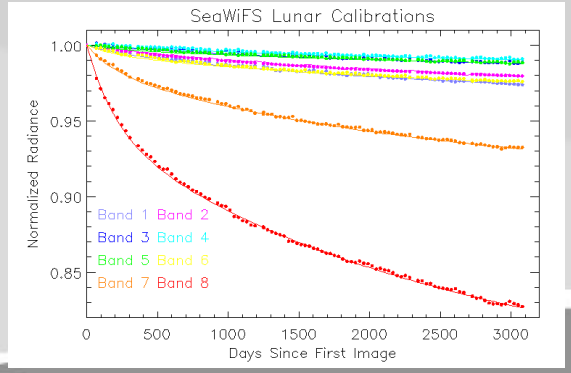
SAGE II Instrument Response Function



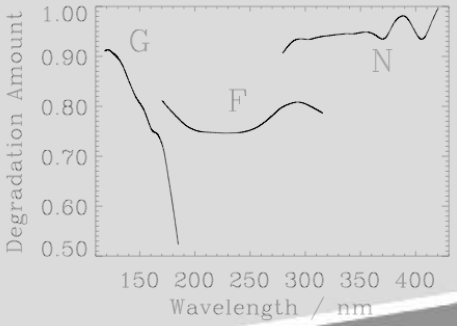
UARS SUSIM Working Channel Responsivity Degradation



SeaWiFS Degradation



UARS SOLSTICE degradation over 3 years

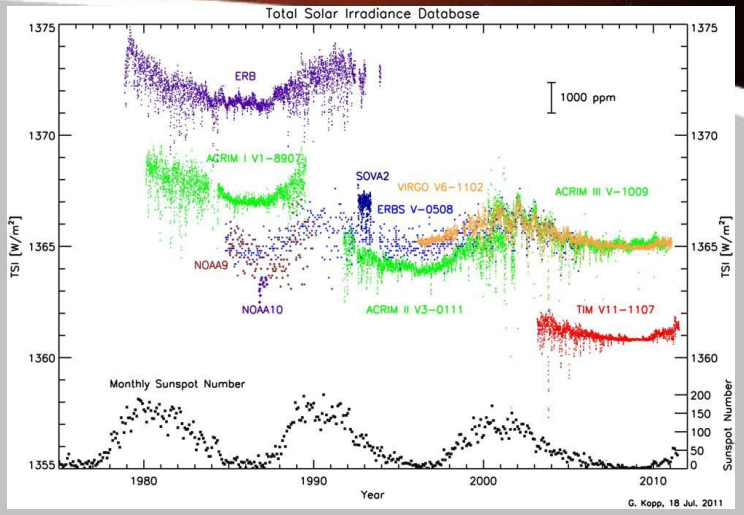


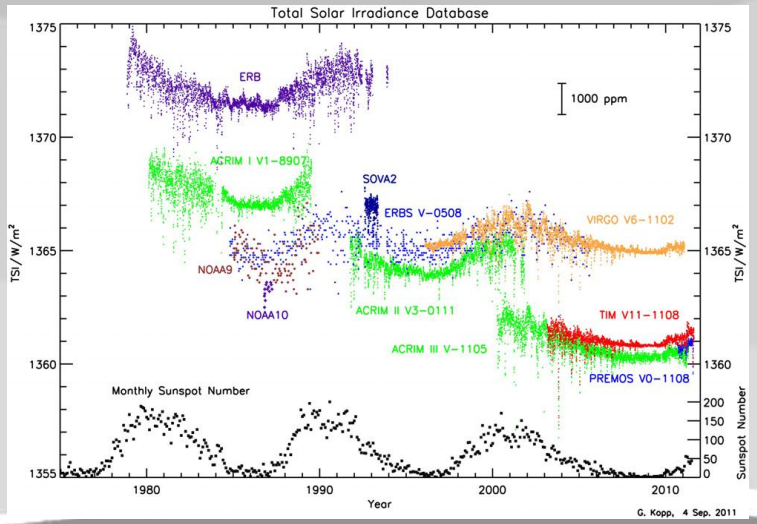
Role of Internal Instrument Optical Scatter in the Measurement of Total Solar Irradiance: a Calibration Success Story

- Using the TSI Radiometer Facility (TRF) at the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP), the TSI measurements of ground-based representative instruments for ACRIM III, SORCE/TIM, SoHO/VIRGO, and the flight and ground PICARD/PREMOS instruments were validated in vacuum at requisite TSI uncertainty levels.

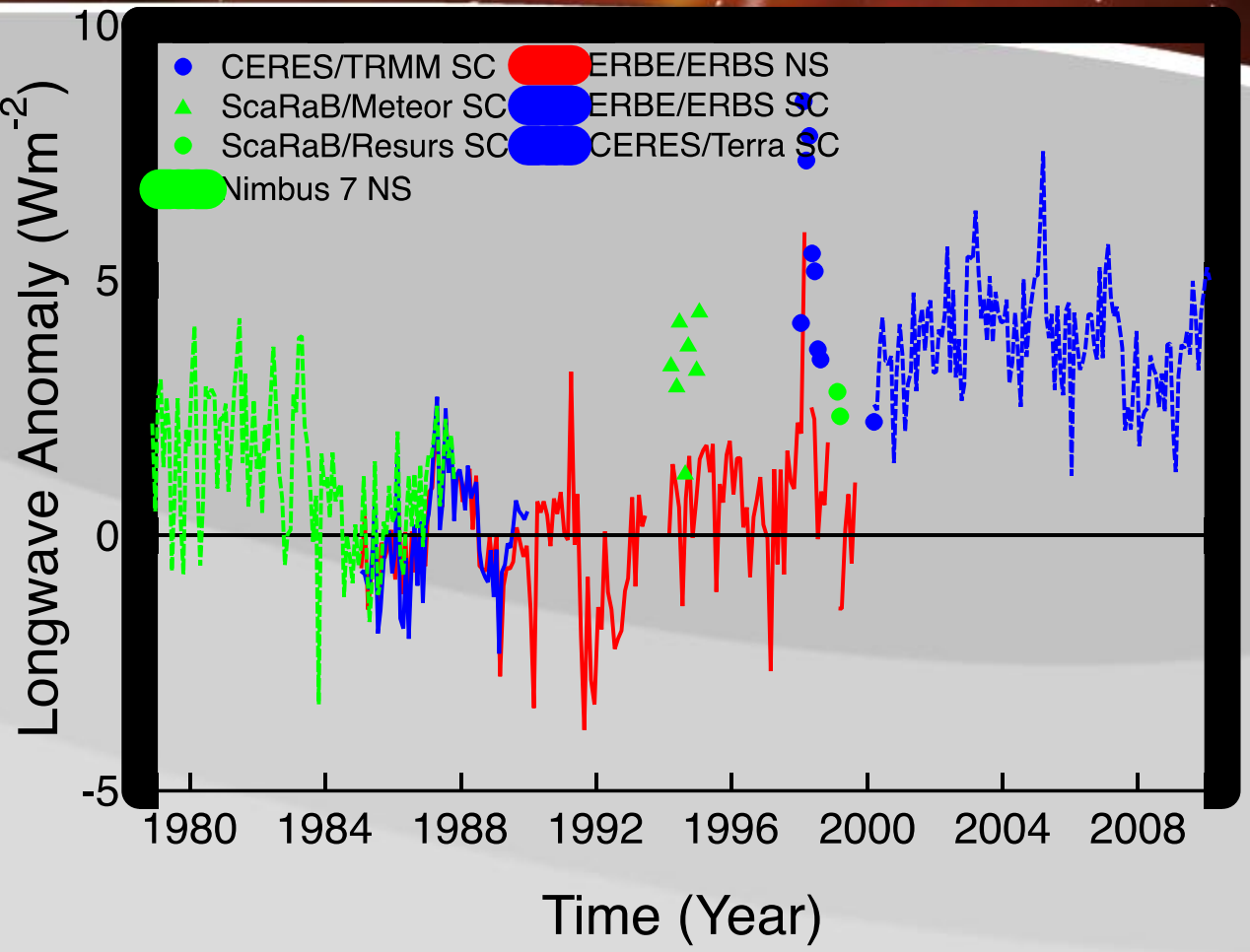
- The ~4 Watt/m^2 difference in the top plot of the historical total solar irradiance data record has been found to be principally caused by scattering and diffraction within certain sensors.

-The ACRIM III and PREMOS TSI data records corrected for scatter and diffraction as measured in the TRF are shown in the bottom plot.



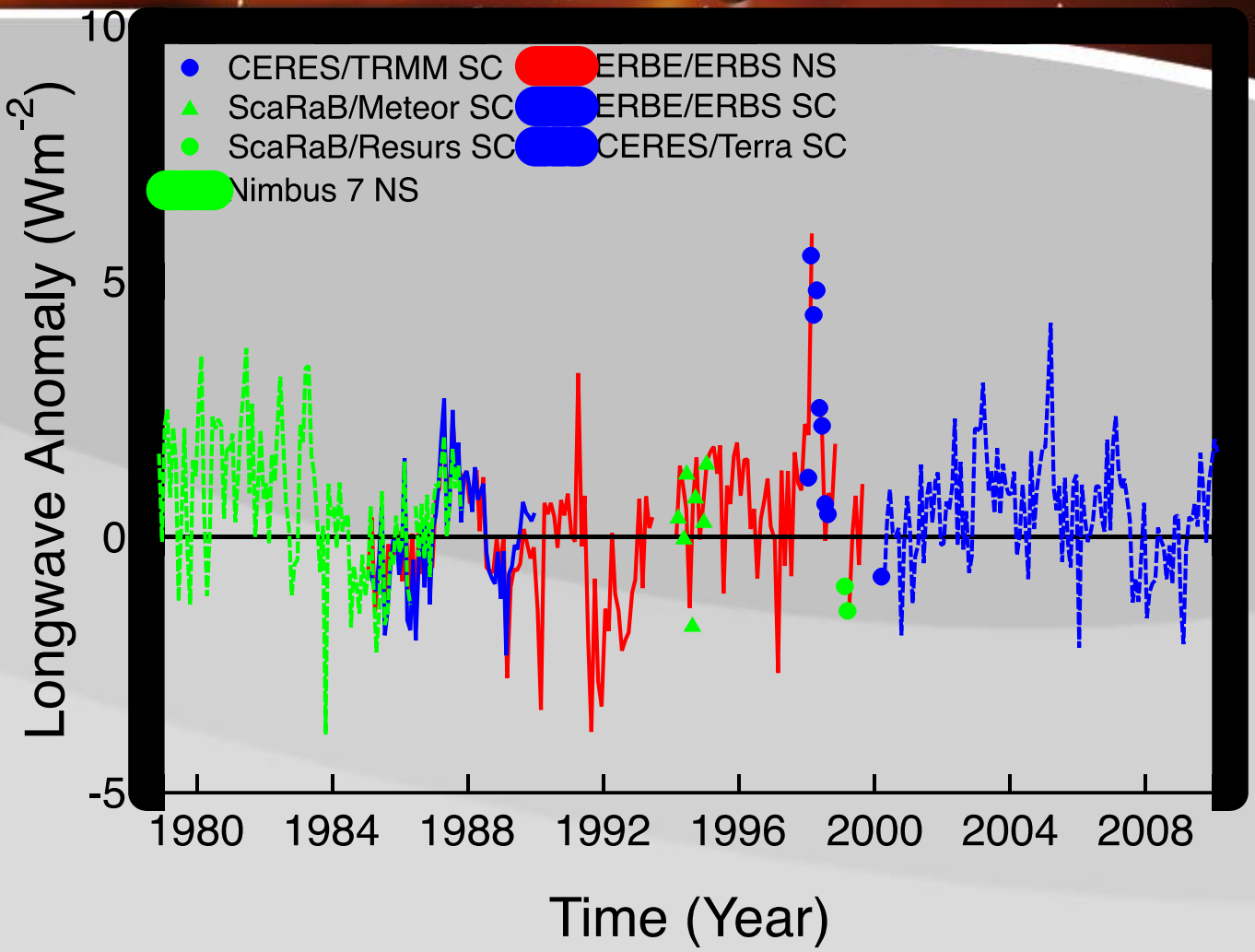


Tropical Mean Outgoing Longwave Radiation (Without Overlap Bias Correction)



Absolute calibration accuracy of current sensors is insufficient to bride data gaps. Overlap is needed to correct for calibration differences between successive instruments.

Tropical Mean Outgoing Longwave Radiation (With Overlap Bias Correction)



With overlapping data, calibration "jumps" can be removed through a simple bias correction.

NASA Support for ESDRs Historically Strong

- NASA institutionalized support for Earth Science Data Records (and Climate Data Records) in the EOS Program, and has continued support via multiple programs in Earth Science for generating and integrating data for science and applications.
  - EOS Pathfinder Data Set program, originally joint with NOAA (POES/GOES) and USGS (Landsat) 1991 - 1995
  - NASA Pathfinder Data Sets 1995-1997
  - Earth Science Information Partners (ESIPs), included research, education, and applications 1998-2002
  - Research, Education and Applications Solution Network (REASoN) 2002-2006
  - Making Earth System data records for Use in Research Environments (MEaSUREs) 2007-2011 (recompeted in 2012)
  - Earth System Data Records Uncertainty Analysis (est. 2011)

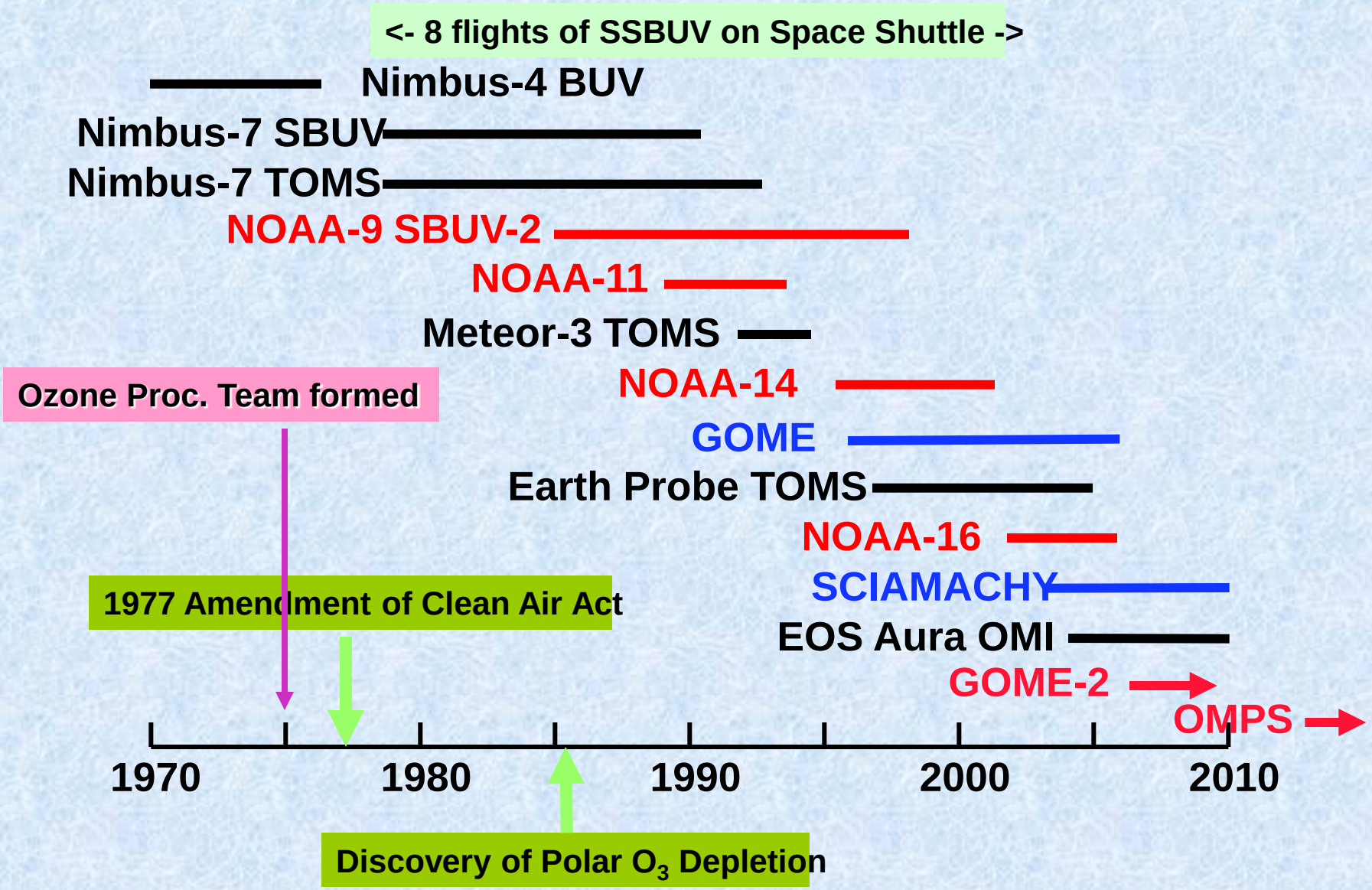
Earth System Data Records Uncertainty Analysis

- New ROSES element in 2011 to extend and enhance the use of Earth System Data Records through rigorous estimation of error in ESDRs used by NASA communities. Projects selected will increase the science value of Earth System science measurements by identifying and validating systematic errors and improving error estimations. Proposals selected should
  - Provide in-depth analysis of the properties of long-term data sets, with a focus on detecting systematic error, better quantifying error, and properly attributing uncertainty sources
  - Seek to resolve known issues of such data sets, utilizing advanced algorithms, techniques, and technologies that advance understanding of uncertainties in Earth system science measurements
  - Seek to develop tools that facilitate production and use of these data sets
- 21 projects were selected (mostly for 3 years)

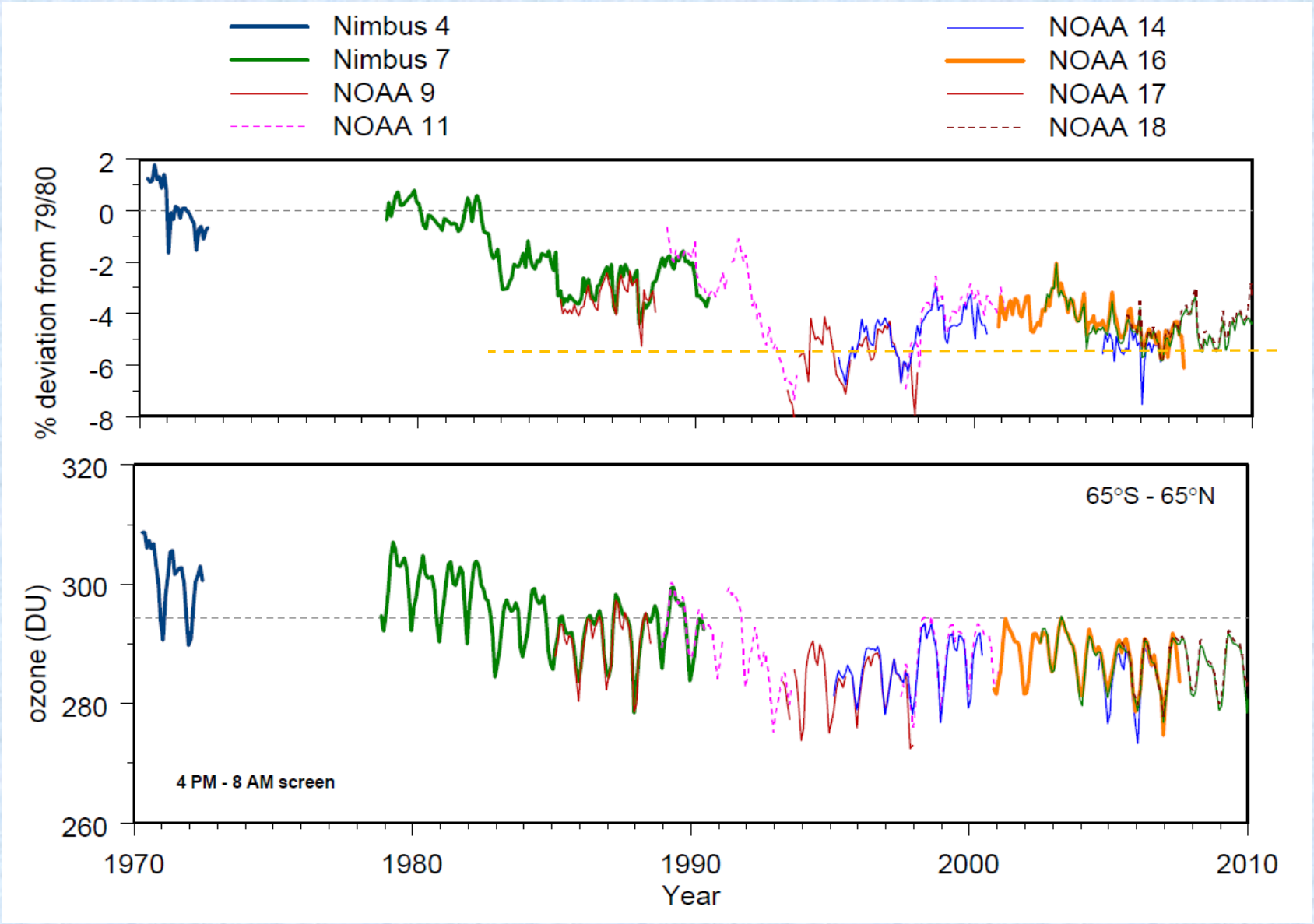
NASA Solicitation: Satellite Calibration Interconsistency Studies

- NASA solicited for proposals to address intercalibration of satellites – specifically emphasizing NASA and non-NASA satellites
  - "This solicitation provides an opportunity for the research community to participate in the quantitative comparison of multiple satellite data products to facilitate the development of multi-instrument/multi-platform data sets involving satellites from multiple providers."
- The scope of research solicited includes:
  - A broad range of techniques for intercomparisons, such as simultaneous nadir overpass, trajectory mapping, and comparison with non-space dat.
  - Issues related to footprint size mismatch, spectral band mismatch and temporal and spatial sampling
  - Proposals responsive to this call MUST address interconsistency issues of two or more satellites, at least one of which must be one currently supported through NASA's Earth Science Program, and at least one of which must be supported by some other organization (U.S. or foreign).
- Selected 12 of 41 proposals covering a range of combinations such as
  - Aquarius/SMOS
  - AIRS/IASI
  - AIRS/HIRS

40 Years of BUV Observations



% Deviation in Column Ozone from 1979 / 1980



From P. Bhartia, NASA/GSFC

Different instruments consistent to better than 1%

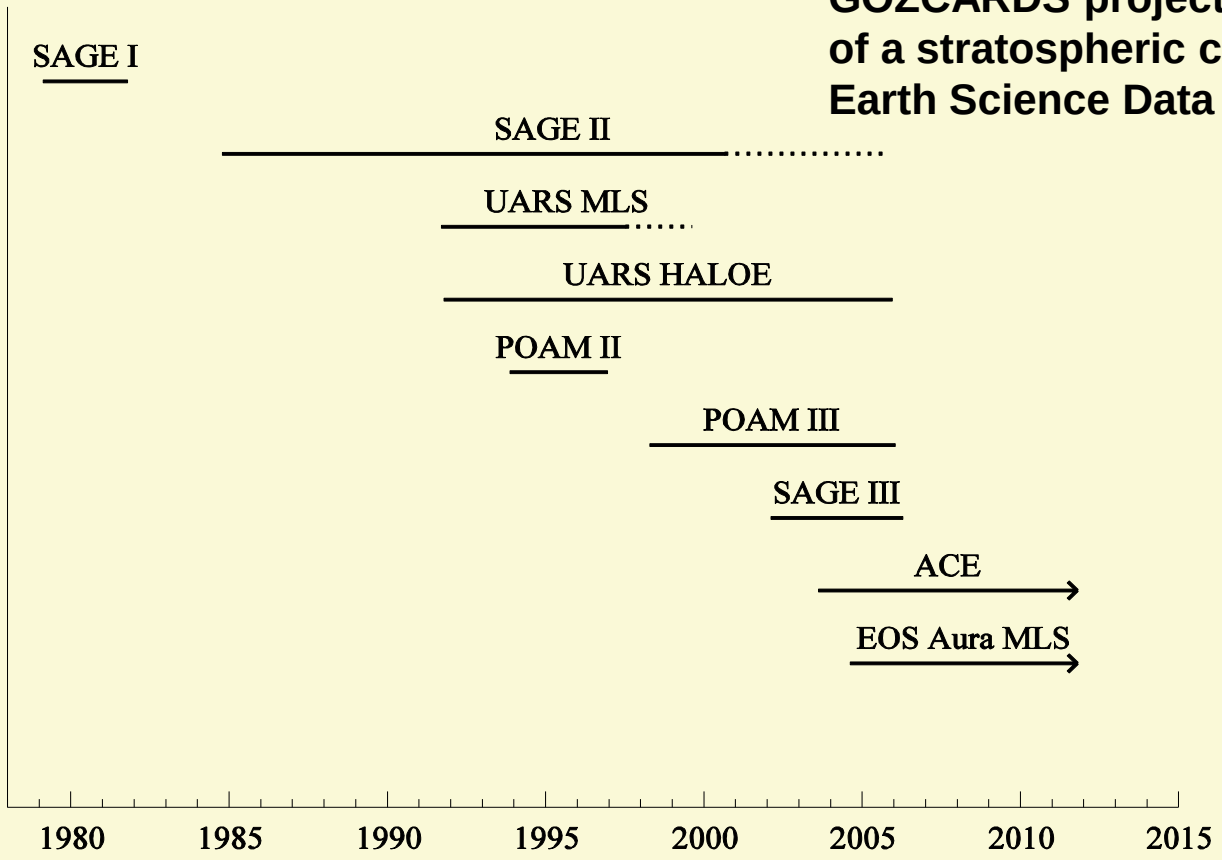
Status of TOMS Algorithm

- Current algorithm is about 10 years old
- New algorithm (V9) is current under development
  - Cross-calibrated to SBUV
  - Brion et al. O_3 abs cross-section
  - Cloud optical centroid pressure climatology from OMI
  - Retrieve O_3 profile in Umkehr layers by optimal estimation using 3 wavelenghs; sum to get total O_3; provide error estimates and smoothing kernels.
  - Simpler correction for aerosols and clouds; badly contaminated data will be flagged

GOZCARDS: Global OZone Chemistry And Related trace gas Data records for the Stratosphere

MEaSUREs: Making Earth Science data records for Use in Research Environments

Timeline of satellite missions and instruments considered for the GOZCARDS project and the creation of a stratospheric composition Earth Science Data Record (ESDR).



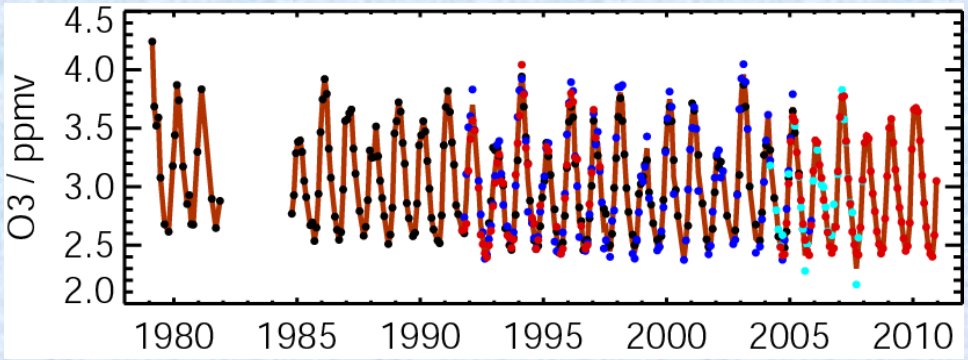
Update on GOZCARDS:
Lucien Froidevaux et al.

MEaSUREs GOZCARDS:

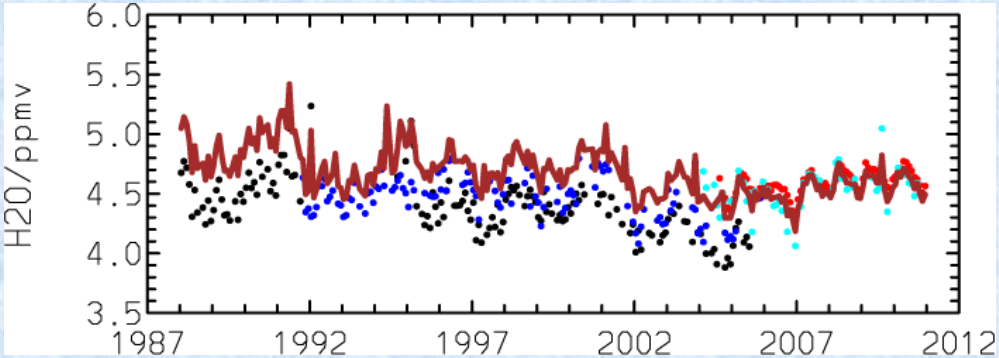
This project's goal is to produce long-term global time series (ESDRs) for ozone & other gas profiles by joining/merging various satellite data – see examples below (test datasets, not quite finalized)

Ozone (O_3) and water vapor (H_2O)

Ozone (46 hPa, 40˚N - 50˚N)

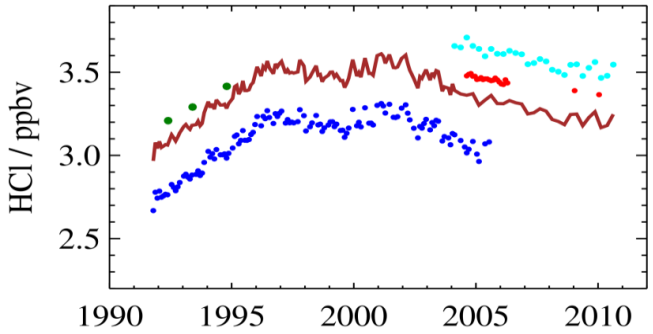


Water Vapor (46 hPa, 40˚N - 50˚N)

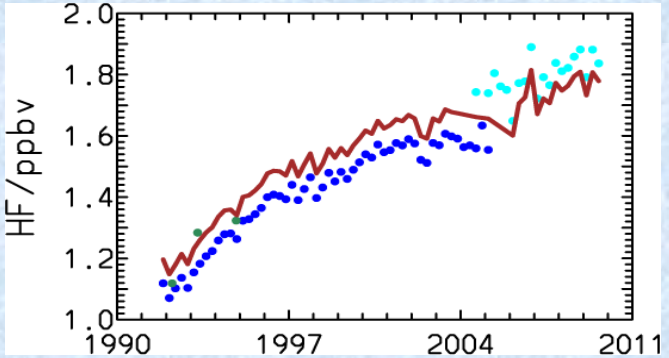


Stratospheric reservoir gases HCl and HF (from CFC emissions)

Global HCl (0.5 hPa)



Global HF (1 hPa)



Data: SAGE I & SAGE II, HALOE, MLS (UARS & Aura), ACE-FTS, ATMOS + merged data

Update on GOZCARDS: Lucien Froidevaux et al.

A 25-Year Stratospheric Aerosol Record based on SAGE II and CALIPSO

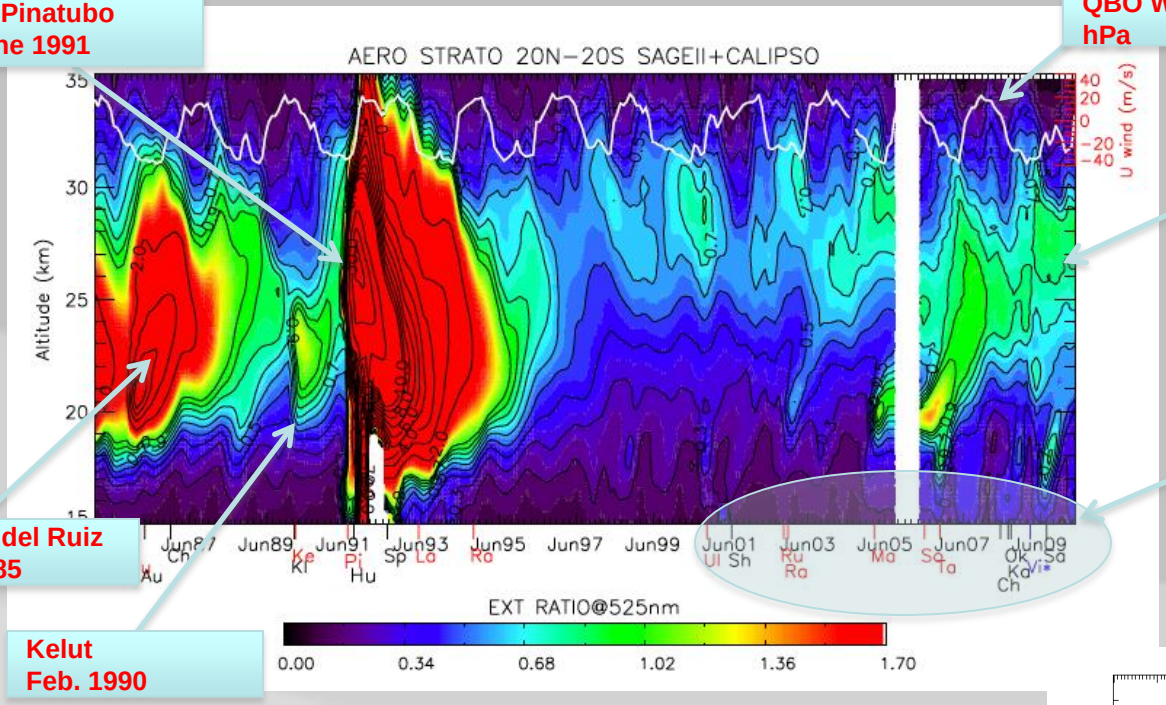
Mt Pinatubo June 1991

QBO Wind 10 hPa

CALIPSO Backscatter converted to extinction with a lidar ratio of 50 sr-1

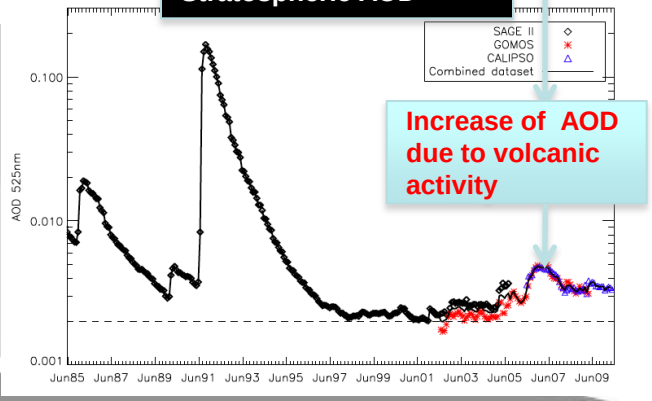
Nevado del Ruiz Nov. 1985

Kelut Feb. 1990



The 2000s had a number of moderate volcanic events including Ruang (2002), Manam (2005), Montserrat (2006), and Sarychev (2009)

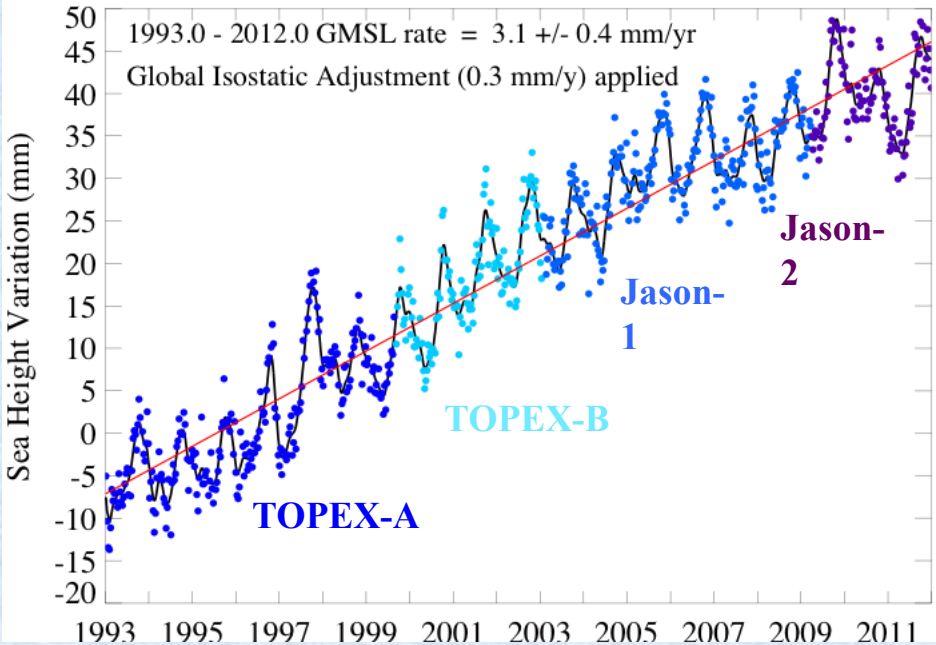
Stratospheric AOD



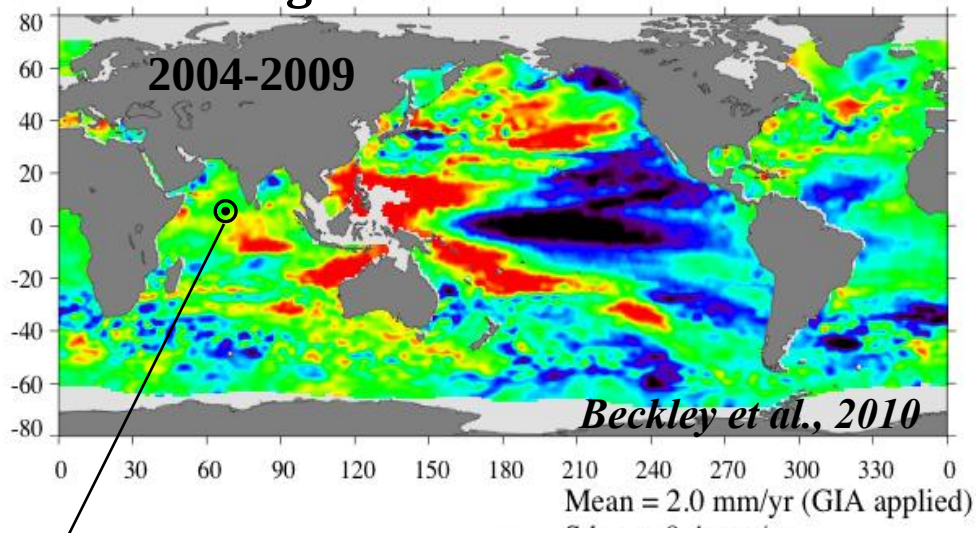
Increase of AOD due to volcanic activity

The combined record is critical in assessing the source of change in aerosol levels and inferring the impact of stratospheric aerosol on the climate and stratospheric chemistry. The increase noted over the last ten years is primarily volcanic in origin (Vernier et al., submitted GRL 2011b) and is likely producing a "global warming slow down" as suggested by Solomon et al.,2011, Science, submitted April 2011.

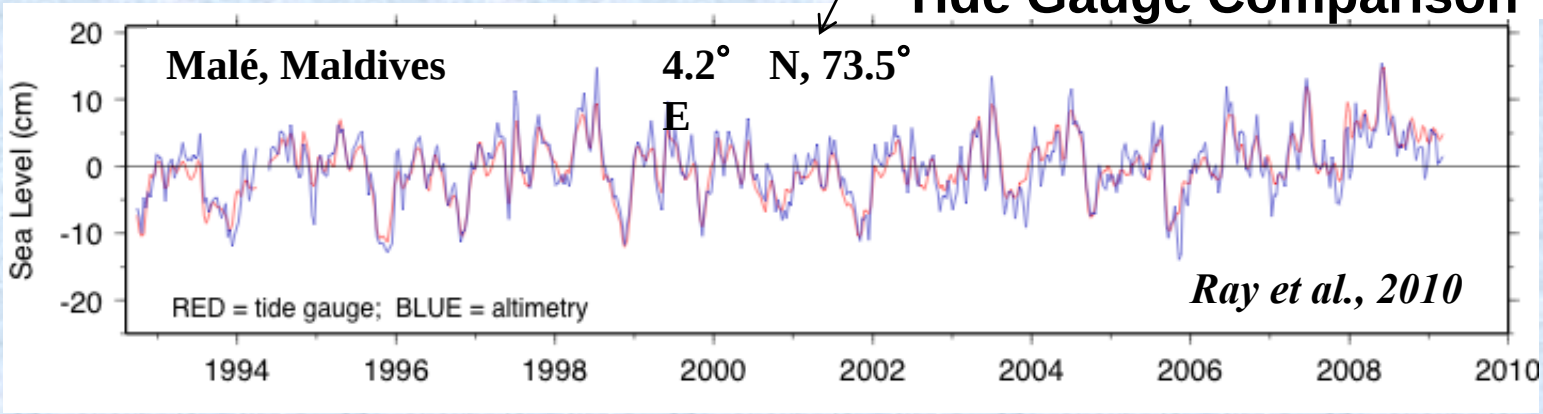
Global Mean Sea Level Estimation



Jason-1 Regional Mean Sea Level Rates



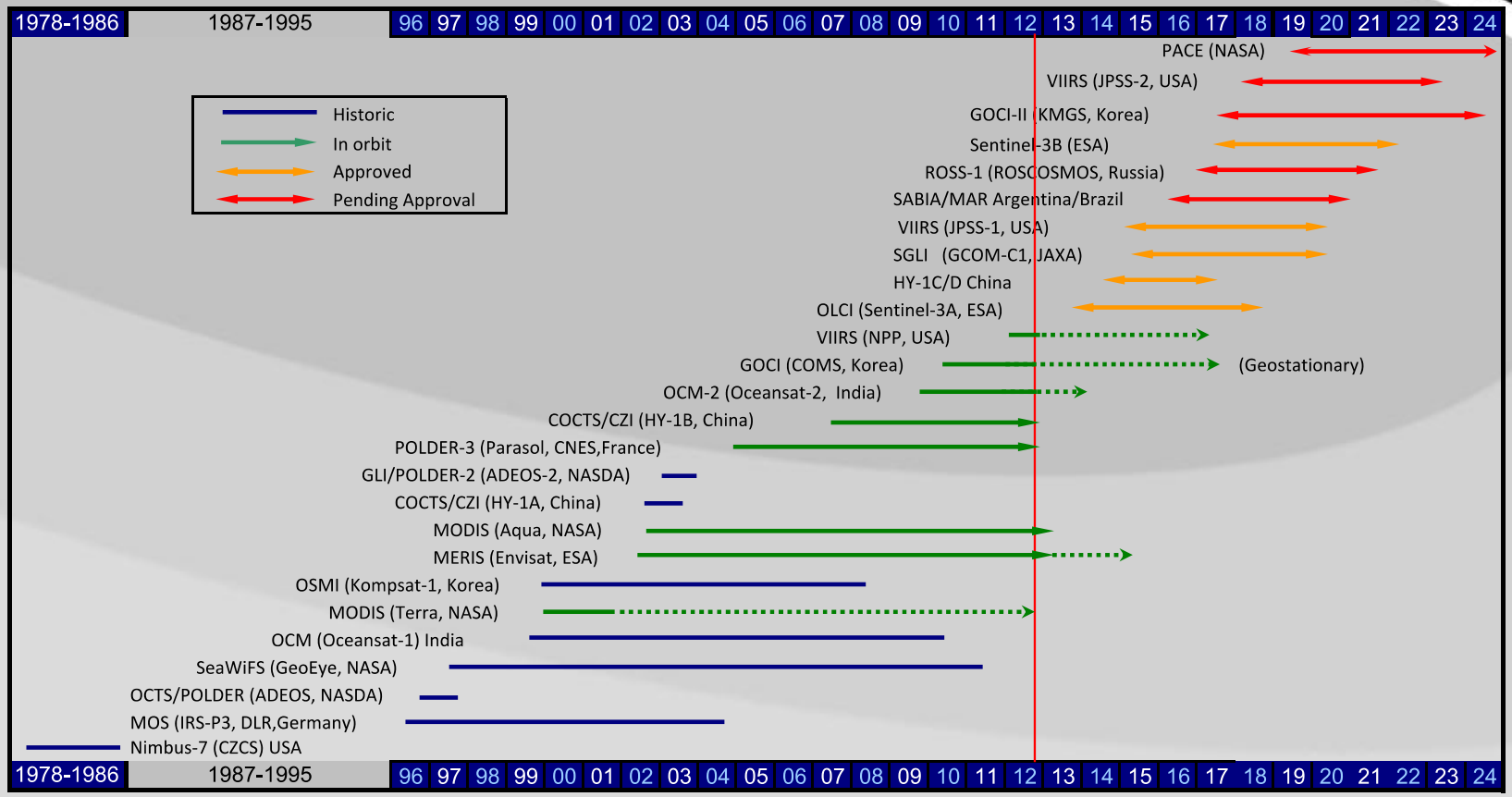
Tide Gauge Comparison

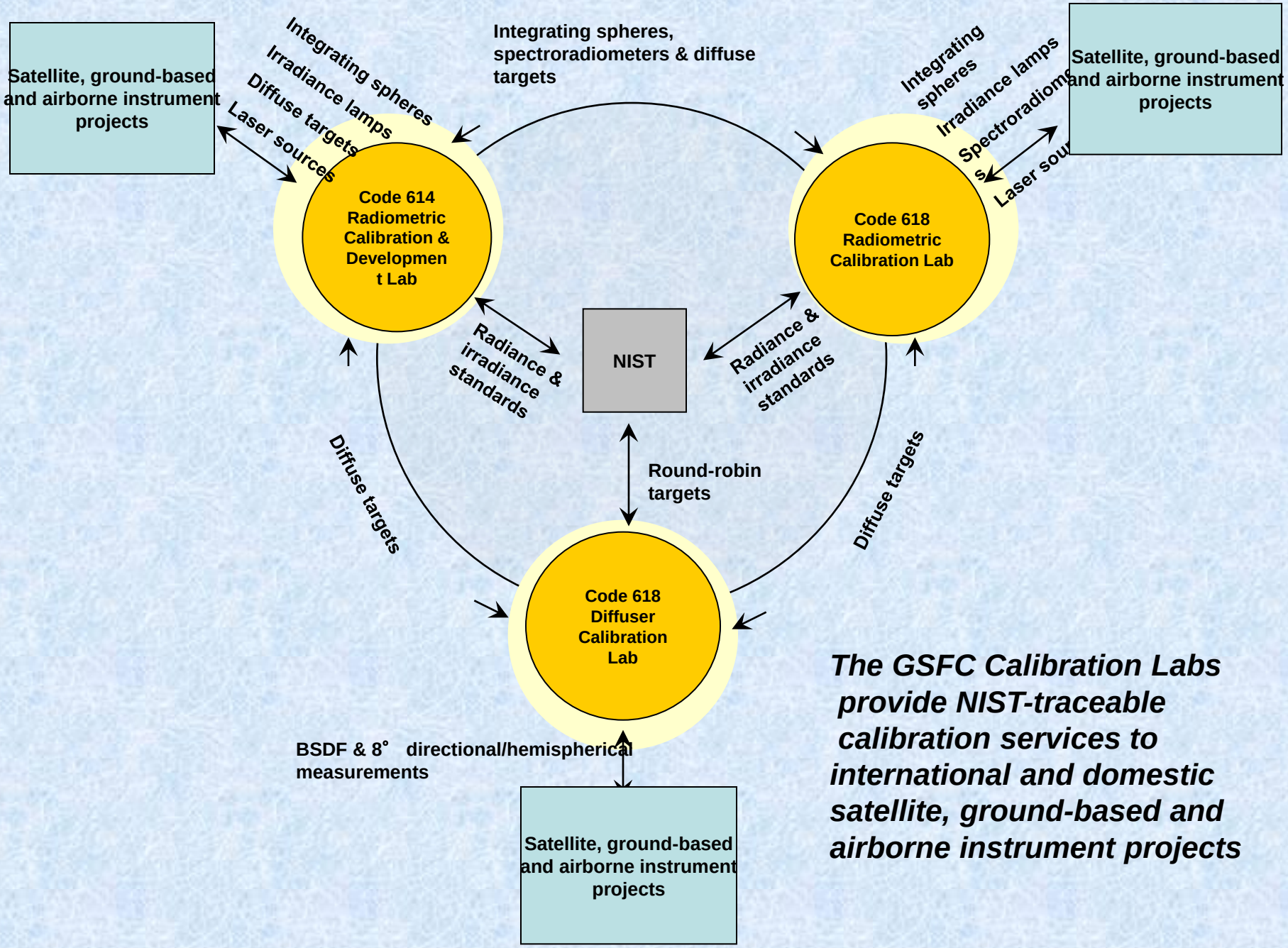


✓MEaSUREs Sea Surface Height Climate Data Record (CDR).
TOPEX/Poseidon, Jason-1&2 primary mission data (Sep. 1992 – present)
http://podaac.jpl.nasa.gov/highlights/MEaSUREs_TPJAOSv1.0_SSH

✓Future Work Plan – extending and maintaining dataset fidelity in anticipation of Jason-3. Applying standards to GEOSAT/GFO and ERS-1&2/EnviSat.

Timeline of Satellite Observations for Ocean Color

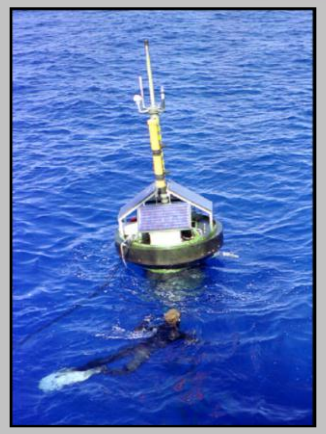


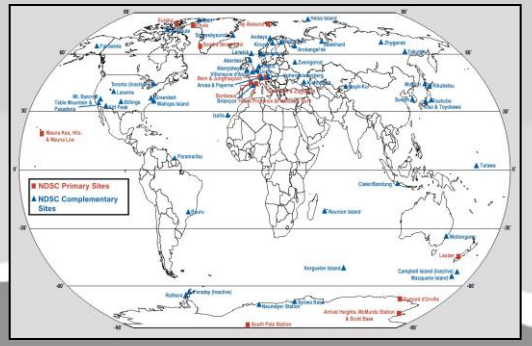


The GSFC Calibration Labs provide NIST-traceable calibration services to international and domestic satellite, ground-based and airborne instrument projects

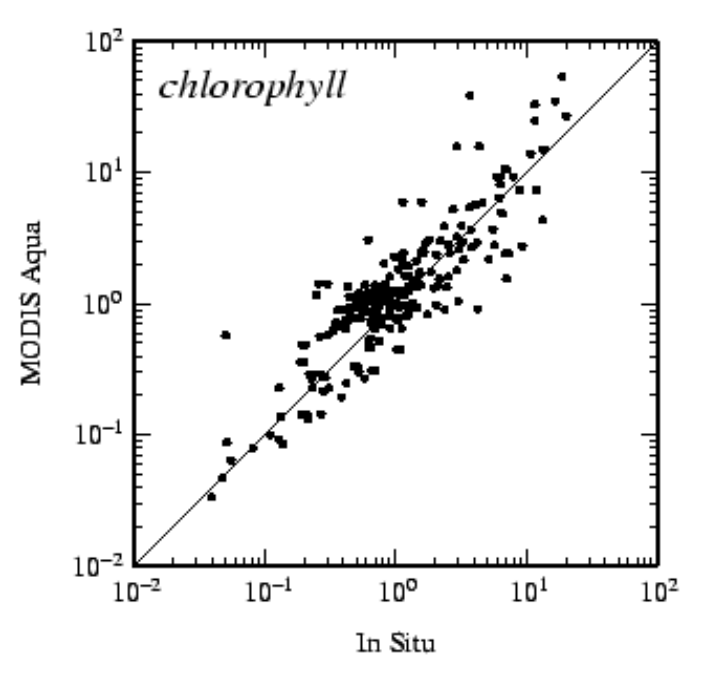
Post Launch Validation

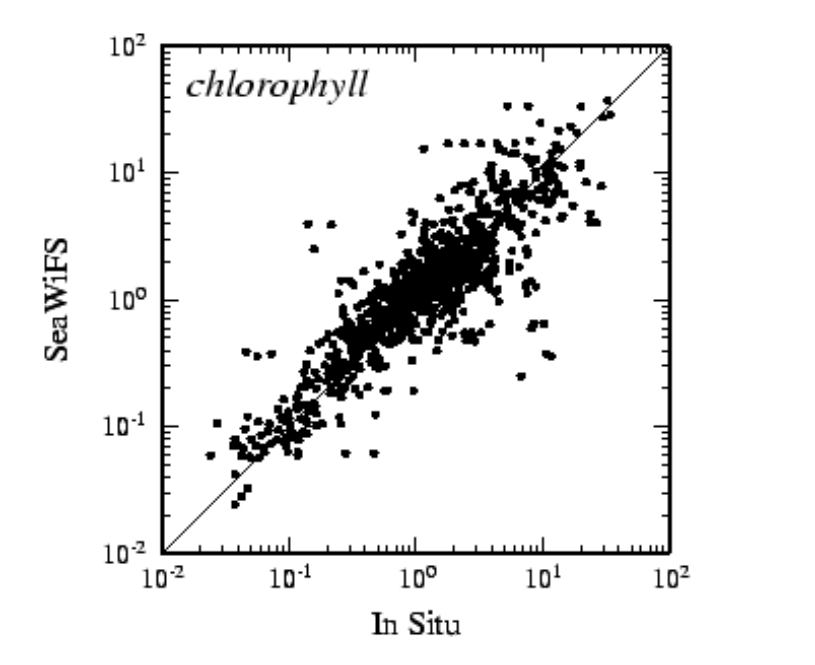
- NASA employs multiple assets for validation
- A major component of mission with allocated resources for conducting and analyzing validation data
- Collaboration with National and International partners is essential for success





MODIS/Aqua & SeaWiFS Chlorophyll Validation
Satellite vs. In Situ Observations



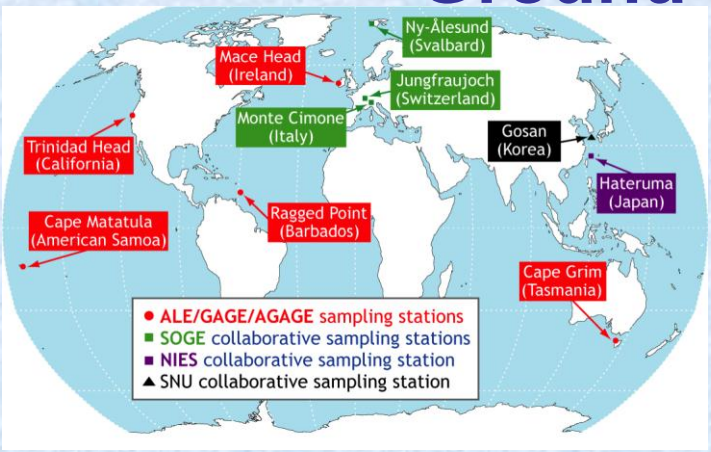


In Situ Statistics:
- # Observations = 263
- Range: 0.03-38 mg/m^3
- Median ratio: 1.08 (satellite/in situ)
- Median abs. % diff: 40.4%

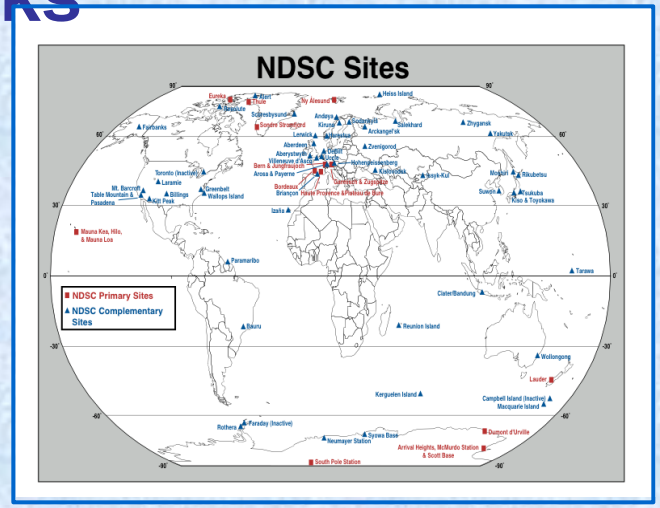
In Situ Statistics:
- # Observations = 1293
- Range: 0.024-30.2 mg/m^3
- Median ratio: 0.998 (satellite/in situ)
- Median abs. % diff: 26%

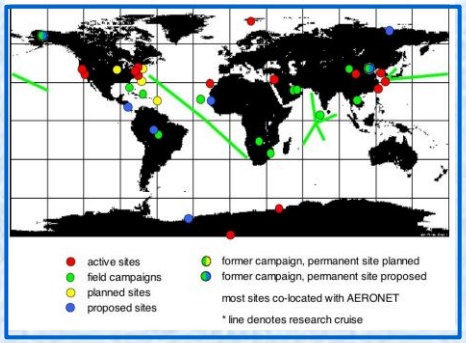
Examples of NASA-Supported International Ground Networks

AGAGE

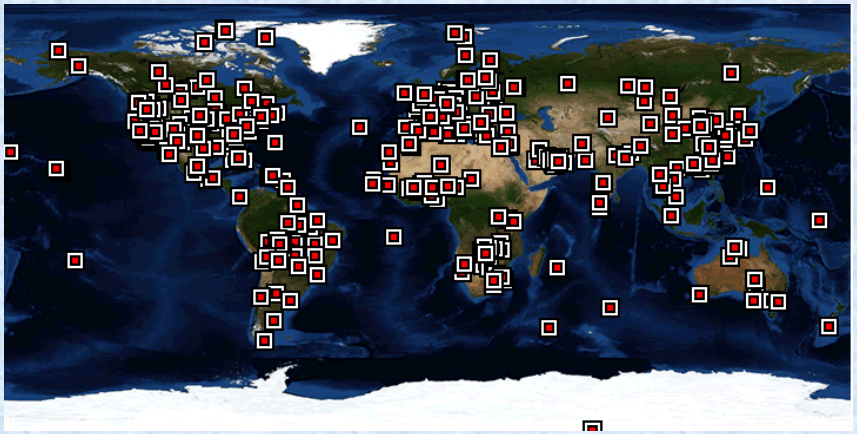


NDACC

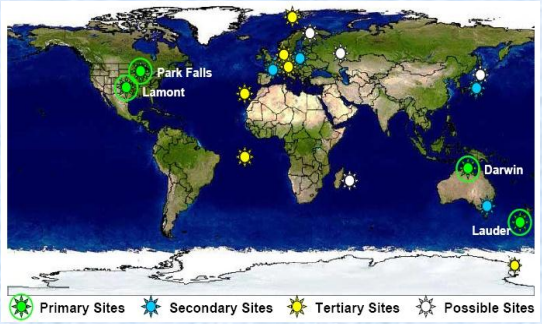




AERONET

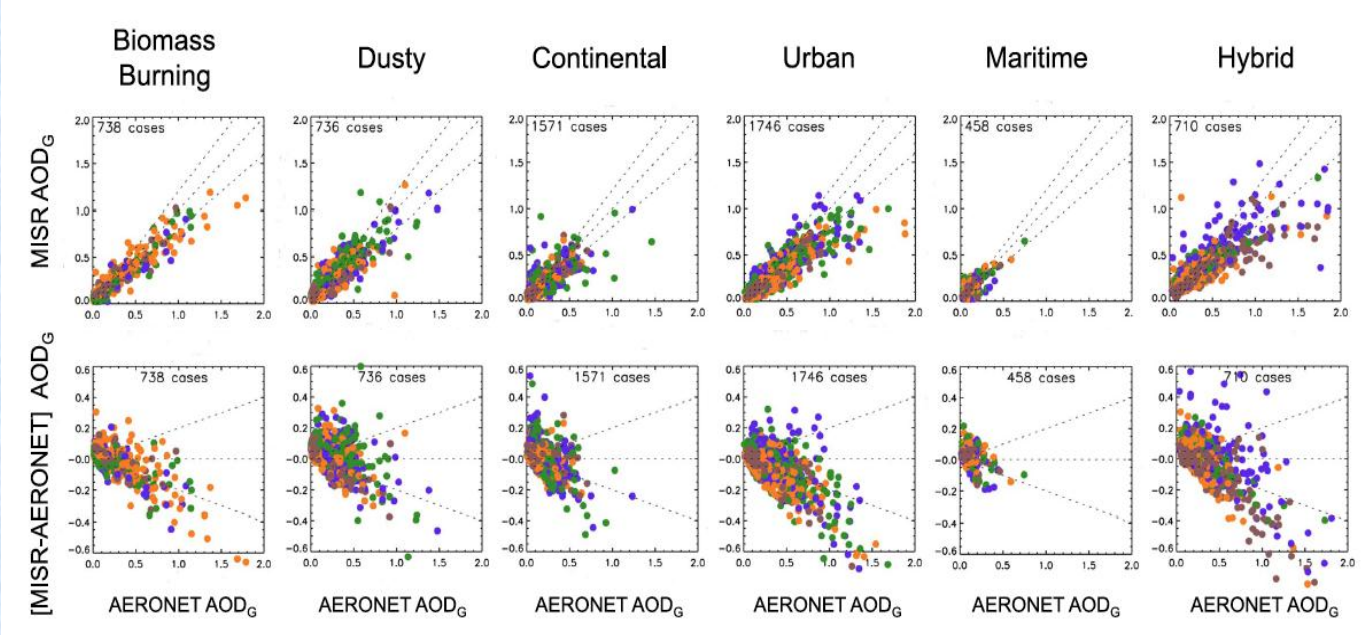


MPLNet



TCCON

The Use of AERONET to Validate MISR AOD



Scatter plots

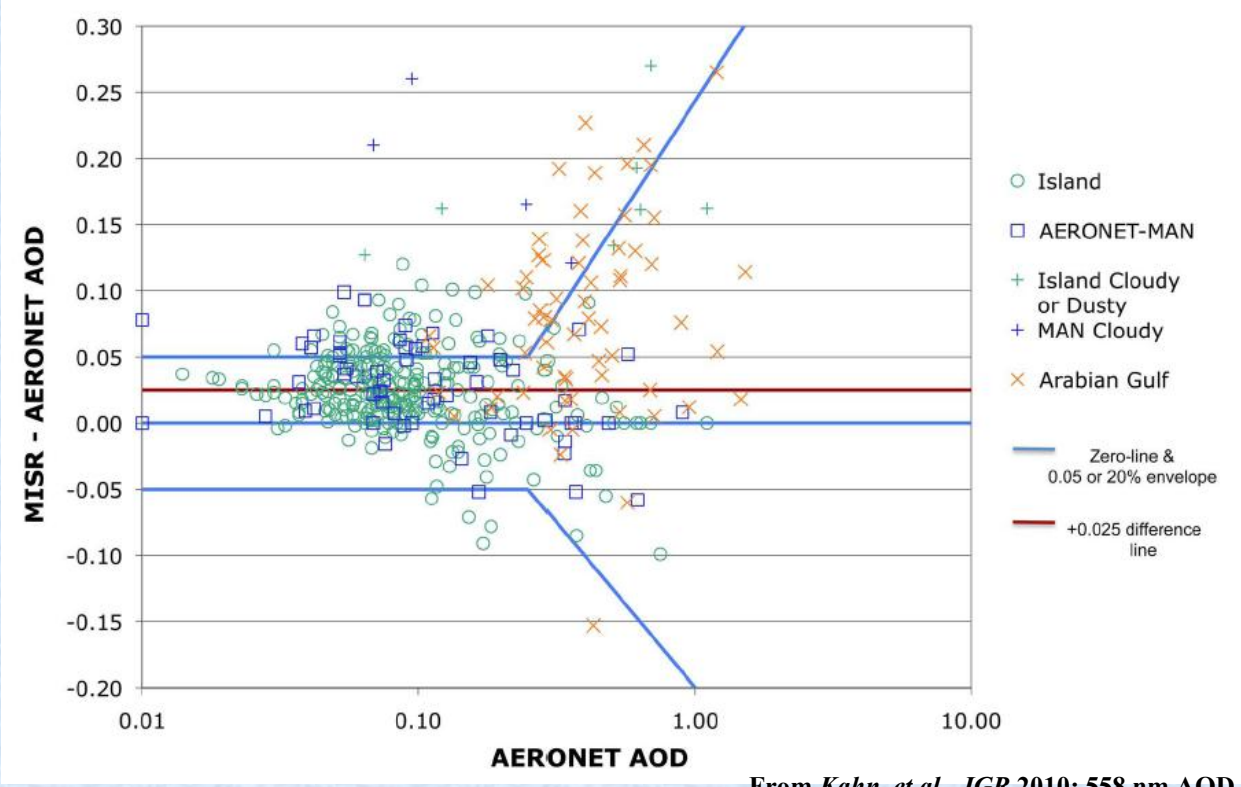
Difference plots

From *Kahn, et al.*, *JGR* 2010; 558 nm AOD

- *Statistical*, as well as case-by-case validation of spectral aerosol optical depth
- *5,156*, MISR-AERONET coincidences, at 81 sites, over eight years
- Enough data to *stratify* into six groups based on dominant aerosol air mass type
- Coincidence defined as:
  - AERONET within ± 1 hour of MISR overpass
  - MISR retrieval over ~20 km and ~50 km regions containing the AERONET station
- Results show strengths and limitations of MISR AOD product

From Ralph Kahn, NASA/GSFC

The Use of ***AERONET-MAN*** to Validate MISR AOD Over Ocean

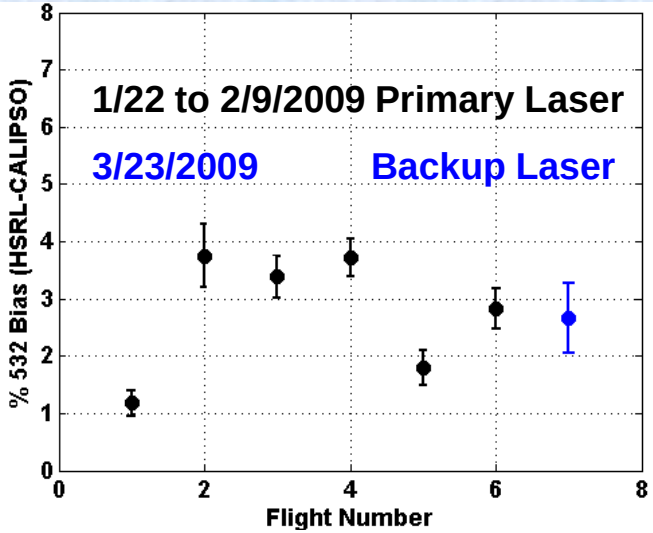


From *Kahn, et al.*, *JGR* 2010; 558 nm AOD

- Ship-based *Marine Aerosol Network* (MAN) + AERONET Island site coincidences
- *62 MAN* cases over *dark water*, along with 282 AERONET Island cases
- Provides best MISR statistical validation over large portion of the planet

From Ralph Kahn, NASA/GSFC

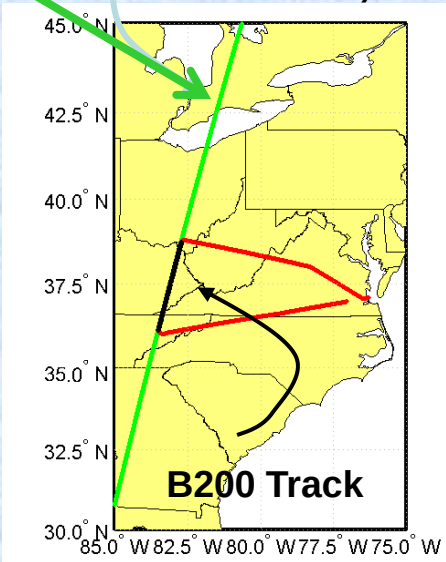
B200/HSRL Validation Flights Supporting CALIPSO Laser Switch

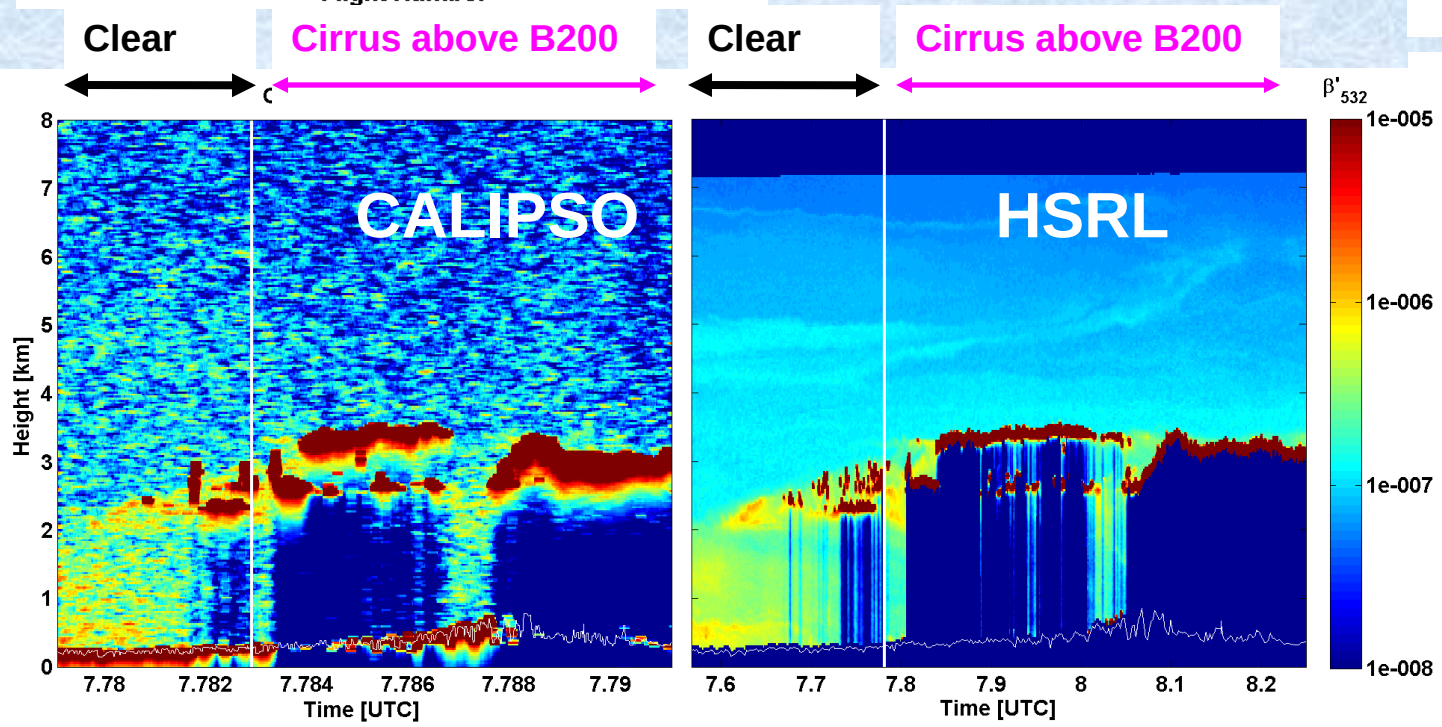


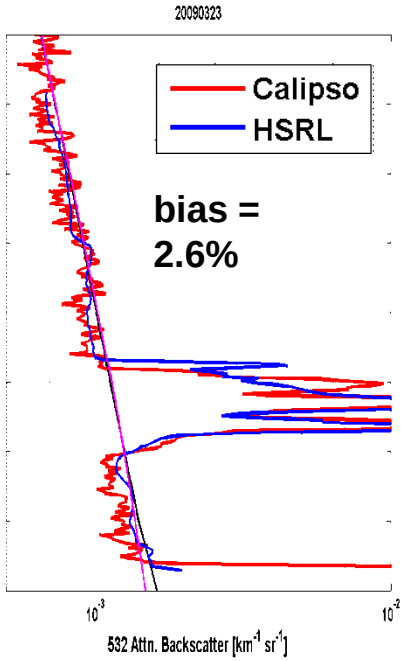
- First flight post-switch (3/23) shows good calibration.
- Bias consistent with primary laser calibration.

CALIPSO Track

March 23, 2009







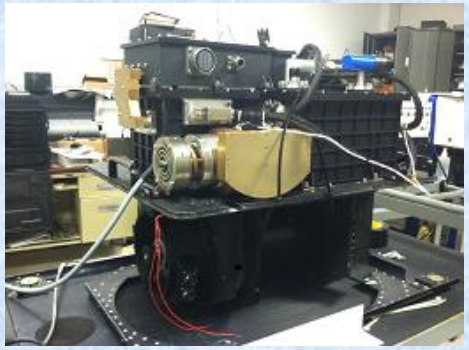
Enhanced MODIS Airborne Simulator

A next-generation airborne imager with high spatial resolution and broad hyper-spectral (VNIR/SWIR) and multi-spectral (MWIR-LWIR) coverage intended to:

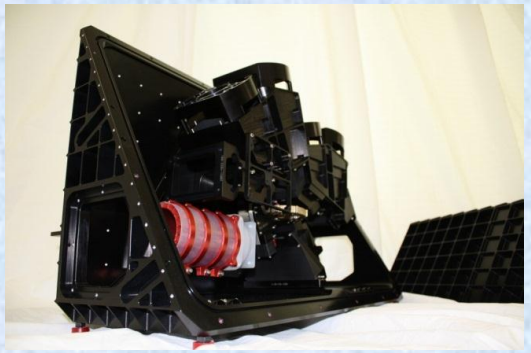
- Simulate existing satellite imager products (MODIS/VIIRS)
- Validate radiances and geophysical retrievals
  (emphasis on cloud and aerosol science)
- Prototype future imager requirements and algorithms (e.g., PACE, ACE)
- Contribute to a wide variety of NASA field studies

Consists of two bore-sighted imaging spectro-radiometers:

- eMAS-IR: 12 bands 6.7 – 13.9mm, plus 3.7mm (+ 25 legacy MAS V/SWIR bands)
- eMAS-HSI: 205 bands 400 – 2450nm



EMAS-IR



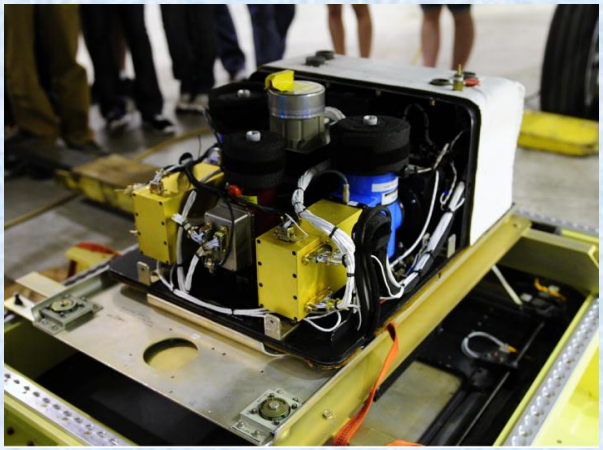
EMAS-HSI

MASTER: the MODIS/ASTER Airborne Simulator

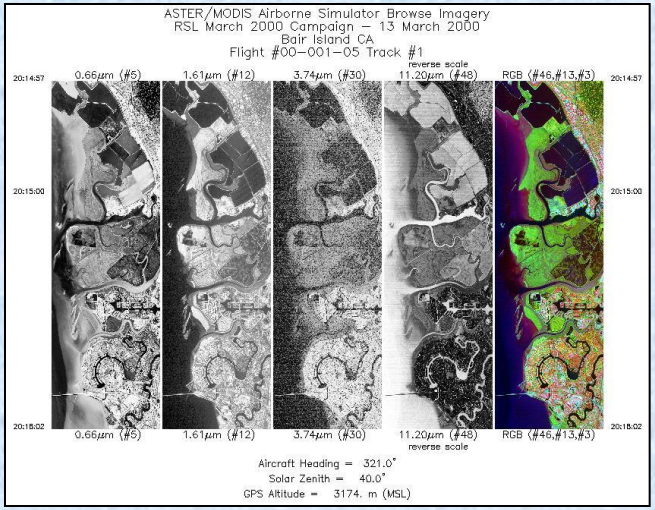
An airborne imager with high spatial resolution and broad multi-spectral (VNIR/SWIR MWIR-LWIR) coverage intended to:

- Simulate ASTER and MODIS satellite imager products
- Validate radiances and geophysical retrievals
  (emphasis on land-surface science)
- Prototype future imager requirements and algorithms (e.g., HyspIRI)
- Support a broad range of multi-disciplinary NASA process studies

Includes 50 spectral bands between 430nm and 13.1mm
Variable spatial resolutions from 3 – 50 meters (operates on multiple NASA platforms)



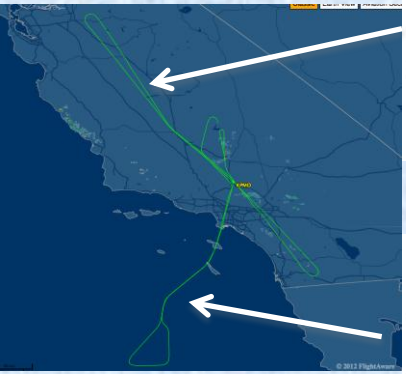
MASTER on DC-8 (SARP)

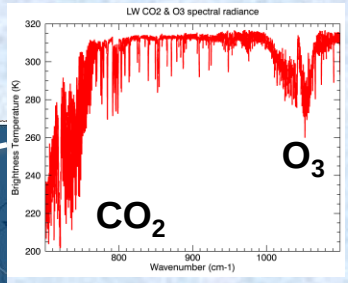


NAST-I re-qualified on ER-2 (20-21 June 2012)

- NAST-I piggybacked on NASA ER-2 flights out of Palmdale, CA on 20-21 June 2012, during CATS science flights
- The sensor needed re-qualification on the ER-2 subsequent to recent refurbishment activities and lack of flying on this platform
- The NAST-I team also needed to ensure optimum sensor performance on the ER-2 since it is intended to be the flight platform for the upcoming Suomi NPP calibration / validation flights (November 2012)
- Preliminary analysis shows all platform qualification and science performance objectives to have been satisfied

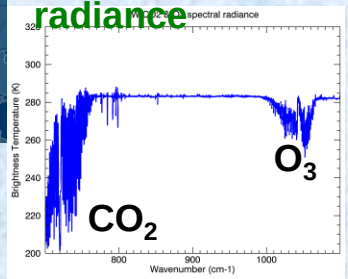
062012 ER-2 track





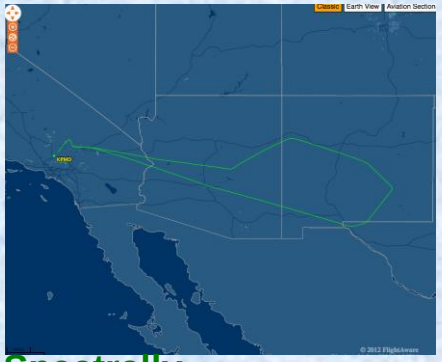
Warm land scene

LW band IR spectral radiance



Cool water scene

062112 ER-2 track

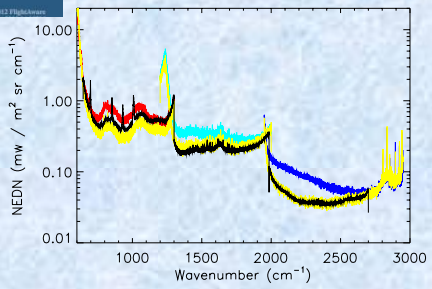


NAST-I noise performance similar to earlier flights

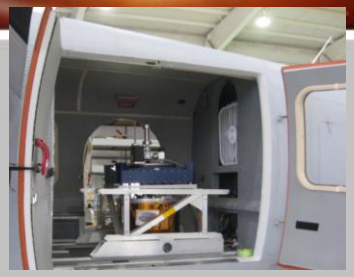
Spectrally uncorrelated noise estimates

062112

Baseline reference



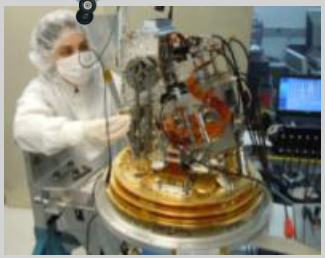
Technology Highlight:
Several New Instruments See First Airborne Flights



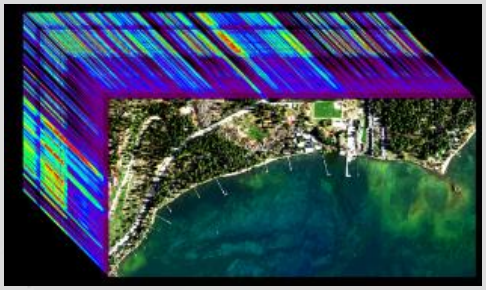
July 2012: the Hyperspectral Thermal Emission Spectrometer (HyTES) – an instrument that aims to provide high spatial and spectral resolution thermal land imaging data – was integrated and flown on a Twin Otter over Cuprite, NV, Nevada.
(PI: Simon Hook, JPL, IIP-07)

July 2012: the High Spectral Resolution Lidar (HSRL-2) is a new, capable HSRL instrument that was developed as a prototype for the lidar on the ACE mission concept. HSRL-2 flew on the NASA B200 as part of the DOE's Two-Column Aerosol Project (TCAP). HSRL-2 is also slated to participate in NASA's DISCOVER-AQ campaign in early 2013.
(PI: Chris Hostetler, NASA LaRC, IIP-04 / AITT-09)

July 2012: the Airborne Scanning Microwave Limb Sounder (A-SMLS) – a prototype of a next-generation MLS for measuring trace species in the upper troposphere – completed test flights near Houston, Texas, on the NASA WB-57. A-SMLS successfully acquired ozone measurements and can be configured for a variety of other trace species. (*PI: Paul Stek, JPL, IIP-07)*



April 2012: the next generation AVIRIS (Airborne Visible/Infrared Imaging Spectrometer), AVIRIS-NG – a new instrument developed to support NASA's Terrestrial Ecology Program – successfully completed its first flight onboard NASA's Twin Otter aircraft. The data AVIRIS-NG collects could be used as a precursor data-set for the HyspIRI mission.
(PI: Robert O. Green, JPL, ATI-09)

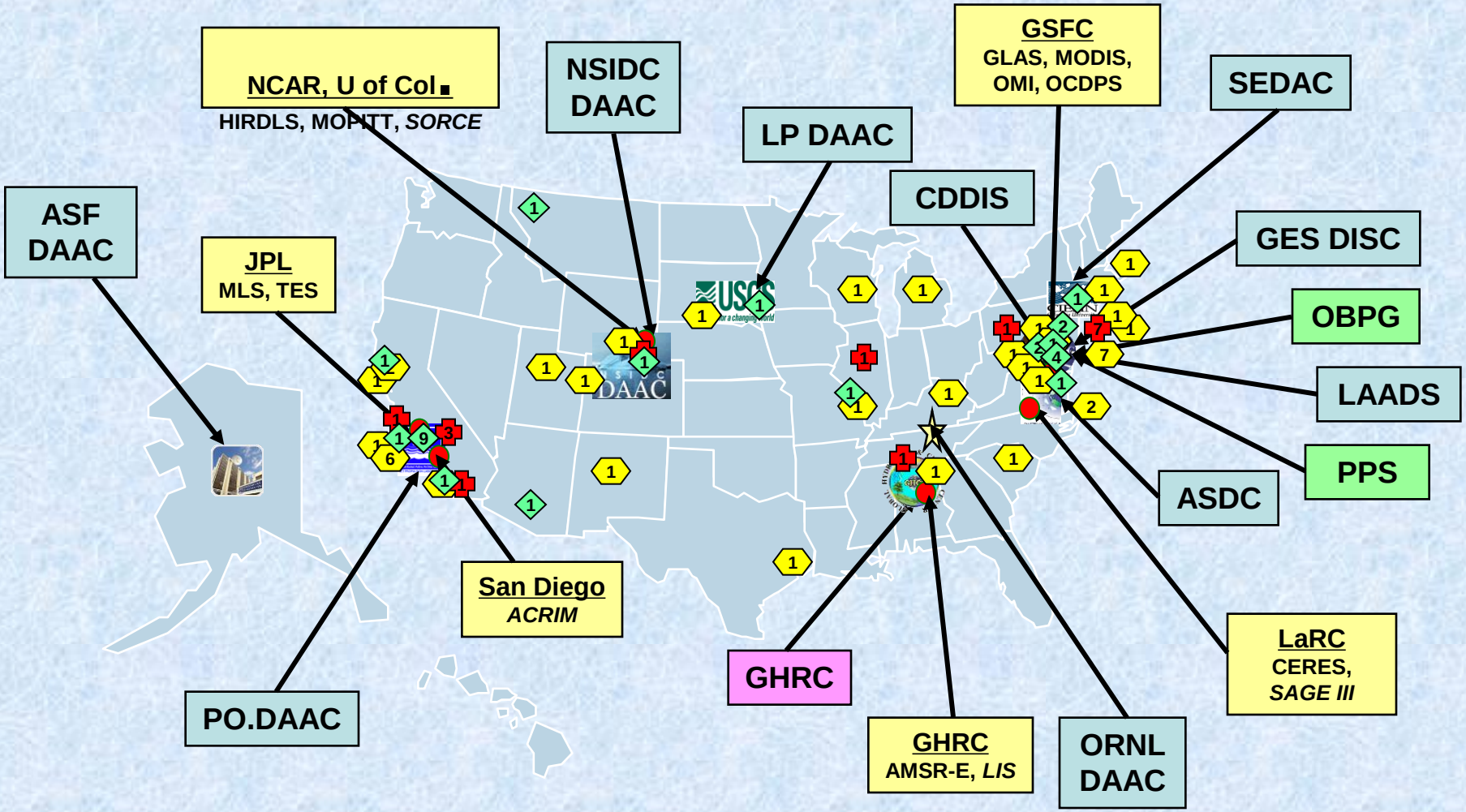


May 2012: the Portable Remote Imaging Spectrometer (PRISM) coastal ocean airborne sensor completed its first test and calibration flight over Ivanpah Playa and Lake Tahoe, CA. PRISM's sensitivity, dynamic range, and polarization properties are specifically designed for the challenges of the coastal ocean environment.
(PI: Pantazis Mouroulis, JPL, ATI-09)

Landcover Project Science Office Accomplishments

- Complete 40-year calibration for Landsat MSS/TM/ETM+ reflective bands
  - Landsat 7 ETM+ serves as the 'Gold Standard'
  - Landsat 5 TM cross-calibration to ETM+
  - Landsat 4 TM cross-calibrated to Landsat 5 TM
  - Landsat MSS series cross-calibrated
    MSS 1→MSS 2→MSS 3→ MSS 4→ MSS 5
  - MSS 5 cross-calibrated to Landsat 5 TM
    (note that band pass differences remain)
- Complete 30-year thermal calibration for TM/ETM+
- Maintenance of TM/ETM+ absolute calibration through campaigns, special sites, and on-board sources
- Other Contributions
  - Image artifact characterization/correction
  - Surface temperature product prototype
  - Education/outreach

Earth Science Data Systems (Core and Community)



KEY

EOSDIS Data Centers

Related Data Providers

Measurement-based Systems

Science Investigator-led Processing Systems (SIPSs)

Core

41 REASoN

29 MEaSUREs

17 ACCESS

Looking Ahead

- Operating missions past prime period (almost all!) are periodically evaluated for mission extension through senior review process and extension is typical but not automatic
  - ICEBridge series of airborne campaigns will help connect observations of ICESat (till 2009) and ICESat II (launch ~ 2016)
- Many measurements made by NASA EOS satellites (Terra, Aqua, Aura) will be continued through NPP satellite (planned launch 2011) and then Joint Polar Satellite System; ocean altimetry being taken over by operational agencies (NOAA, EUMETSAT)
- NASA Mission Plan includes several missions designed to extend previous records in ways not likely to be done by operational or international partners
  - SAGE III/ISS for high vertical resolution ozone (and aerosol) profile
  - GRACE-FO for several parameters (including ice mass)
  - PACE for ocean color product suite
- Importance of international missions is likely to increase in future

Conclusions

- Creation of long-term, multi-instrument/multi-platform data sets is a research activity that requires significant effort over the course of decades
- Overlap of instruments and stable orbits are exceedingly helpful for producing such records
- Calibration/validation activities of all forms (e.g., pre-launch, on-orbit, lunar calibration, vicarious calibration, etc.) over the lifetime of the mission are crucial
- Detailed attention to algorithms is needed, with understanding of full complexity of situation
- Expectation should be that such data sets will involve instruments from different providers (increasingly international) so open data policy and cooperation among teams is important
- Stability of team to assure consistency of data over long term is crucial, especially to support reprocessing (including “orphaned” data sets)