Calibration and Recalibration: Theory, Practice and Future Perspective

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Outline

- WMO WIGOS Space Vision 2040 and CGMS Baseline
- Calibration: Concept, Difficulty and Solution
- GSICS Activities to Support Operational Meteorological Satellite
- Calibration to Sensor-dependent Data Record (SDR): FY as example
- Recalibration to Fundamental Climate Data Record (FCDR): FY as example
- Future: Radiometric Benchmark Satellite to SI Traceability

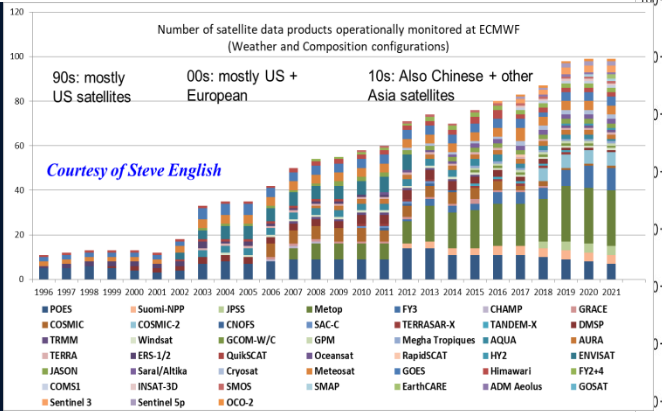
Abstract

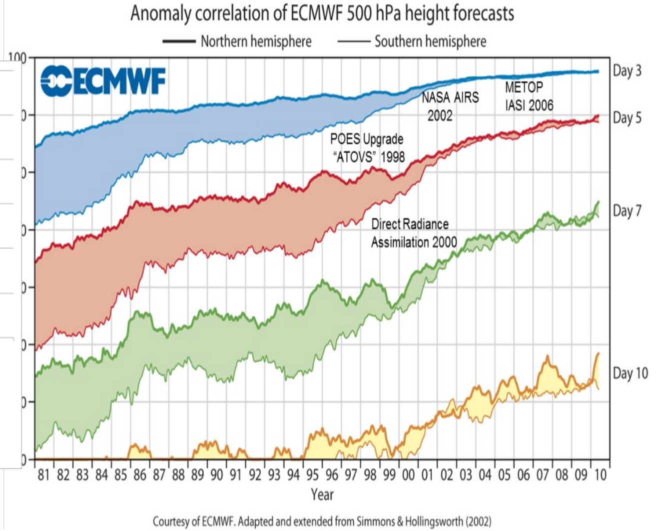
To support the quantitative remote sensing, especially the satellite data assimilation, the calibration activities is one of fundamental work to control the uncertainty of the satellite measurement. In the first part of the presentation, WMO WIGOS space vision 2040 and CGMS baseline will be reviewed briefly. To be reliable and interoperable, the satellite measurements from different agency must be precisely calibrated with similar methods and common references. Therefore, the concept, difficulty and solution of calibration has been introduced in principle. The Global Space-based Inter-calibration System (GSICS) activities has been highlighted to improve the poor or inhomogeneous calibration which could result in degraded performance. As a example, the calibration and recalibration of Fengyun meteorological satellite data to generate the sensor-dependent data record (SDR) and the fundamental climate data record (FCDR) have been illustrated. The bias and instrument physical cause has been analyzed. At last, the space-based radiometric reference systems, such as CLARREO in US, TRUTHS in Europe and LIBRA in China has been presented.

1. WMO WIGOS Space Vision 2040 and CGMS Baseline

- 1957, first man-made satellite Sputnik by former Soviet Union
- 1960, first meteorological satellite TIROS-1 by US
- 1966, first Geo meteorological satellite ATS by US
- 1988, first FY meteorological satellite in China

AMS100: meteorological satellites have changed the way scientists understand the Earth

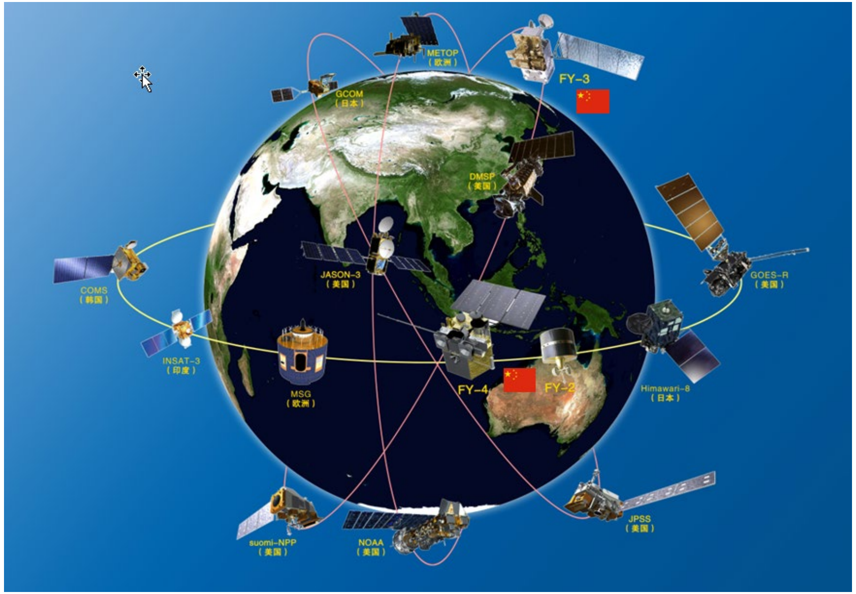




- Eyre and Lore (1989): the direct use of satellite sounding radiances in the NWP
- Eyre et al. (1993): successfully assimilated the radiation information provided by the TIROS Operational Vertical Sounder into the NWP system through one-dimensional variational analysis.

WMO Space Program Vision 2040

- reliable and sustained observation in operation
- open data policy to free access



WMO WIGOS Space Vision 2040

- Rather than prescribing every component, try to strike a balance:
  - Specific enough to provide clear guidance on system to be achieved (including which constellations are needed for each application area)
  - Open to opportunities and encouraging initiatives

- Promote complementary 4-tier **space segment** for national/international contributions, all with data freely, accessible in timely manner with metadata, sensor characteristics, etc.
  - **Tier 1: backbone component, specified orbital configuration and measurement approach**
    - Basis for Members' commitments, should respond to the vital data needs
    - Similar to the current CGMS baseline with addition of newly mature capabilities
  - **Tier 2: backbone component, keeping open the orbital configuration and measurement approach,** leaving room for further system optimization
    - Basis for open contributions of WMO Members, responding to target data goals,

- **Tier 3: Operational pathfinders and technology and science demonstrators**
  - Responding to R&D needs

- **Tier 4: Other operators** (e.g. academic, commercial) exploiting technical/ business /programmatic opportunities are likely to provide additional data
- WMO should recommend standards, best practices, guiding principles to maximize the chance that these additional data sources contribute to the community
- Implemented through dedicated missions or hosted payload opportunities

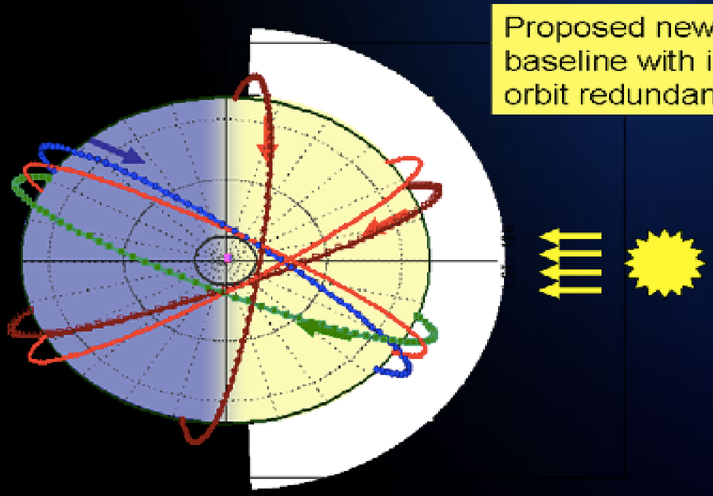
Tier 1. Backbone system - with specified orbital configuration and measurement approaches (1/2)

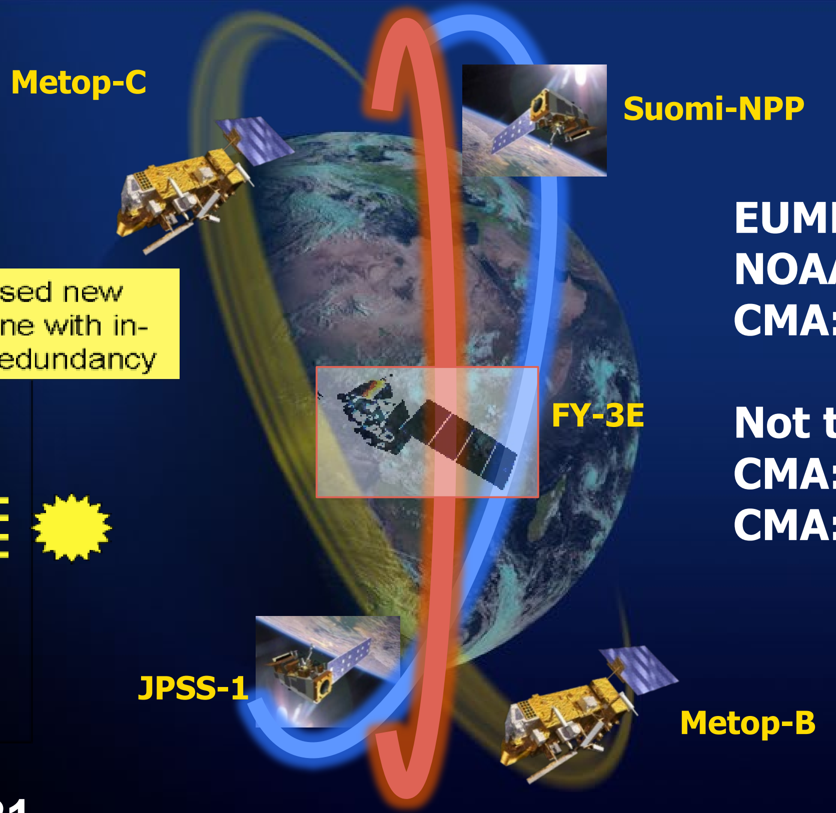
- **Geostationary** ring providing frequent multispectral VIS/IR imagery
  - with IR hyperspectral, Lightning mapper, UV/VIS/NIR sounder
- **LEO sun-sync. core constellation** in 3 orbit planes (am/pm/earlymorning)
  - hyperspectral IR sounder, VIS/IR imager including Day/Night band
  - MW imager, MW sounder, Scatterometer
- **LEO sun-sync. at 3 additional ECT** for improved robustness and improved time sampling particularly for monitoring precipitation
- Wide-swath radar altimeter, and high-altitude, inclined, high-precision orbit altimeter,
- IR dual-angle view imager (for SST)
- MW imagery at 6.7 GHz (for all-weather SST)
- Low-frequency MW (for soil moisture and ocean salinity)
- MW cross-track upper stratospheric and mesospheric temperature sounder
- UV/VIS/NIR sounder , nadir and limb (for atmospheric composition, incl H_2O)

Tier 1. Backbone system - with specified orbital configuration and measurement approaches (2/2)

- Precipitation and cloud radars and MW sounder and imager on inclined orbits
- Absolutely calibrated broadband radiometer and TSI and SSI radiometer
- GNSS radio-occultation (basic constellation) for temperature, humidity and electron density
- Narrow-band or hyperspectral imagery (ocean colour, vegetation)
- High-resolution multispectral VIS/IR imagers (land use, vegetation, flood monitoring)
- SAR imagery (sea state and sea-ice observations, soil moisture)
- Gravimetry mission (ground water, oceanography)
- Solar wind in situ plasma and energetic particles, magnetic field, at L1
- Solar coronagraph and radio-spectrograph, at L1
- In situ plasma, energetic particles at GEO and LEO, and magnetic field at GEO
- On-orbit measurement reference standards for VIS/NIR, IR, MW absolute calibration

The value of international cooperation: "LEO Three Orbits"



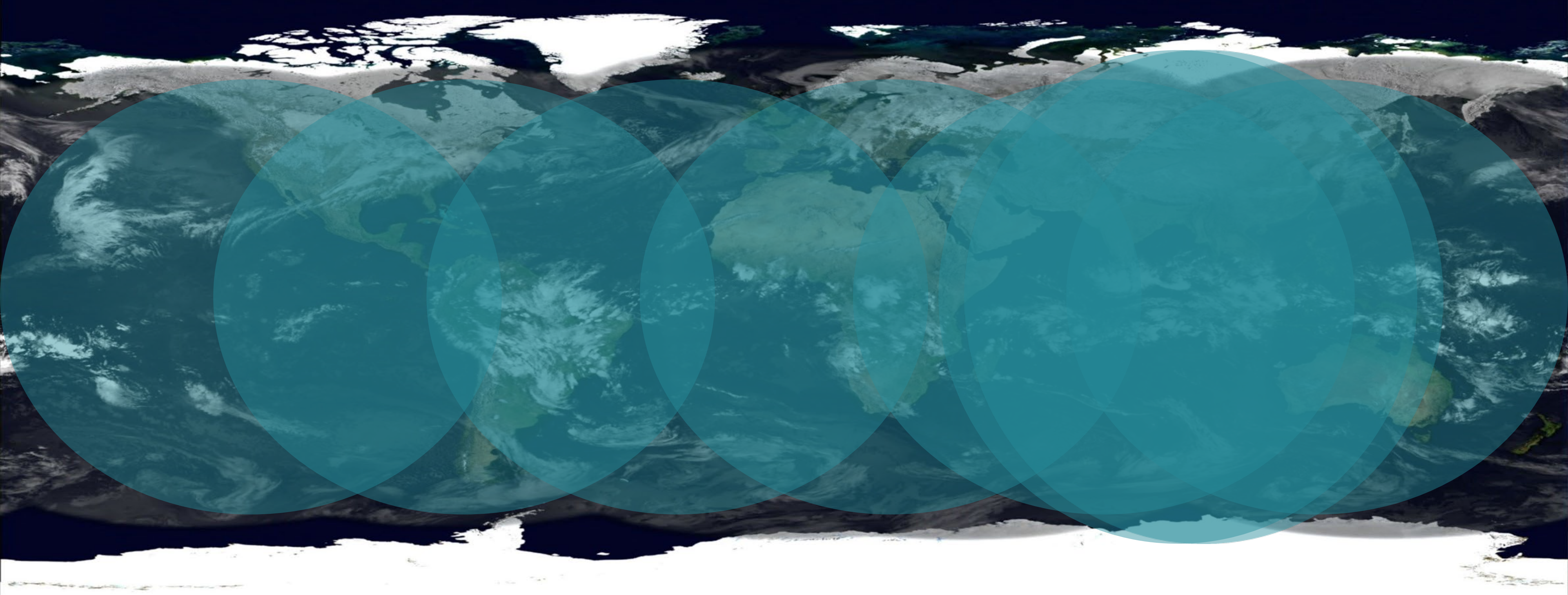


EUMETSAT: 09:30 desc
NOAA:13:30 asc
CMA: 06:00 desc

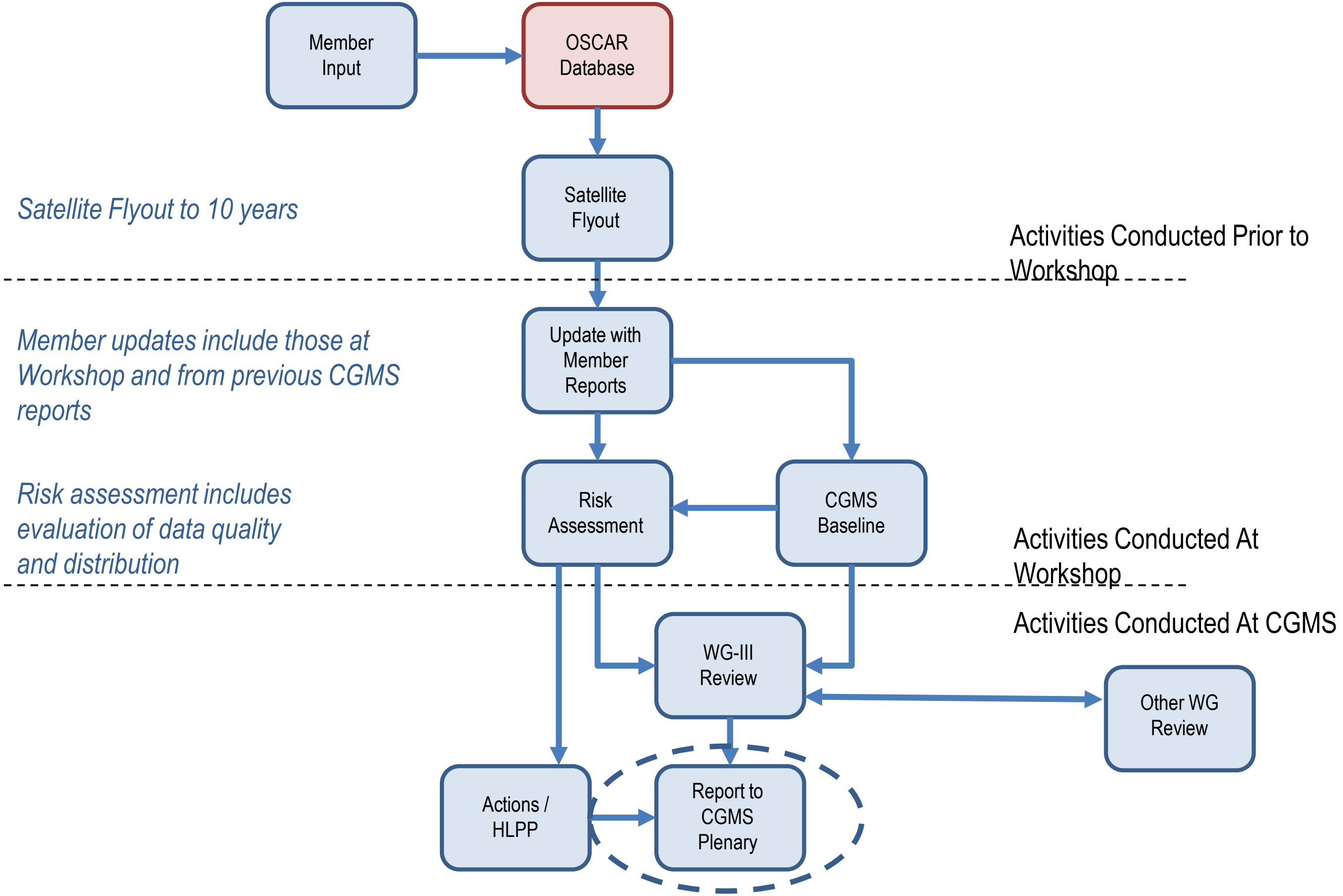
Not to forget
CMA: 10:00 asc
CMA: 14:00 asc

P. Zhang, et al., AAS, 2021

The value of international cooperation: "the GEO ring"



CGMS Baseline Update / Risk Assessment Process

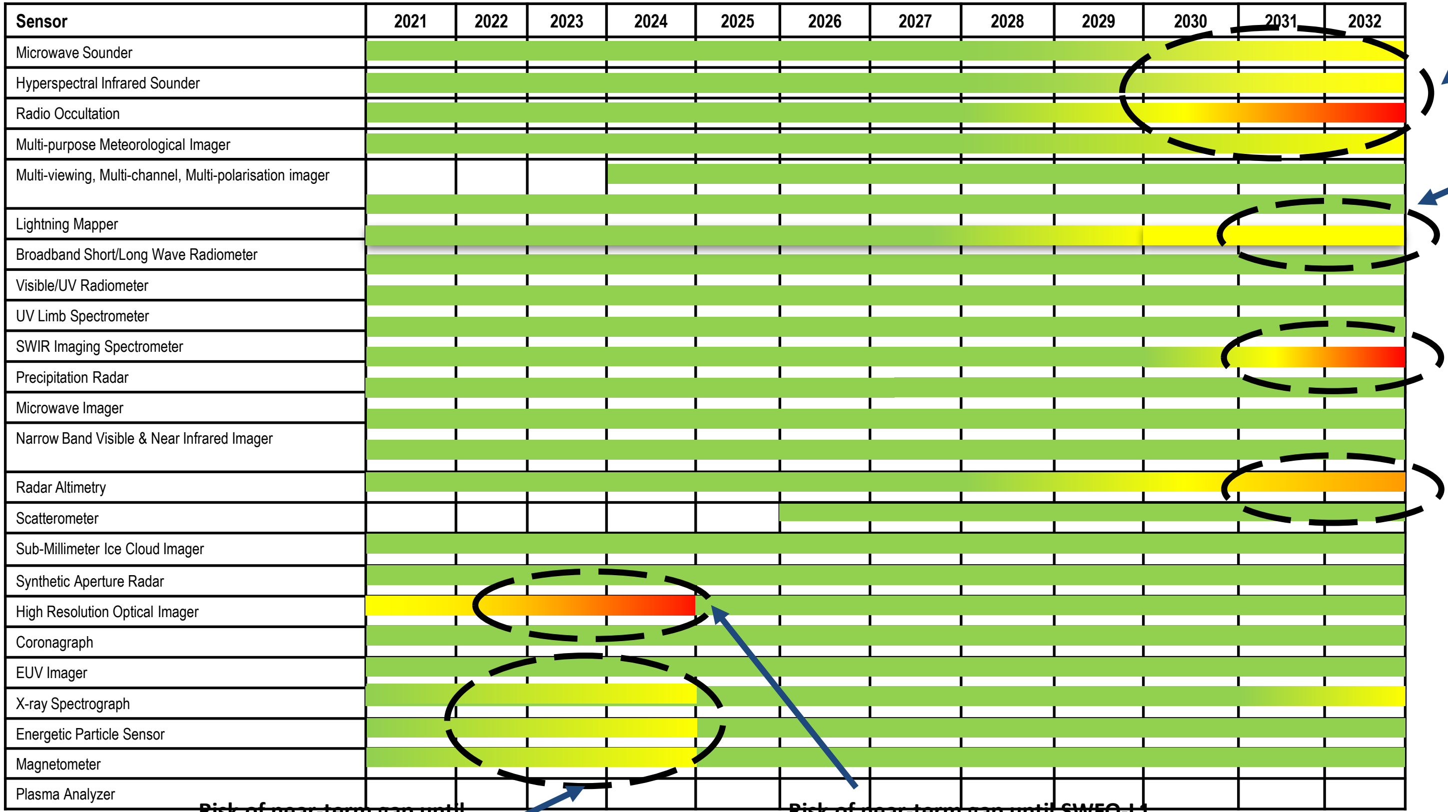


CGMS Risk Assessment Assumptions

- CGMS Risk Assessment uses **Green**, Yellow, and Red to graphically represent the overall status of that sensor/observation. The criteria for each colour is as follows:
  - **Green:** CGMS Baseline met with a low risk of a gap.
  - **Yellow:** The CGMS Baseline is at moderate risk of not being fully met. Some mitigation by CGMS Members may be required.
  - **Red:** There is a high risk of not meeting the CGMS Baseline without CGMS Member action
  - No Colour: Observation is not planned to be available until a later date

Top-Level Risk Assessment (2021)

Risk in the early morning orbit after FY-3E; no planned low-inclination RO observations after COSMIC-2



Risk in the early morning orbit after FY-3E

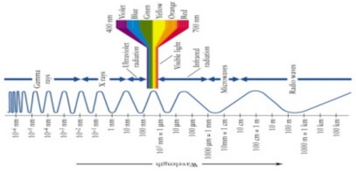
Risk in continuity after FY-3G and GPM Core

Risk in the early morning and afternoon orbits after FY-3E and Oceansat-3A

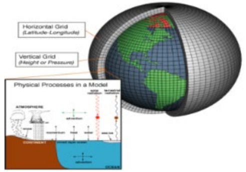
Risk of near-term gap until SWFO-L1 is launched

Risk of near-term gap until SWFO-L1 and GOES-U are launched

2. Calibration: Concept, Difficulty and Solution



3 Fundamental Process for Quantitative Remote Sensing



Where the data located ?	How accuracy of the data ?	Which parameter measured?
Sat Obs DN	Sat Obs DN	Sat Obs Rad
↓	↓	↓
Geolocation	**Calibration**	**Retrieval**
↓	↓	↓
Longitude and Latitude Zenith angle and azimuth angle of the solar and satellite	Radiance in the defined wavelength	Geophysical Parameters

Definition: radiometric calibration is the process to quantitatively determine the electro-optical instrument's response between the incident signals at the instrument entrance aperture (radiance) and the output of the instrument (digital numbers).

$$I(\lambda) = \cdot DN_{i,j} \frac{1}{G \cdot A_{i,j} \cdot \Omega \cdot \Delta\lambda \cdot \eta \cdot t \cdot \tau}$$

$I(\lambda)$: the spectral radiance at the instrument entrance aperture

$DN_{i,j}$: the digital number output by instrument detector i in band j

G : the digitization gain of the instrument detector

$A_{i,j}$: the area of detector i in band j

Ω : the instrument acceptance solid angle

$\Delta\lambda$: the bandwidth

η : detector quantum efficiency in electrons per incident photon

t : the integration time

τ : the instrument optical transmission

Five Domains

- ☐ Radiometric
- ☐ Spectral
- ☐ Spatial
- ☐ Temporal
- ☐ Polarization

R.U. Datla, et al. JRNIST, 2011

Classification：

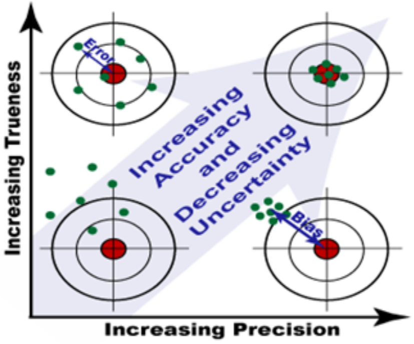
- According to the lifetime cycle
  - pre-launch (laboratory) calibration
  - post-launch (on-orbit) calibration: near real-time calibration, offline calibration (validation, calibration correction)
- According to the traceable reference
  - calibration with onboard calibrator: standard lamp, diffusive reflectors, Integrating sphere, blackbody
  - vicarious calibration: natural stable targets (earth targets: PICs, DCC,… + extraterrestrial targets: moon, …), benchmark instruments (Inter-calibration such as SNO), model simulations (such as O-B)
- According to the instrument type
  - Ultraviolet, Visible and Near Infrared, Infrared, Microwave, Broadband, Active Instrument

G. Ohring, et al. ASIC3, 2007

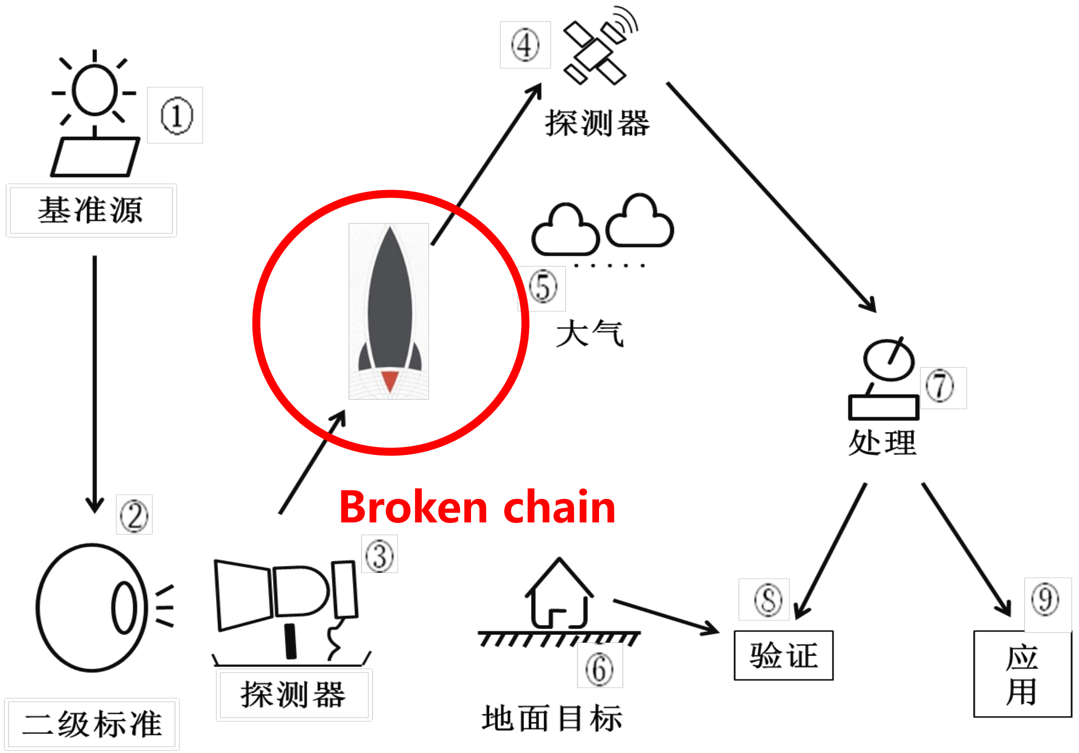
Terminology

1. **Accuracy**: a measure of how close a measured results is to the "true" value.
2. **Uncertainty**: as the "true" value is unknown, **accuracy** is estimated by a measurement **uncertainty**, a combination of the standard deviation of multiple measurements (random effects) and an estimate of the size of an uncorrectable systematic bias.
3. **Precision**: a measure of the repeatability (standard deviation of multiple measurements under the same conditions) and reproducibility (standard deviation of multiple measurements with different instruments or under different conditions) of a measured value. (can by improved by averaging)
4. **Bias**: a measure of the non-random or systematic errors of a result. (cannot be improved by averaging)
5. **Stability**: a measure of the change of **bias** with time.

G. Chander, et al. TGRS, 2013



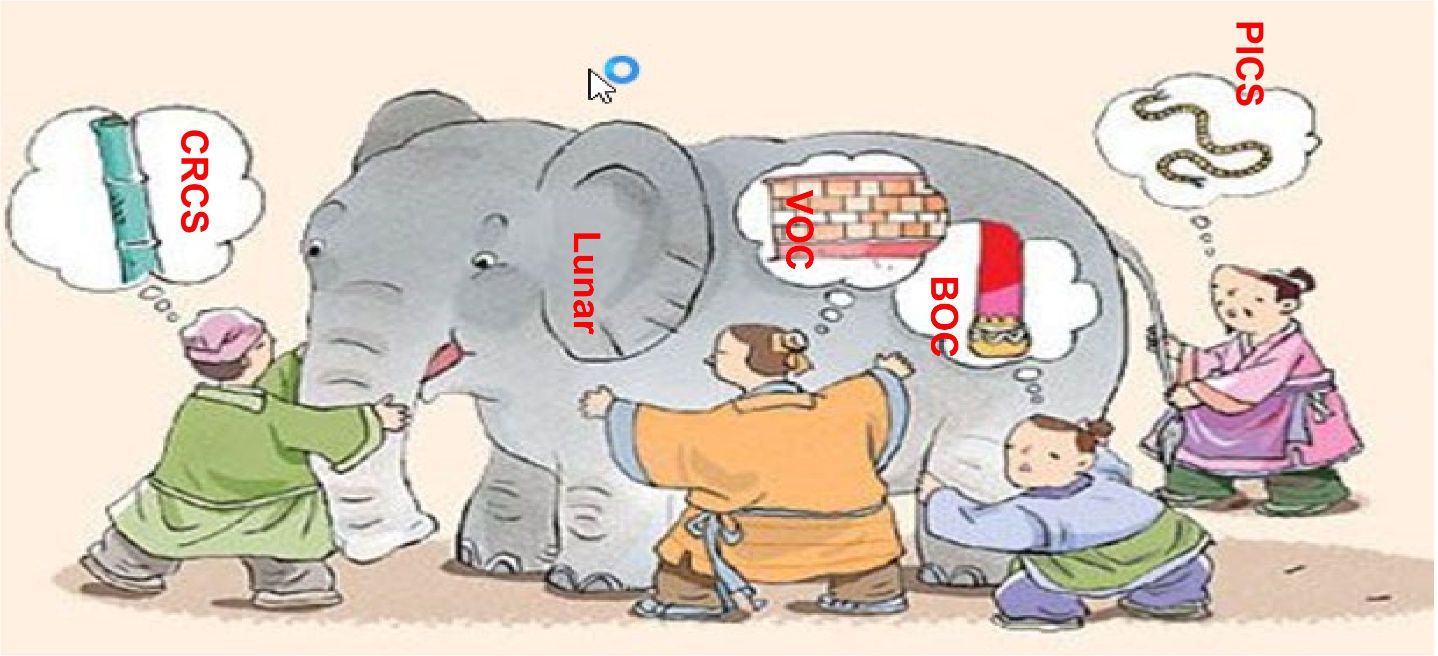
Difficulties Faced: Radiometric Traceability of satellite sensors



- Uncertainty of calibration source
- Detector Response (nonlinearity)
- Variation of satellite operation environment status
- Degradation of instrument performance
- Contamination of Instrument

How to make the satellite observed data traceable to the reference/SI ?

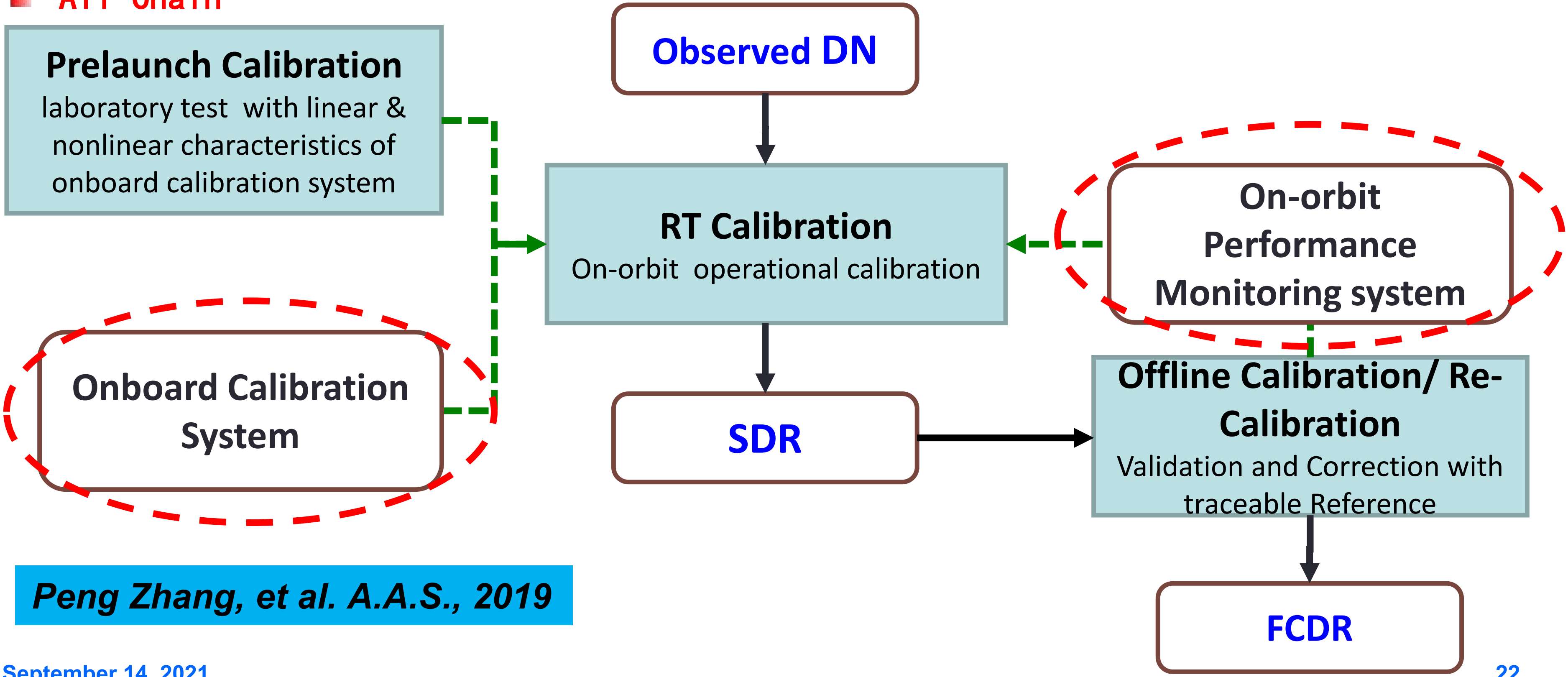
Reference/SI Traceability



- earth stable targets (PICs, DCC,...)
- extraterrestrial stable targets (sun, moon, ...)
- model simulations (O-B)
- benchmark instruments (direct / indirect inter-calibration)
- space-based benchmark

Solution: All Calibration Procedure

- All Phase: design phase to on-orbit operation
- All Lifetime
- All Chain



Peng Zhang, et al. A.A.S., 2019

All Phase: Best Practice Guidelines for Pre-Launch Characterization and Calibration of Instruments for Optical Remote Sensing

NISTIR 7637

Best Practice Guidelines for Pre-Launch Characterization and Calibration of Instruments for Passive Optical Remote Sensing

(Report to Global Space-based Inter-Calibration System (GSICS) Executive Panel, NOAA/NESDIS, World Weather Building, Camp Springs, Maryland 20746)

R. U. Datla, J. P. Rice, K. Lykke and B. C. Johnson
NIST Optical technology Division

J.J. Butler and X. Xiong
NASA Goddard Space Flight Center

September 2009

U.S. DEPARTMENT OF COMMERCE
Gary Locke, Secretary

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Patrick D. Gallagher, Director

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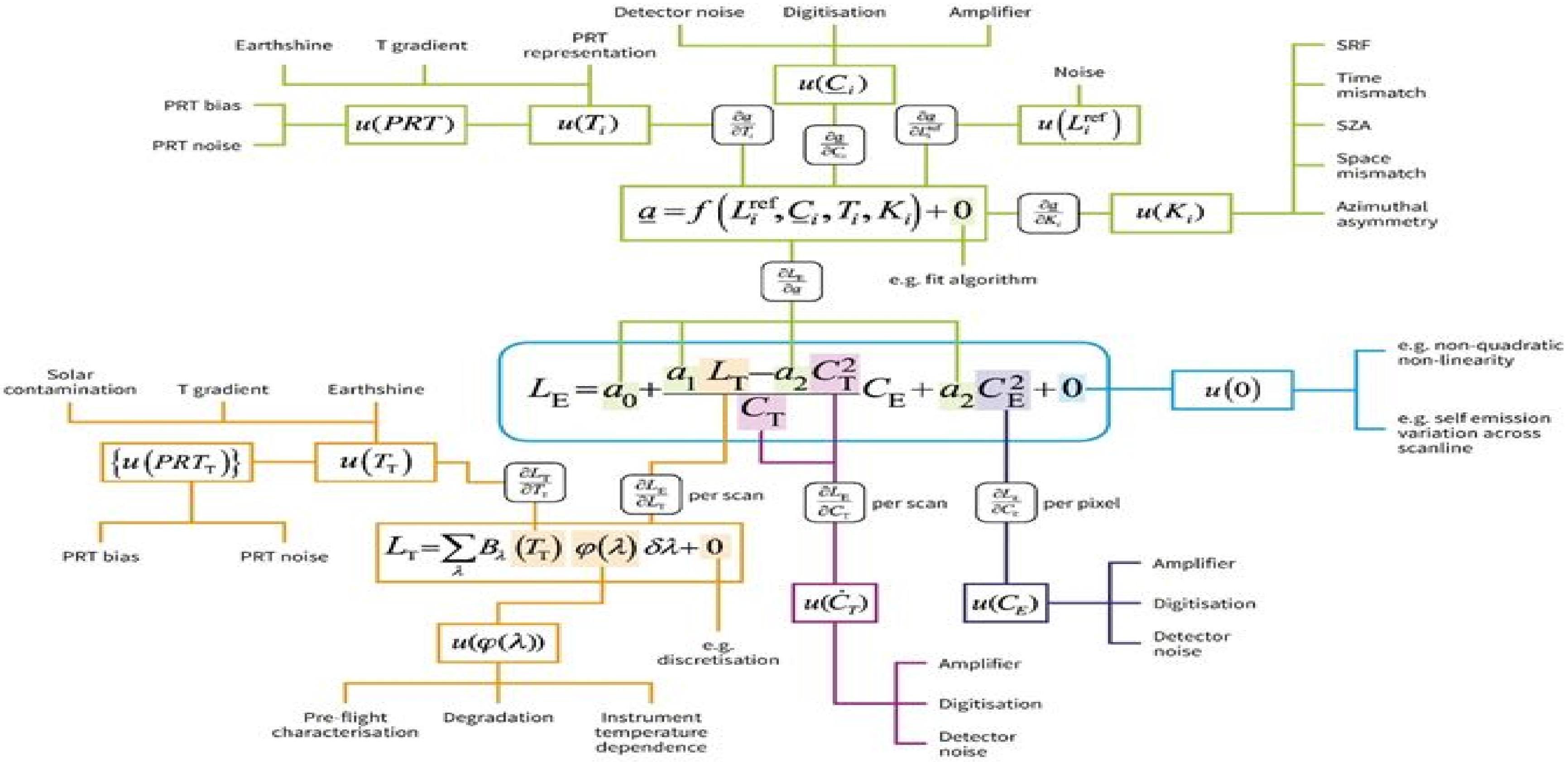
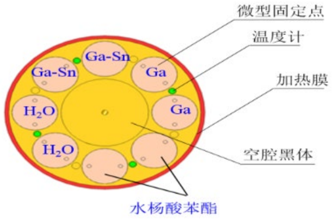
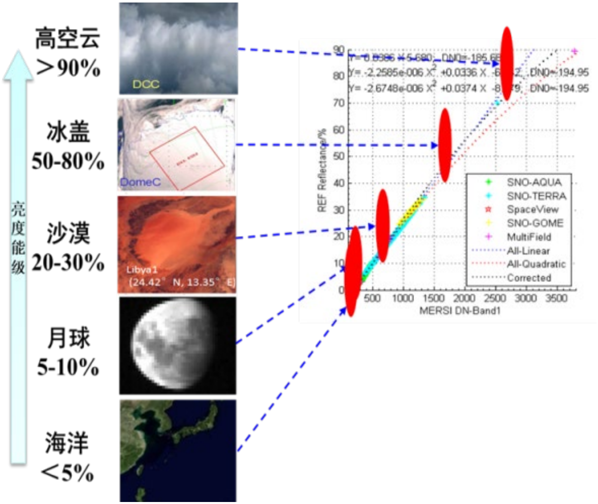
All Calibration Chain: example

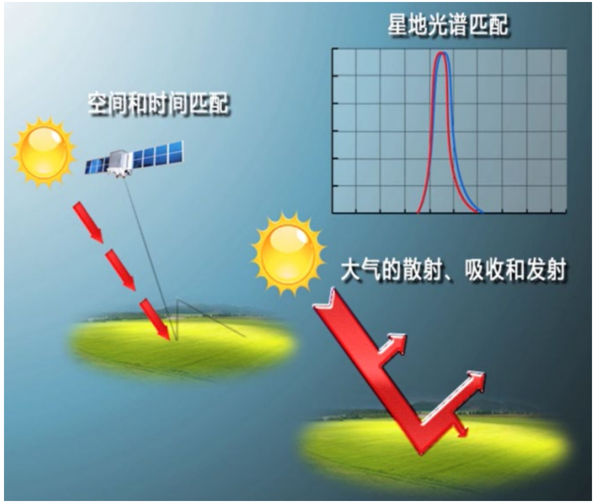


Calibration: the interdiscipline including material science, metrology, geoscience

The integration of space and ground







1. Making benchmark

2. Finding benchmark

3. Radiometric transfer & SI traceability

3. GSICS Activities to Support Operational Meteorological Satellite

To be reliable and interoperable, the satellite measurements from different agency must be precisely calibrated with similar methods and common references.

Global Space-based Inter-Calibration System

- instruments meet specifications,
- pre-launch tests are traceable to SI standards,
- on-orbit instrument performance is carefully analysed,
- instruments are inter-calibrated against reference instruments,
- and measurements are validated with reference sites.

Working Group on Calibration and Validation

- QA4EO (quality assurance for earth observation)
- Dome C Experiment
- Cal/Val Portal and Post-Launch Test Sites
- Radiometric Standards
- Benchmark Mission Coordination
- Ground Based Cal/Val Campaign
- Reference Test Site Data Collaboration and Comparison

Why GSICS?

- Space-based observations required for weather and climate applications rely on multiple satellite missions from different agencies around the world
- To be reliable and interoperable, these different sources must be precisely calibrated with similar methods and common references. Poor or inhomogeneous calibration would result in degraded performance
- **GSICS members are collaborating to develop and apply "best practices" for state-of-the-art and homogeneous calibration**
- GSICS provides references, tools and guidelines, for prelaunch characterization, instrument performance monitoring, anomaly resolution, comparison of sensors, and correction if necessary.

M. Goldberg, et al. BAMS, 2011

Who benefits from GSICS ?

- **Satellite operators benefit from participating in GSICS**
  - Sharing development effort and sharing resources (calibration references, datasets, software tools)
  - Capacity building in sharing best practices (for instrument monitoring, traceability, sensor comparison and correction)

- **Satellite data users benefit from GSICS**
  - Calibration is improved
  - Corrections available to align to a common reference
  - Assessments, reports, for better understanding
  - Algorithms enabling to reprocess data records

  - ➢ Improved and consistent calibration across the different agencies builds confidence on reliability of each other's data
  - ➢ Interoperability increases the benefit of data exchange

GSICS membership

GSICS members:

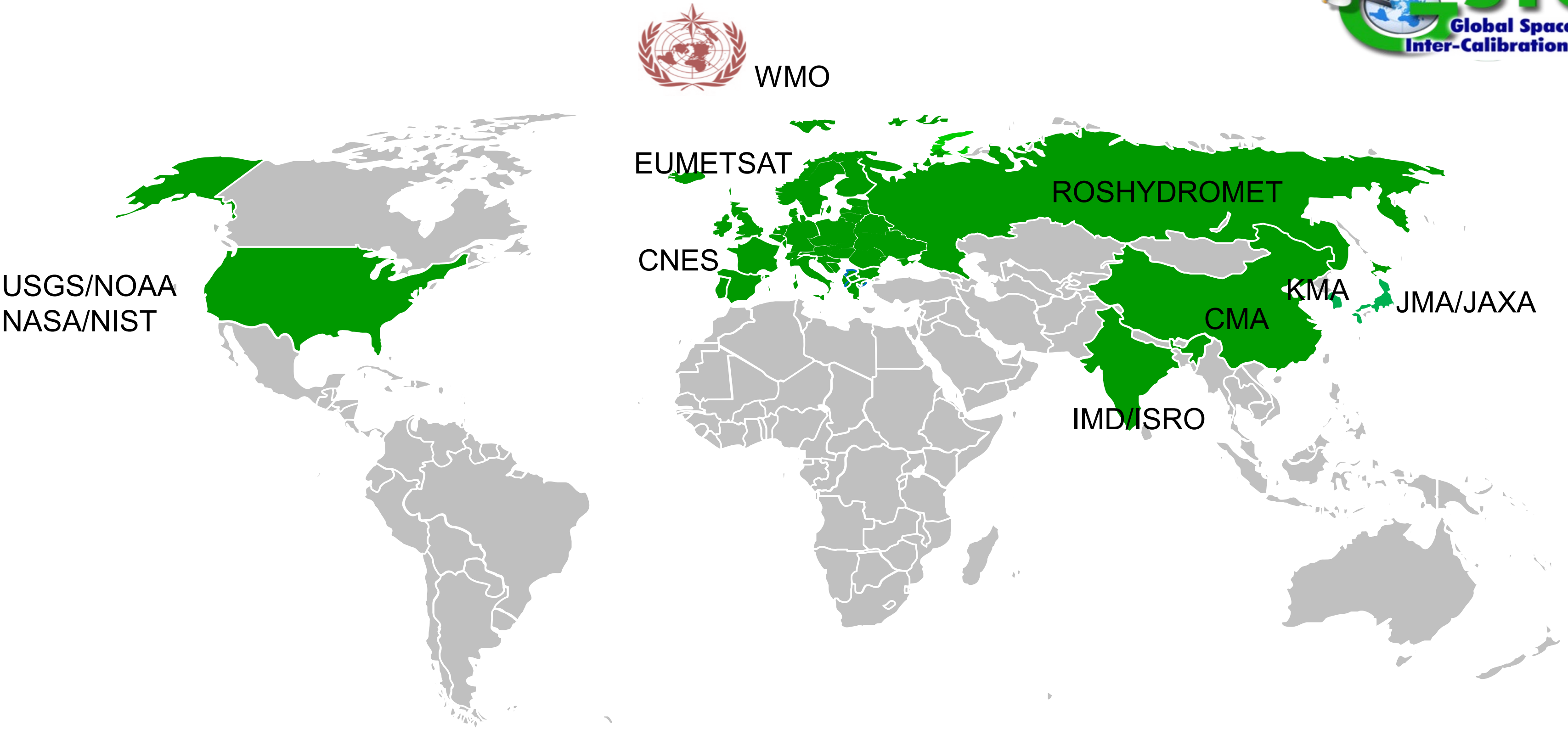
- China Meteorological Administration (CMA)
- Centre National d'Etudes Spatiales (CNES)
- European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)
- Indian Space Research Organization (ISRO)
- India Meteorological Department (IMD)
- Japan Aerospace Exploration Agency (JAXA)
- Japan Meteorological Agency (JMA)
- Korea Meteorological Agency (KMA)
- National Aeronautics and Space Administration (NASA)
- National Institute of Standards and Technology (NIST)
- National Oceanic and Atmospheric Administration (NOAA)
- Russian Federal Service for Hydrometeorology and Environmental Monitoring (ROSHYDROMET)
- United States Geological Survey (USGS)
- World Meteorological Organization (WMO)

Associate member:

- Inter-satellite Calibration WG of the Global Precipitation Measurement Mission (GPM X-Cal)

Observer:

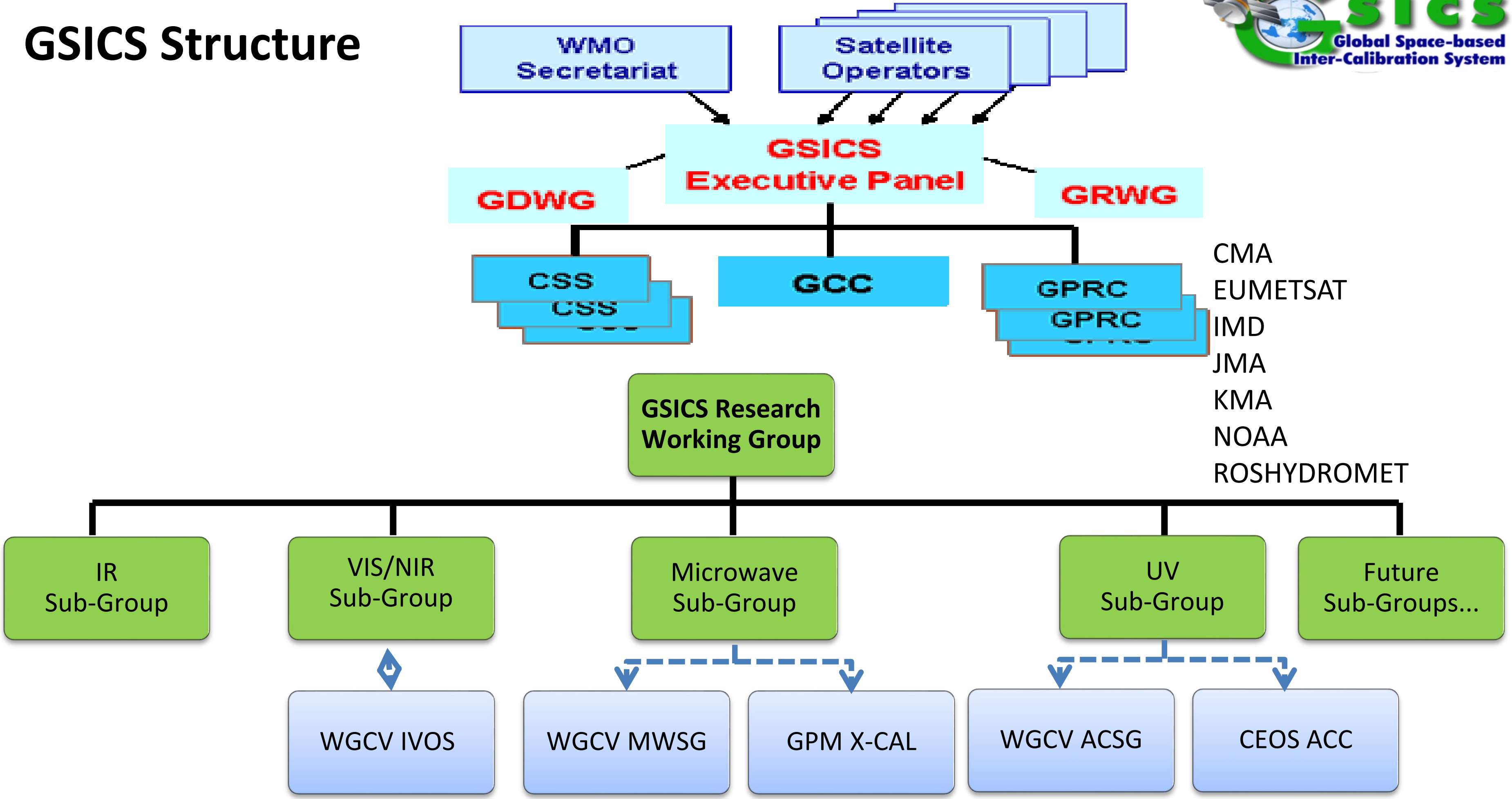
- European Space Agency (ESA)
- CEOS (CEOS) Working Group on Calibration and Validation (WGCV)
- **Occasional participation of CNSA, ROSCOSMOS, encouraged to join as observer**



Obs. **ESA + CEOS**
ASSO. **GPX**

14 GSICS Members Worldwide

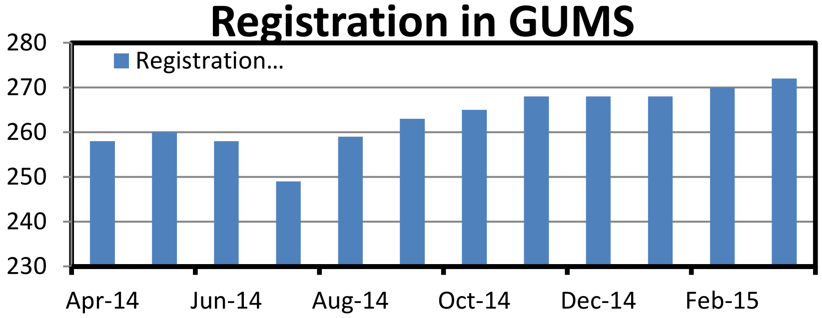
GSICS Structure



GSICS holdings and deliverables

	Holdings or Deliverables	Examples
Resources	Calibration references and databases	GIRO lunar model, ground sites Solar irradiance spectrum
	Software and hardware tools	Plotting tool, THREDDS servers, product generation environment, wiki
	Standards, conventions, guidelines	Formats, etc.
Products	Calibration methodologies	ATBD for NRT correction or re-calibration
	Analysis, monitoring results, assessments	Updated SRF; assessment of bias, of non-linearity, polarization sensitivity,
	Routine operational corrections	Near Real Time or delayed corrections
Services	Information on GSICS &calibration	Science publications, GSICS Quarterly, Outreach material
	User registration, product subscription	
	Web services	

User services



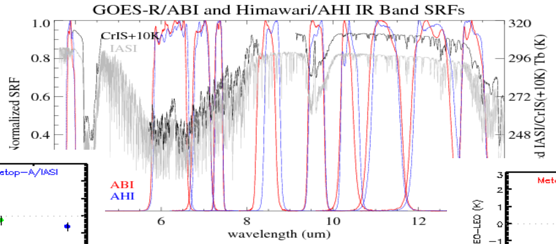
- Growing audience of GSICS user messaging service

- Widely disseminated GSICS Quarterly
- GSICS User Workshops
  – 2014: AOMSUC, Shanghai
  – 2015: Toulouse
  – ……
  – 2019: ITSC-22, Quebec

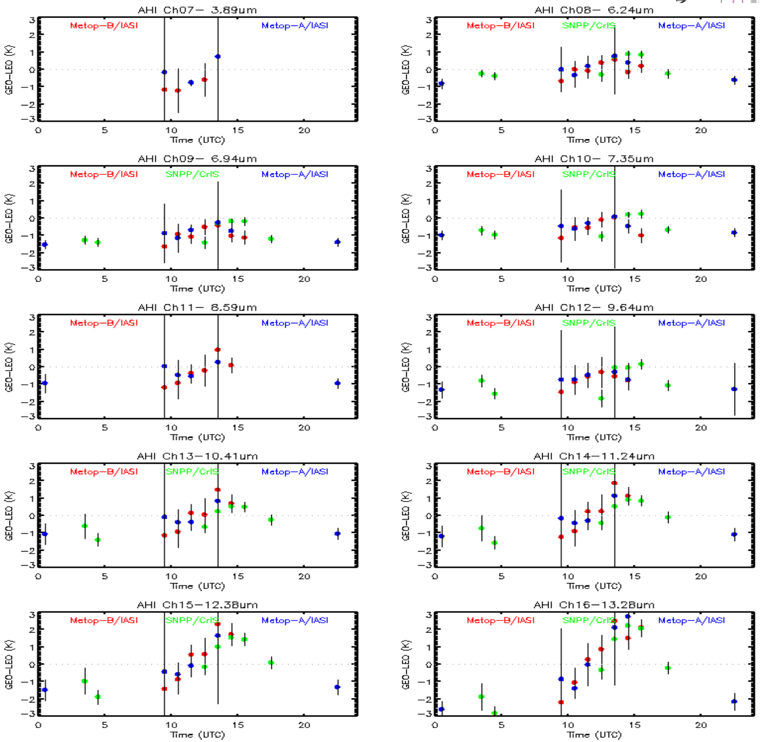
Through GSICS satellite operators improve calibration and detect /correct anomalies

- Examples:
  - Correction of GOES IR bias through intercalibration with Metop/IASI and SNPP/CrIS
  - Adjustment of SRF of COMS/MI
  - Support to commissioning test of Himawai-8, INSAT-3D, FY-2G and FY-3C

NOAA Highlight
GEO-LEO Inter-calibration using CrIS/IASI as reference

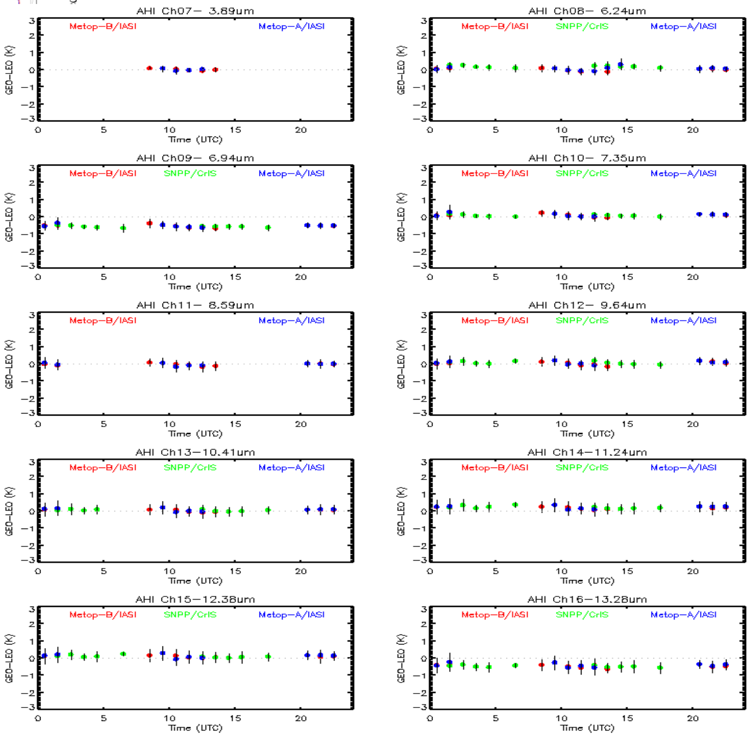


Feb 8, 2015



After Correction

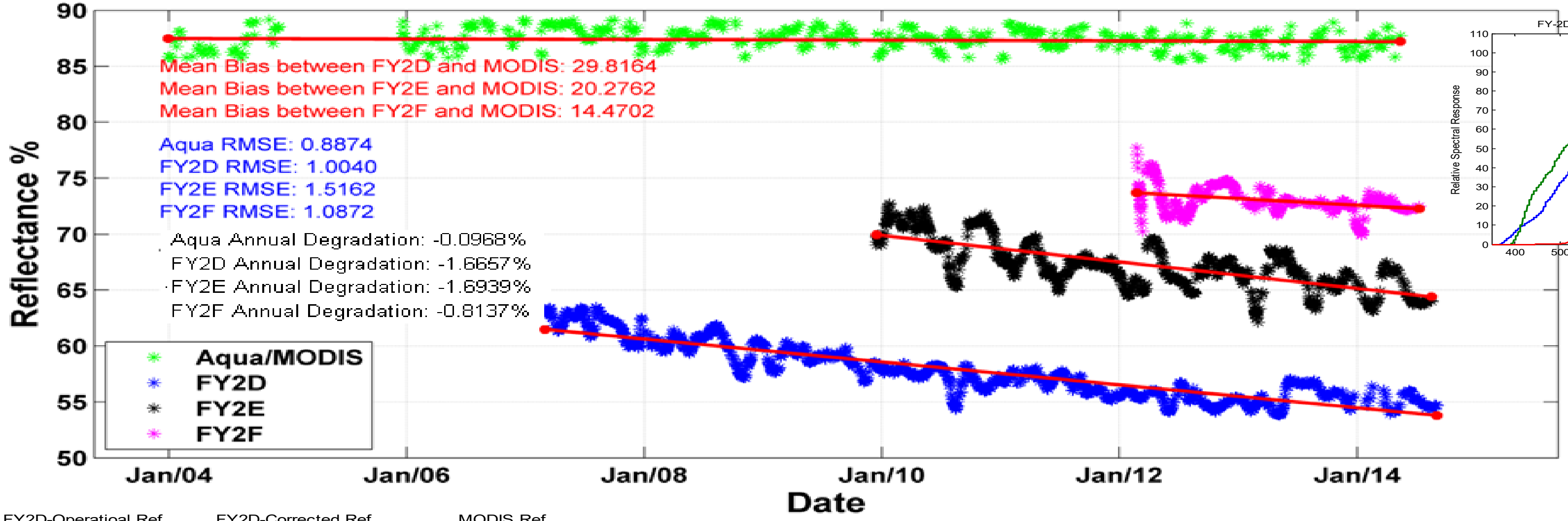
April 18, 2015

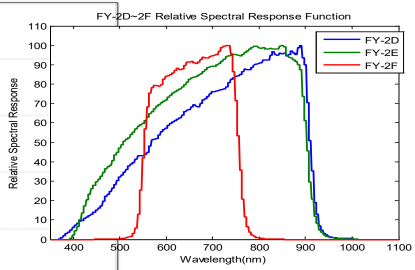


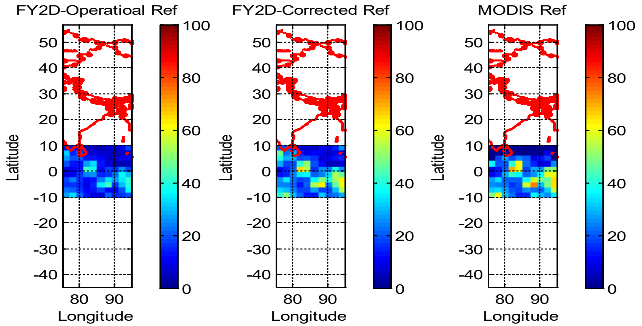
Courtesy. FangFang Yu

CMA Highlight: DCC monitoring for FY-2D/2E/2F

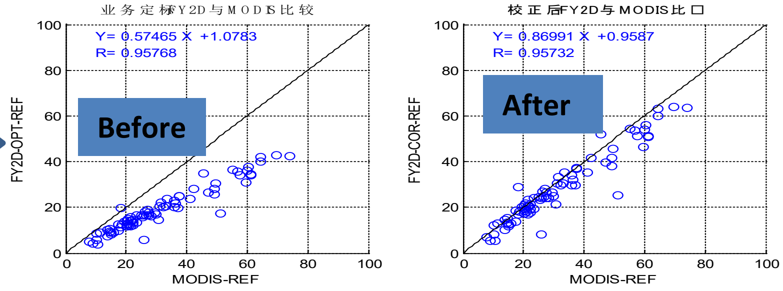
1. There is evident inconsistency between FY-2D/2E/2F and large bias with respect to MODIS.
2. There is long term degradation of FY-2 visible band.







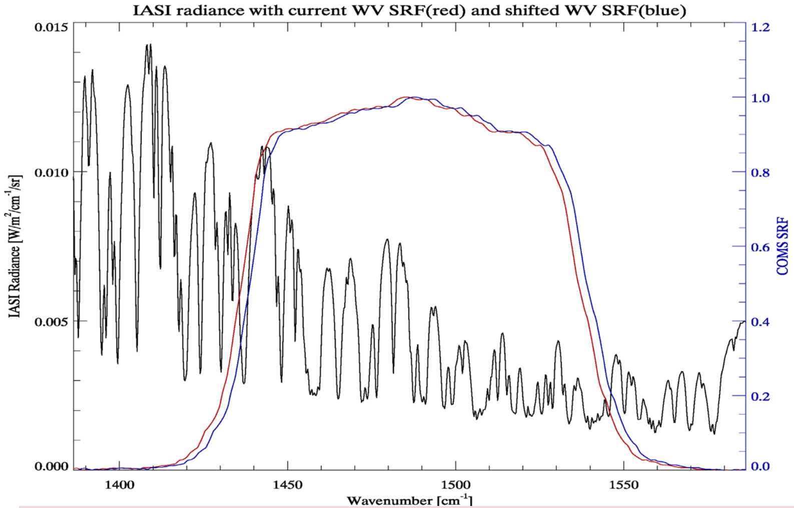
Before and after DCC correction

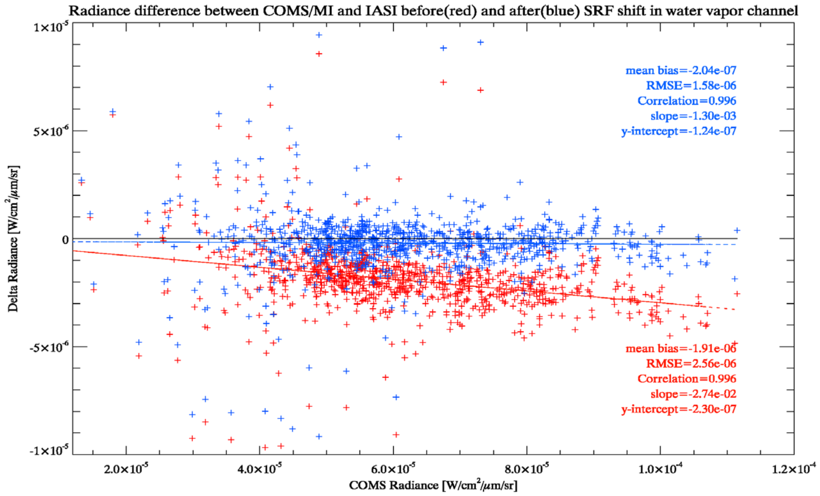


Highlights of KMA calibration activities

Cold Bias Correction in Water Vapor Channel

The radiance difference between COMS/MI and IASI as a function of the COMS/MI radiance for the data obtained before (red) and after (blue) the **SRF shifts**





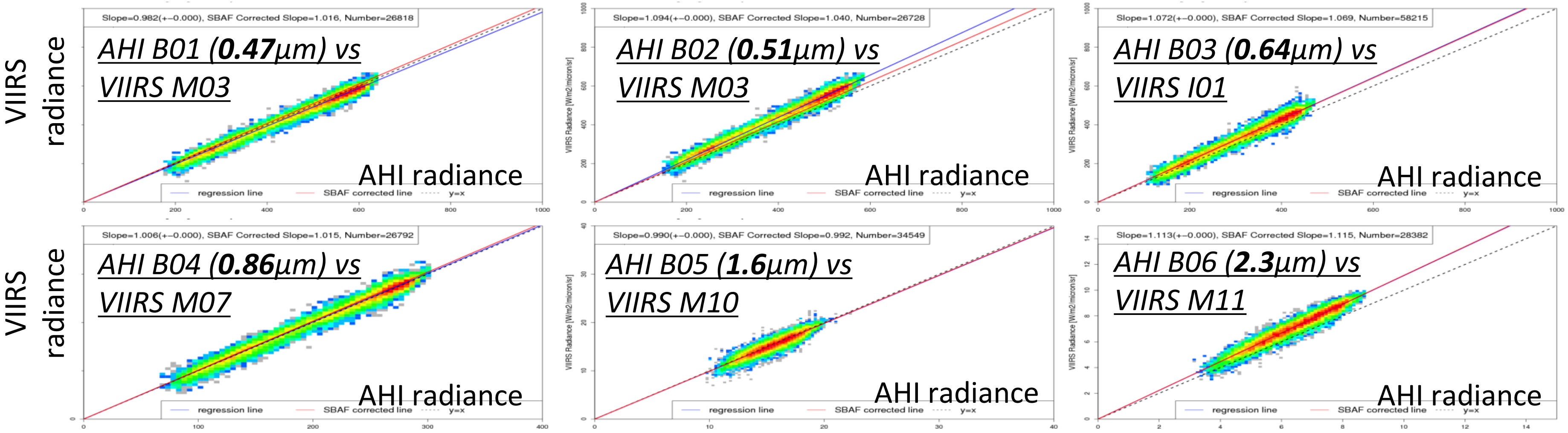
❖ **TB bias between MI and IASI reduced by ~ 0.4K (-0.71K → -0.32K)**

Highlights of JMA calibration activities

Himawari-8/AHI ray-matching with S-NPP/VIIRS

- Bands #3 (0.64μm) and #6 (2.3μm) show 5 to 10 % discrepancy
- Roughly consistent with vicarious calibration using RT simulation

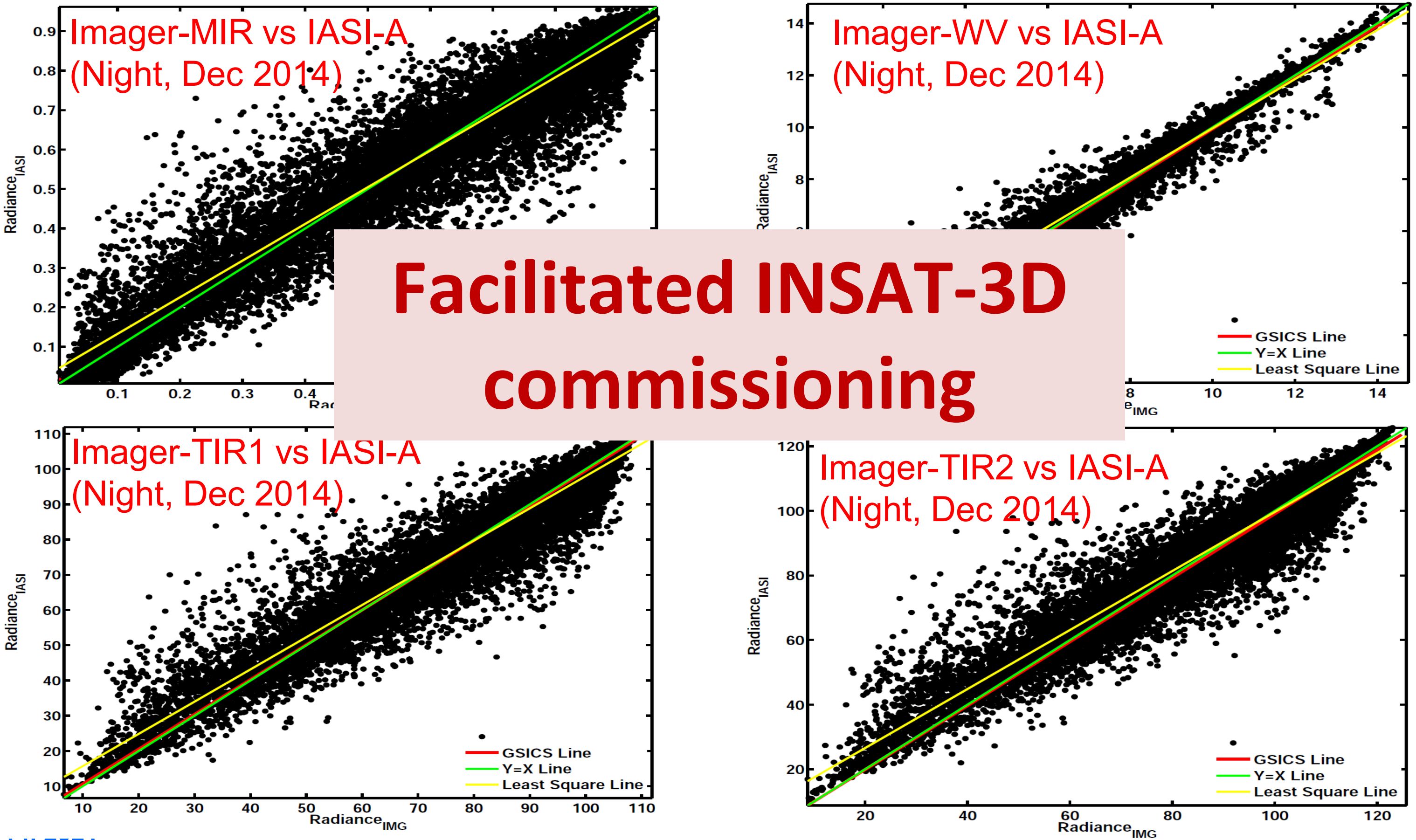
Facilitated Himawari-8 commissioning



Blue: regression line Red: regression after SRF difference correction between AHI and VIIRS

Highlights of ISRO calibration activities

Intercalibration Results: INSAT-3D Imager



Facilitated INSAT-3D commissioning

4. Radiometric Calibration to Sensor-dependent Data Record (SDR): FY as example

Chinese FENGYUN Meteorological Satellites

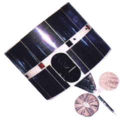
LEO System

First Generation
FY-1 A, B, C, D

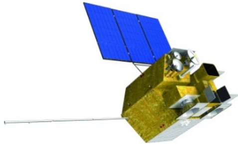
Second Generation
FY-3 A, B, C, D, E

FY-3F, G, H planned until 2030

GEO System



First Generation
FY-2 A, B, C, D, E, F, G, H

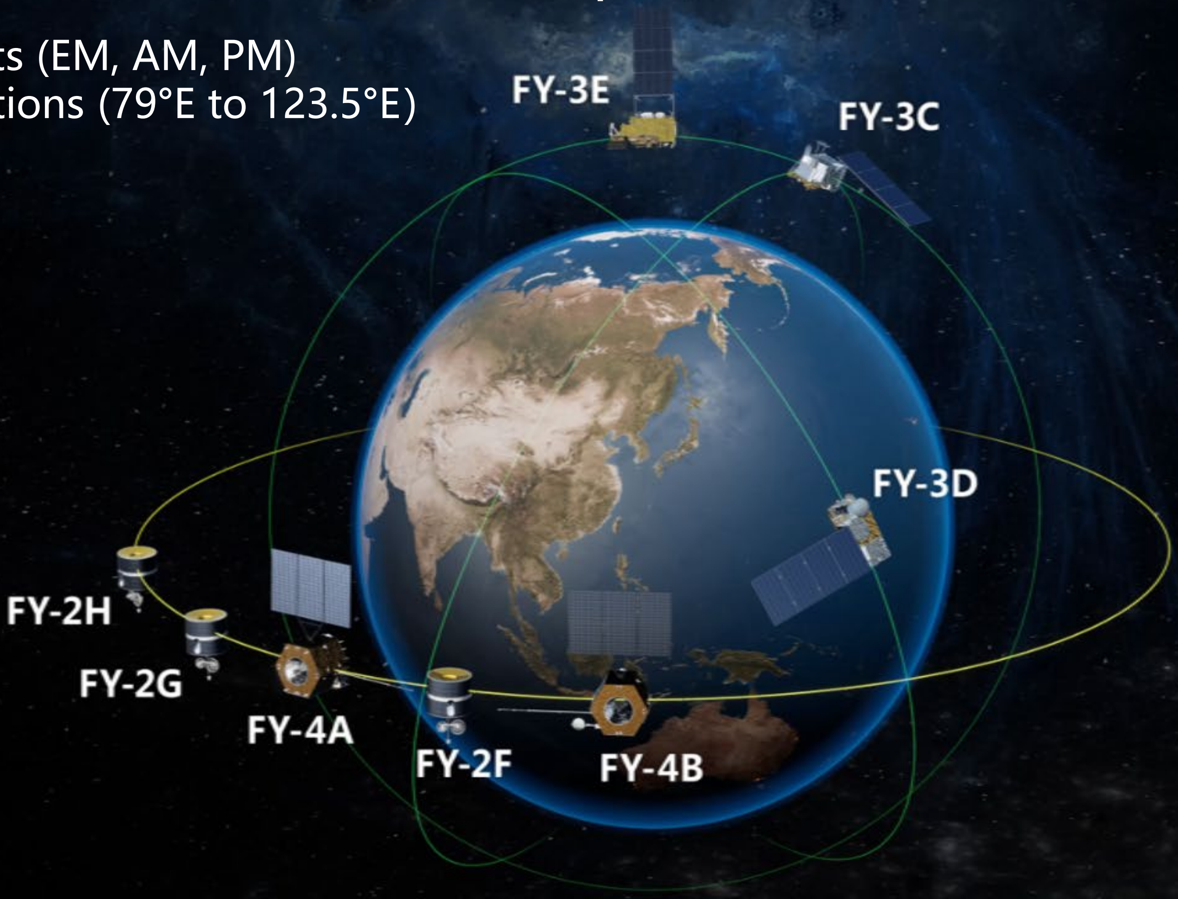


Second Generation
FY-4 A, B

FY-4C, D planned until 2035

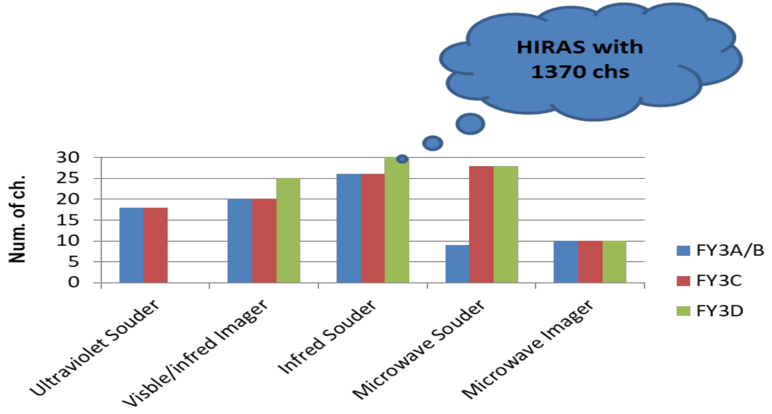
On-Orit in Operation（8 satellites)

LEO : 3 orbits (EM, AM, PM)
GEO: 5 positions (79°E to 123.5°E)



Current Instruments for EO

Satellite		No. of Instruments	Name in Abbrev.
FY-1	FY-1 A/B	2	5-channel VIRR
	FY-1 C/D	2	10-channel VIRR
FY-2	FY-2 A/B	1	3-channel VISSR
	FY-2 C/D/E	1	5-channel VISSR
FY-3	FY-3 A/B	10	10-channel VIRR
			MERSI
			IRAS
			MWTS
			MWHS
			MWRI
			SBUS
			TOU
			ERM
			SIM
	FY-3C	11	GNOSS
	FY-3D	10	HIRAS
			GAS
FY-4	FY-4A	3	AGRI
			GIIRS
			LMI



Optical Imager

Atmospheric Sounder

Microwave Imager

Atmospheric Composition Detector

Radiation Budget Monitor

On-orbit Calibration Methodology

Calibration Equation

$$L_O = L_W + \frac{L_W - L_C}{C_W - C_C} \times (C_O - C_W) + L_{nl} + \Delta L_A$$

Blackbody

$$L_W = T_{EA}(1-\eta_A) + \eta_A\{T_{ET}(1-\eta_T) + \eta_T[(1-\varepsilon)T_{EC}(1-\eta_H) + (1-\varepsilon)T_H\eta_H$$

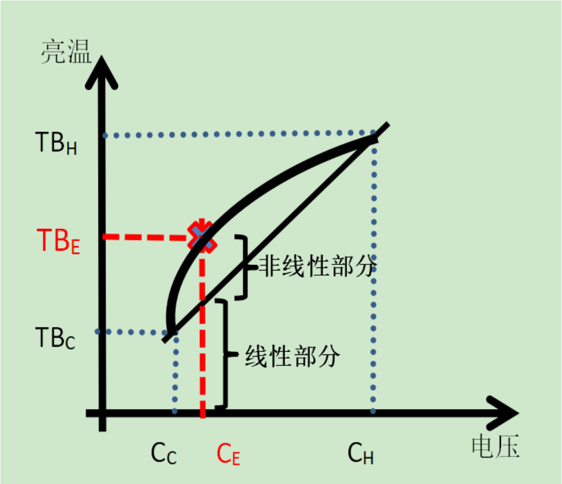
Non-linearity

$$L_{nl} = u \times G^2 \times (C_O - C_C) \times (C_O - C_W)$$

$$u = f(T_{rec}, AGC)$$

Residual Term

$$\Delta L_A = L_{sys}\left[\frac{1}{\Delta v\tau} + \left(\frac{\Delta G}{G}\right)^2\right]^{1/2}$$



Onboard Calibration System

- **State of art:** International: visible 2%, infrared 0.2K, stability <1%
- **Fengyun:** visible 7-10%, infrared 1-1.5K, stability?
- **Fengyun:** Large change before and after launch, poor in-orbit stability

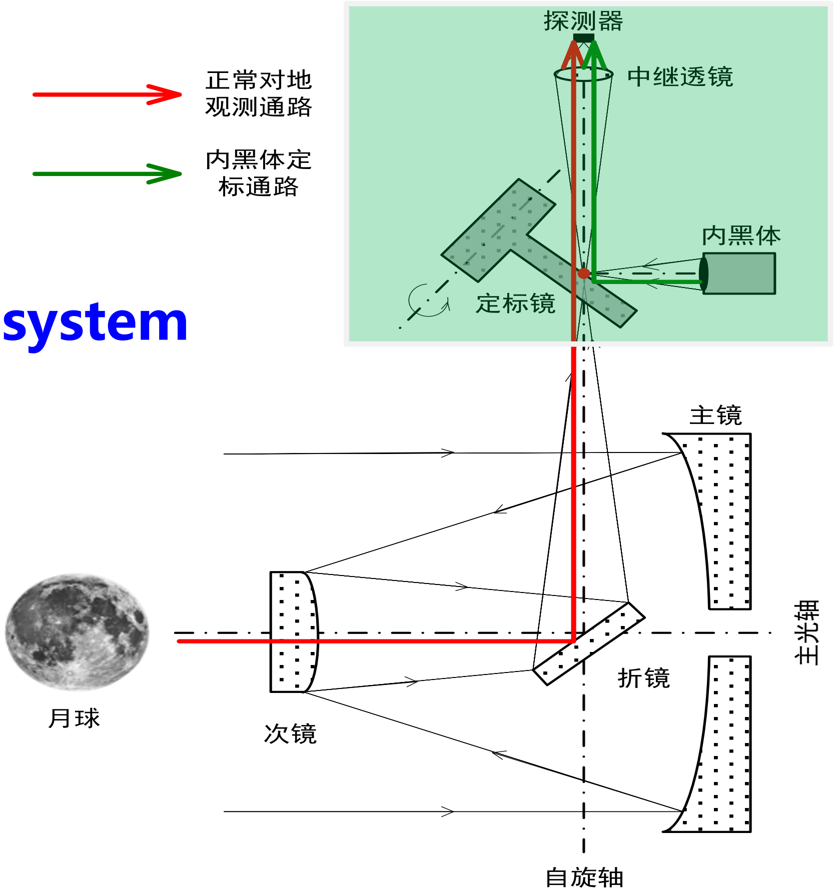
Onboard Calibration System on FY-2 and FY-3 satellites

Spectral band	On-board calibration	Instrument	uncertainties
UV bands	Sun + diffuse reflector Mercury lamp + solar continuous spectrum	TOU/FY-3 SBUS/FY-3	1) State change before and after launch 2) Attenuation of diffuse reflector
Visible and NIR bands	VOC: small integrating sphere with diameter of 6 cm, light beam expanding system, trap detector	MERSI/FY-3	1) State change before and after launch 2) Degradation
	Moon observation	MERSI/FY-3C	Moon model accuracy
	Tungsten halogen lamp	ERM/FY-3	1) State change before and after launch 2) Degradation
	Absolute radiometer	SIM/FY-3	1) State change before and after launch 2) Degradation
Infrared bands	Onboard blackbody + space view	VISSR/FY-2 VIRR/FY-3 MERSI/FY-3 IRAS/FY-3	1) State change before and after launch 2) Blackbody temperature control accuracy 3) Accuracy and changes in blackbody emissivity 4) Extent of the cold space contaminated by radiation
	Onboard blackbody (two temperature points)	ERM/FY-3	1) State change before and after launch 2) Blackbody temperature control accuracy 3) Accuracy and changes in blackbody emissivity
Microwave bands	Onboard blackbody + space view	MWTS/FY-3 MWHS/FY-3 MWRI/FY-3	1) State change before and after launch 2) Blackbody temperature control accuracy 3) Accuracy and changes in blackbody emissivity 4) Extent of the cold space contaminated by radiation

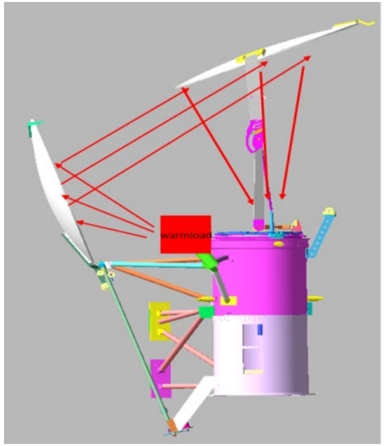
FY-2 VISSR onboard calibration system

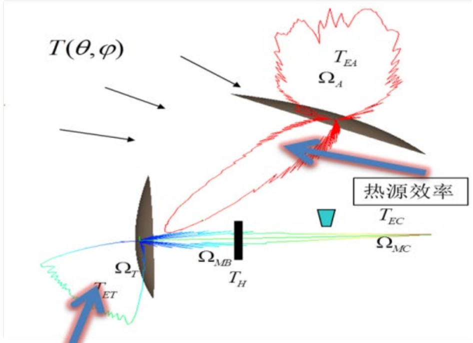
Semi-optical path calibration system

Calibration Uncertainty about 2~8K on TIR bands

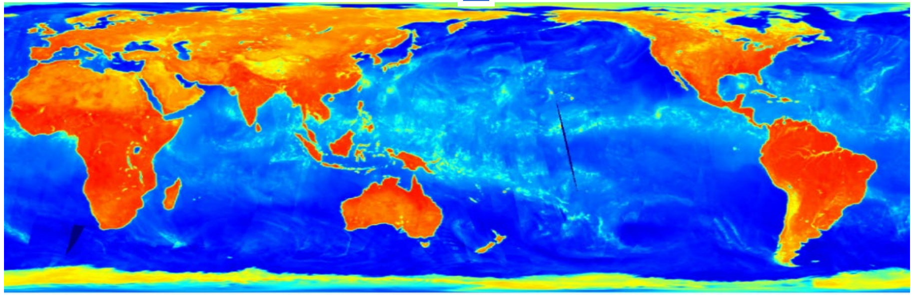


FY-3 MWRI onboard Calibration System

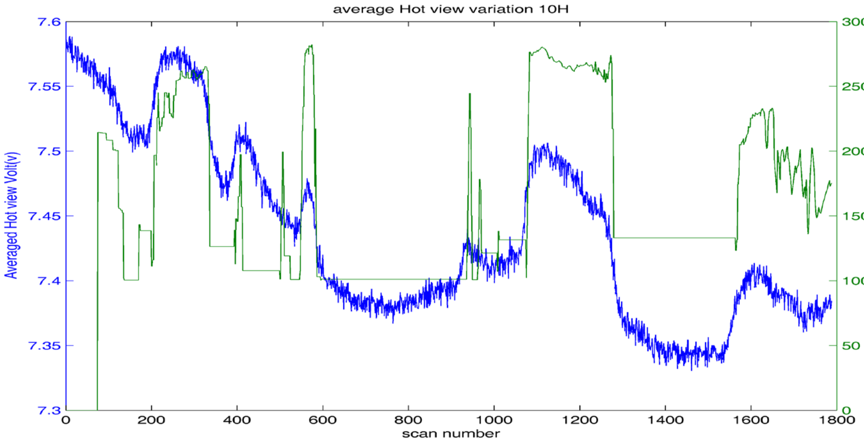




热镜背瓣



Hot mirror dorsal lobe effect



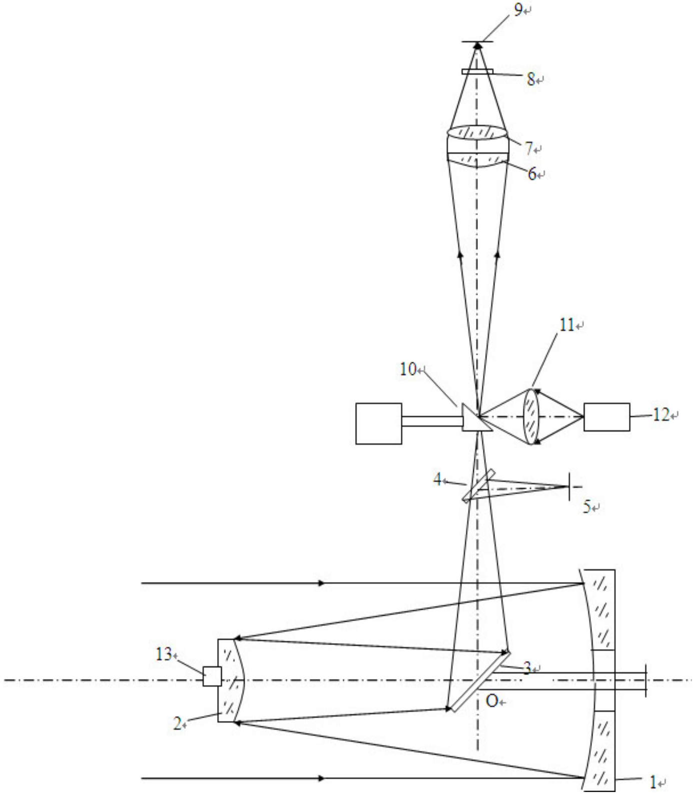
Calibration Uncertainty about 0.2~0.4K on MW bands

Nonlinearity comparison among Microwave sounding instruments (vacuum calibration test)

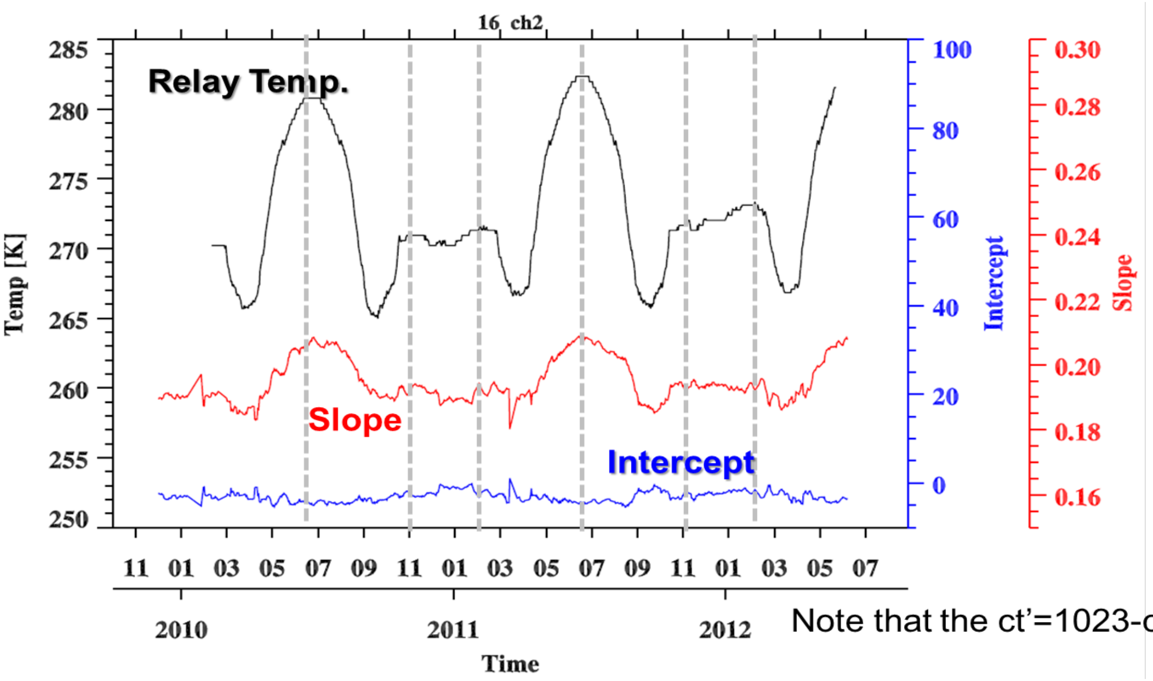
CH	1	2	3	4	5	6	7	8	9	10	11	12
Fre. (GHz)	23.8	31.4	50.3	51.76	52.8	53.596±0.115	54.4	54.94	55.5	f0±57.29	f0±0.3222±0.217	f0±0.3222±0.048
SNPPATMS (K)	0.3	0.4	0.1	-0.08	-0.05	-0.08	0.07	0.1	0.1	0.4	0.4	0.4
FY-3D MWTS MWHS (K)			-0.48	-0.99	-0.73	-0.59	-0.65	-0.64	-0.58	-0.80	-0.82	-0.80

CH	13	14	15	16	17	18	19	20	21	22
Fre. (GHz)	f0±0.3222±0.022	f0±0.3222±0.010	f0±0.3222±0.0045	88.2	165.5	183.31±7	183.31±4.5	183.31±3	183.31±1.8	183.31±1
SNPP ATMS (K)	0.5	0.4	0.5	0.2	0.4	0.2	0.2	0.2	0.3	0.3
FY-3D MWTS MWHS (K)	-0.96	-0.75	-0.58	2.7	0.9	3.4	1.9	0.9	0.2	0.5

Satellite Environment Status:



VISSR/FY-2 radiometric uncertainty affected by relay mirror temperature

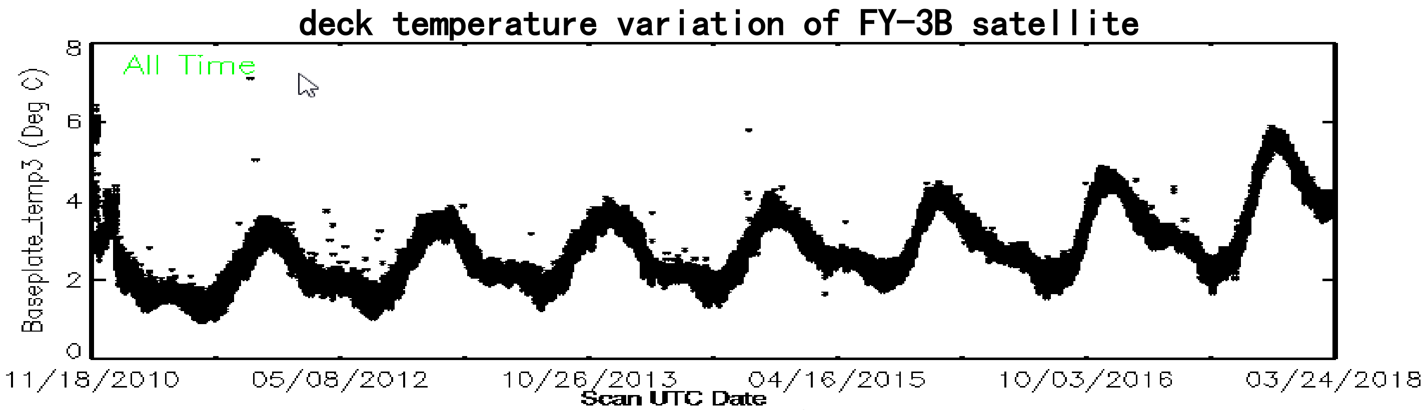


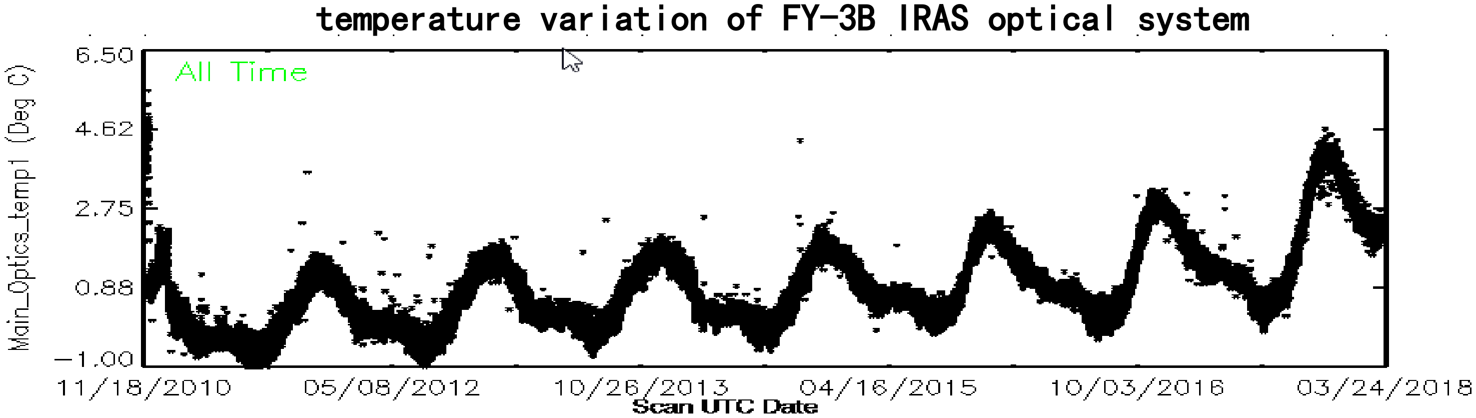
Note that the ct’=1023-ct

FY-2E VISSR Relay Miror Temp

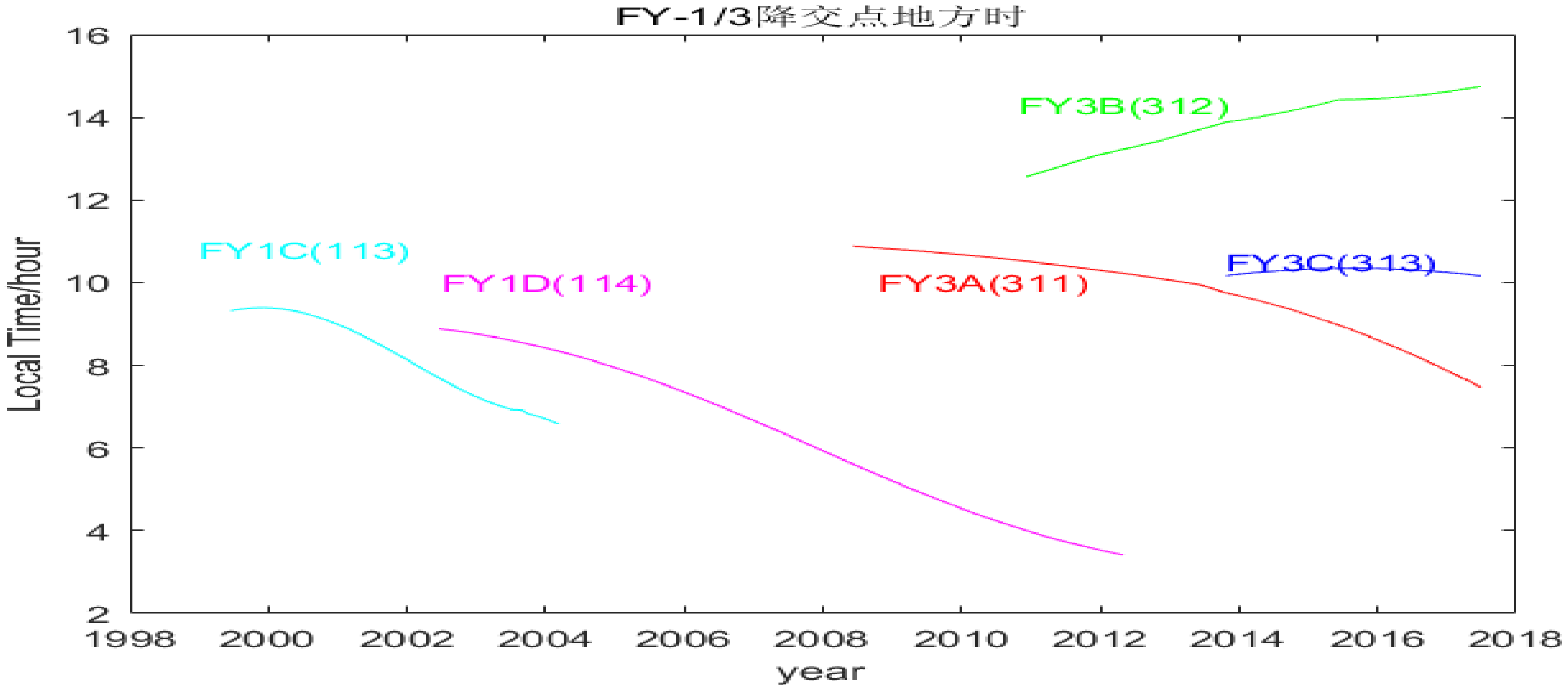
Satellite Environment Status: all-life-time model

Temperature Status of IRAS/FY-3b

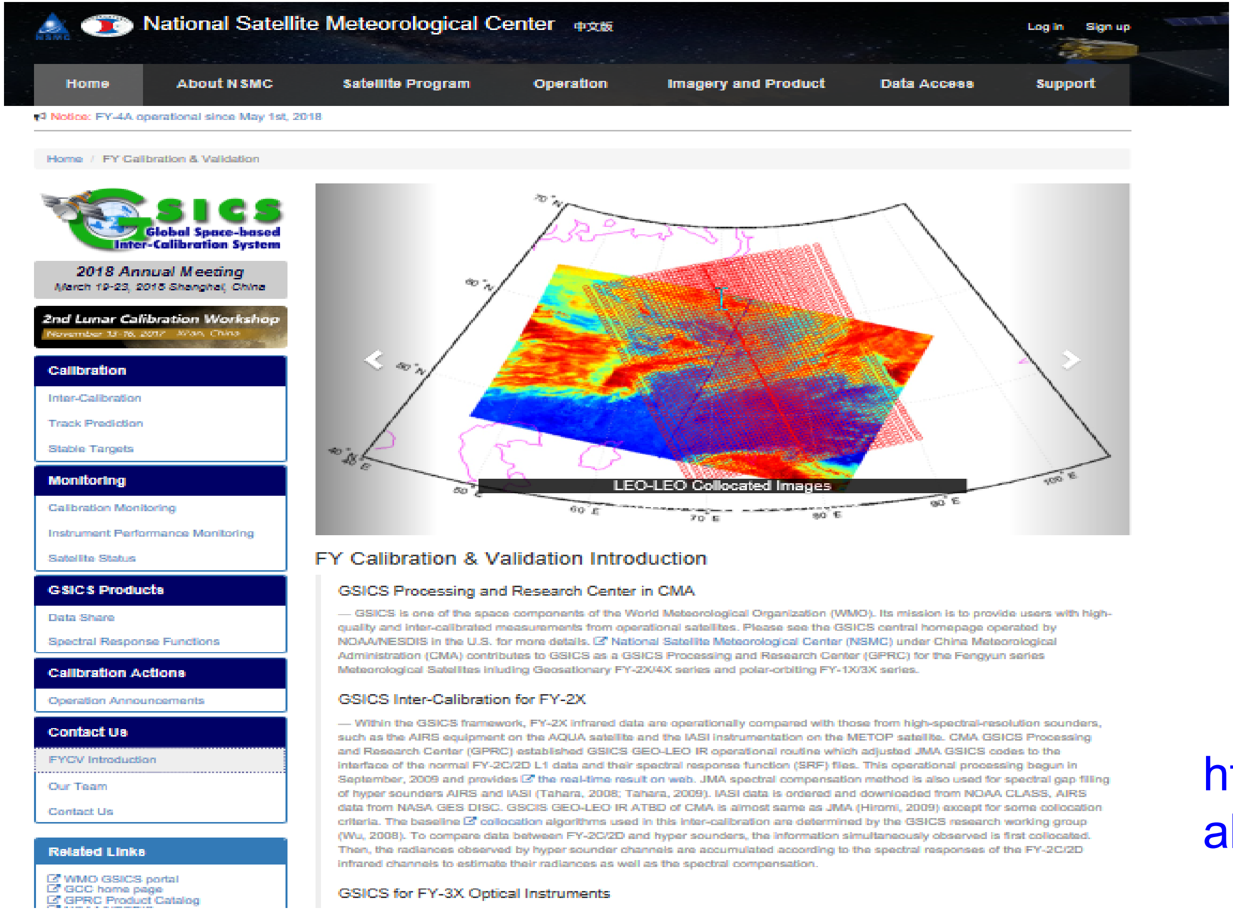




FY Polar orbit drift (Local time at descending node)

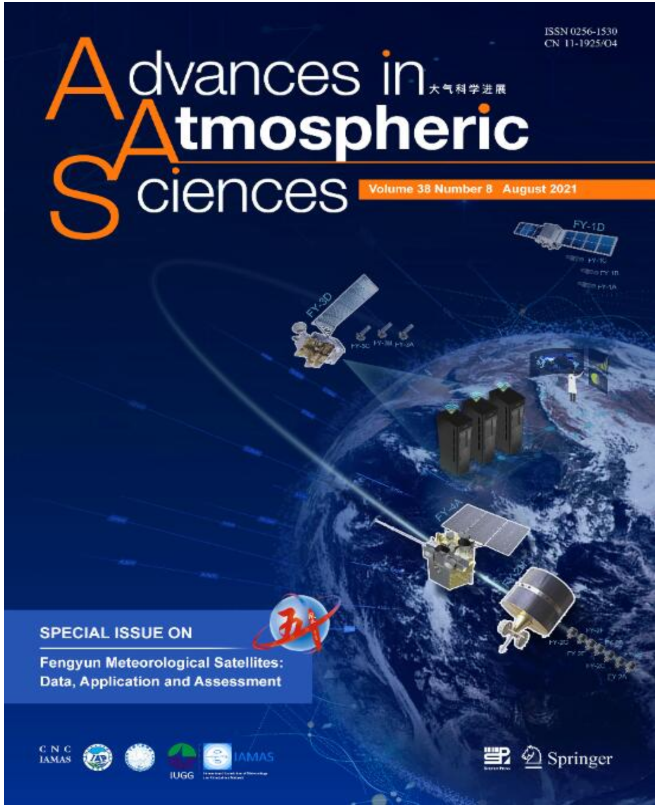


FY Calibration Information can be found



http://gsics.nsmc.org.cn/portal/en/fycv/index.html

Special Issue has been published



The First Fengyun Satellite International User Conference

Di XIAN, Peng ZHANG, Meng FANG, Chang LIU, Xu JIA
Accepted Manuscript, Available online 11 March 2020 , Manuscript accepted 09 March 2020, doi: 10.1007/s00376-020-2011-5
[Abstract](434) [FullText HTML] (167) | [PDF 1536KB](63)

Insights into the Microwave Instruments Onboard the Fengyun 3D Satellite: Data Quality and Assimilation in the Met Office NWP System

Fabien CARMINATI, Nigel ATKINSON, Brett CANDY, Qifeng LU
Accepted Manuscript, Available online 04 June 2020 , Manuscript accepted 28 May 2020, doi: 10.1007/s00376-020-0010-1
[Abstract](474) [FullText HTML] (188) | [PDF 2395KB](54)

Water Vapor Retrievals from Near-infrared Channels of the Advanced Medium Resolution Spectral Imager Instrument onboard the Fengyun-3D Satellite

Ling WANG, Xiuqing HU, Na XU, Lin CHEN
Accepted Manuscript, Available online 08 September 2020 , Manuscript accepted 07 September 2020, doi: 10.1007/s00376-020-0174-8
[Abstract](83) | [FullText HTML] (34) | [PDF 3047KB](46)

Growing operational use of FY-3 data in the ECMWF system

Niels Bormann, David Duncan, Stephen English, Sean Healy, Katrin Lonitz, Keyi Chen, Heather Lawrence, Qifeng Lu
Accepted Manuscript, Available online 05 November 2020 , Manuscript accepted 04 November 2020, doi: 10.1007/s00376-020-0207-3
[Abstract](34) | [FullText HTML] (18) | [PDF 1312KB](7)

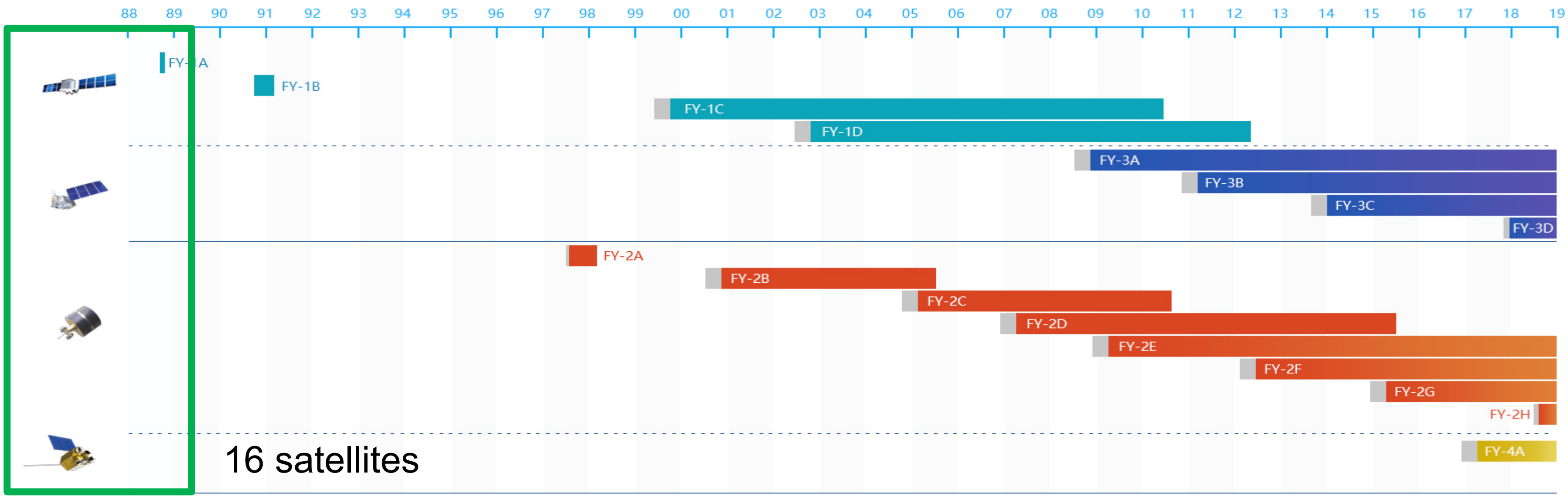
Rainfall Algorithms Using Oceanic Satellite Observations from MWHS-2

Ruiyao Chen, Ralf Bennartz
Accepted Manuscript, Available online 17 November 2020 , Manuscript accepted 13 November 2020, doi: 10.1007/s00376-020-0258-5
[Abstract](24) | [FullText HTML] (12) | [PDF 1638KB](6)

5. Recalibration to Fundamental Climate Data Record (FCDR): FY as example

- In 1998, Pathfinder project was proposed by NOAA and NASA for reprocessing AVHRR,TOVS,GEOS,SSM/I.
- In 2010, GCOS proposed satellite observed ECV concept, ESA started CCI(Climate Change Initiative), including 14 ECV products.
- CEOS WGCV proposed QA4ECV plan, aiming at an internationally recognized QA framework, providing understandable and traceable quality.
- C3S was proposed coordinating with Copernicus space program, FIDUCEO and GAIA-CLIM were funded.
- Satellite based climate dataset construction was supported by Chines 11^{th} and 12^{th} Five-Year plans, mainly using overseas satellites.

Goal for FY series: FCDR



Instruments:

- **VIRR:** **FY-1A/B/C/D FY-3A/B/C**
- **MERSI/IRAS/MWTS/MWHS/MWRI:** **FY-3A/B/C**
- **VISSR:** **FY-2A/B/C/D/E/G**

Accuracy:

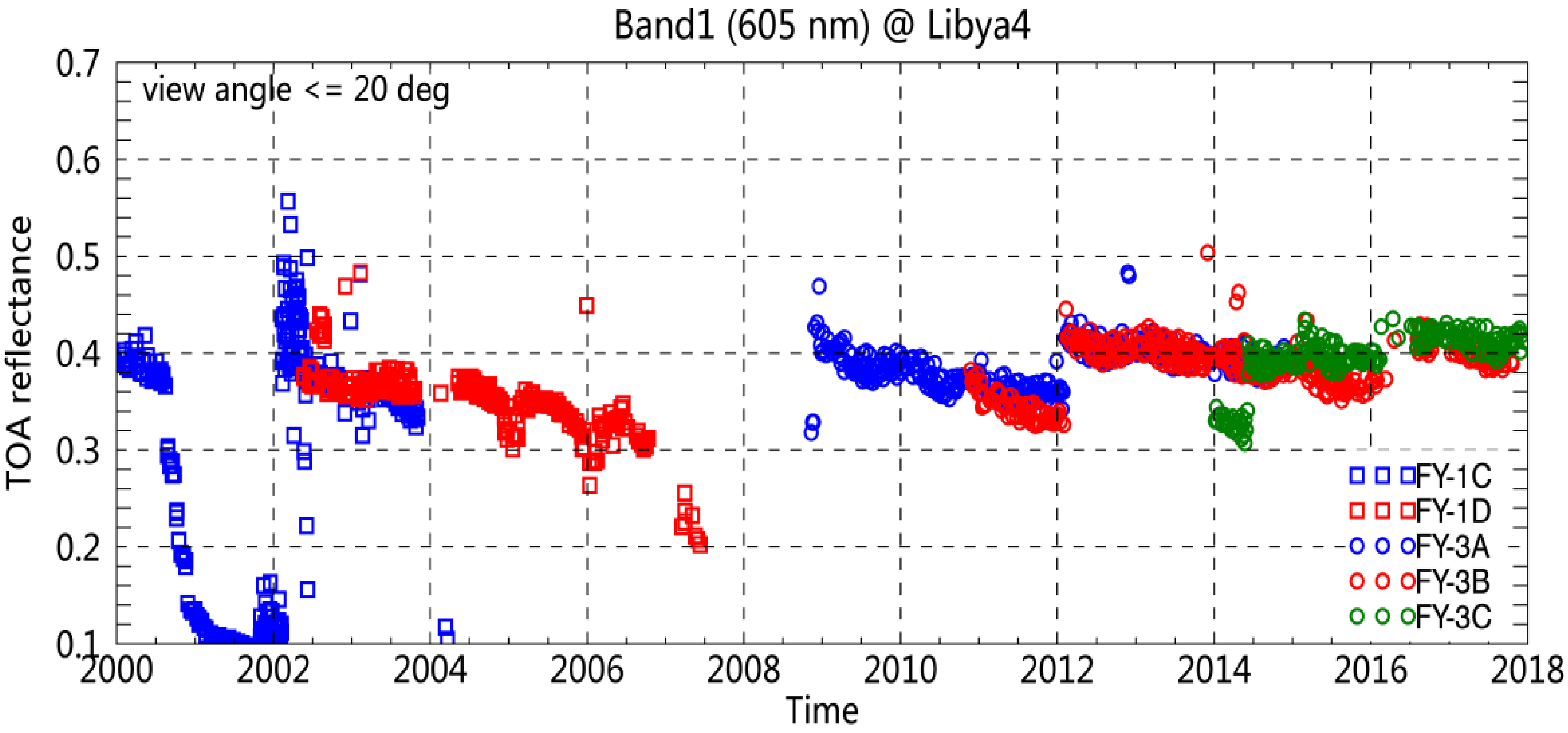
- **RSB: 8%(R&D), 5%(O)**
- **TIR: 1K(R&D), 0.5K(O)**
- **MW: 1K(Absorption),1.5K(Window)**

FY：13 satellites and 7 instruments

Satellite	Instrument	Wavelength	Total Channel No.	Spatial Resolution	Lifetime
FY-1A	VIRR	0.48 – 12.5 μm	5	1.1 km	1988.9.8（1988.9.7） – 1988.10.17（1988.10.17）
FY-1B	VIRR	0.48 – 12.5 μm	5	1.1 km	1990.9.3 （1990.9.3）– 1991.2.15（1991.2.15）
FY-1C	VIRR	0.43 – 12.5 μm	10	1.1 km	1999.5.10（1999.5.10）– 2004.4.26（2004.4.26）
FY-1D	VIRR	0.43 – 12.5 μm	10	1.1 km	2002.5.15（2002.5.15）– 2012.4.1（2012.4.1）
FY-2A	VISSR	0.5 – 12.5 μm	3	1.25 km, 5 km	1997.6.10（1997.6.10） – 1998.2.12（1998.2.12）
FY-2B	VISSR	0.5 – 12.5 μm	3	1.25 km, 5 km	2000.7.19（2000.6.25） – 2005.6.2（2005.6.2）
FY-2C	VISSR	0.5 – 12.5 μm	5	1.25 km, 5 km	2004.10.27（2004.10.19） – 2010.8.2（2010.8.2）
FY-2D	VISSR	0.5 – 12.5 μm	5	1.25 km, 5 km	2006.12.19（2006.12.8）– 2015.6.30（2015.6.30）
FY-2E	VISSR	0.5 – 12.5 μm	5	1.25 km, 5 km	2009.2.17（2008.12.23） – 今
FY-2G	VISSR	0.5 – 12.5 μm	5	1.25 km, 5 km	2015.6.3（2014.12.31） – 今
FY-3A	VIRR 2	0.43 – 12.5 μm	10	1.1 km	2008.5.29（2008.5.27） – 2018.3.6（2018.3.6）
	MERSI 1	0.41 – 11.25 μm	20	250 m, 1 km	2008.6.2（2008.5.27） – 2018.2.11（2018.3.6）
	IRAS	0.69 – 1.64 μm & 3.76 – 14.95 μm	26	17 km	2008.6.26（2008.5.27） – 2016.8.13（2018.3.6）
	MWTS 1	50 – 57 GHz	4	50 – 60 km	2008.6.8（2008.5.27） – 2013.5.6（2018.3.6）
	MWHS 1	150 GHz, 183 GHz	5	15 km	2008.5.31（2008.5.27） – 2016.8.13（2018.3.6）
	MWRI	10 – 89 GHz	10	12 – 75 km	2008.6.6（2008.5.27） – 2010.5.18（2018.3.6）
FY-3B	VIRR 2	0.43 – 12.5 μm	10	1.1 km	2010.11.18（2010.11.5） – 今
	MERSI 1	0.41 – 11.25 μm	20	250 m, 1 km	2010.11.18（2010.11.5） – 今
	IRAS	0.69 – 1.64, 3.76 – 14.95 μm	26	17 km	2010.11.18（2010.11.5） – 今
	MWTS 1	50 – 57 GHz	4	50 – 60 km	2010.11.18（2010.11.5） –2014.2.21
	MWHS 1	150 GHz, 183 GHz	5	15 km	2010.11.18（2010.11.5） – 今
	MWRI	10 – 89 GHz	10	12 – 75 km	2010.11.18（2010.11.5） – 今
FY-3C	VIRR 2	0.43 – 12.5 μm	10	1.1 km	2013.9.25（2013.9.23） – 今
	MERSI 1	0.41 – 11.25 μm	20	250 m, 1 km	2013.9.30（2013.9.23） –2015.5.30
	IRAS	0.69 – 1.64, 3.76 – 14.95 μm	26	17 km	2013.9.29（2013.9.23） – 今
	MWTS 2	50 – 57 GHz	4	50 – 60 km	2013.9.30（2013.9.23） – 今
	MWHS 2	150 GHz, 183 GHz	5	15 km	2013.9.30（2013.9.23） – 今
	MWRI	10 – 89 GHz	10	12 – 75 km	2013.9.29（2013.9.23） – 今

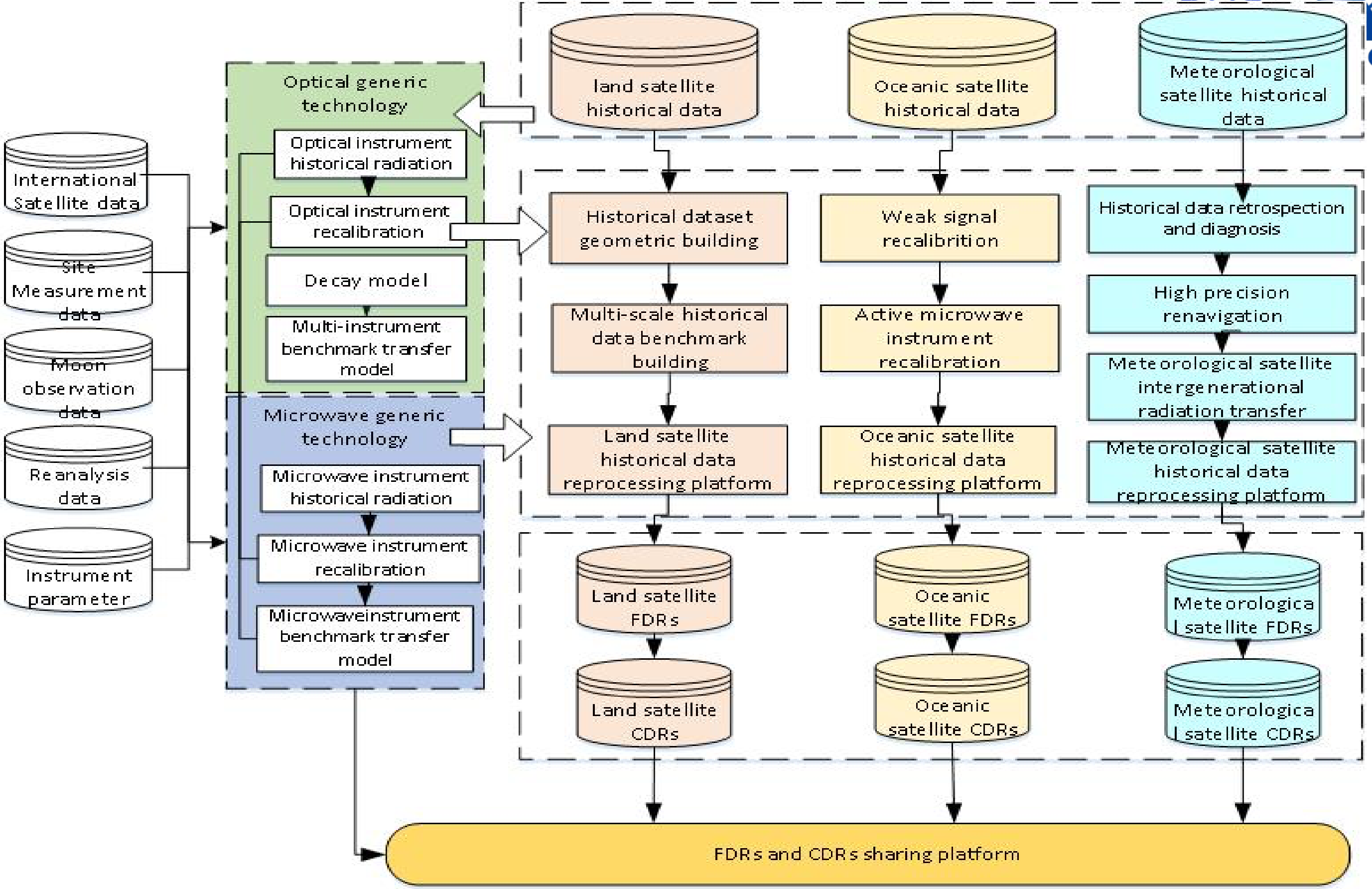
RSB channels Degradation monitoring by PICS

VIRR Harmonization Check with Libya 4



Solution

- Historic Status Document Re-building
- Onboard Calibration Model Re-building
- Reference/Benchmark Collection (model reanalysis dataset, PICs, Lunar, DCC, reference instrument, Gruan, etc.)



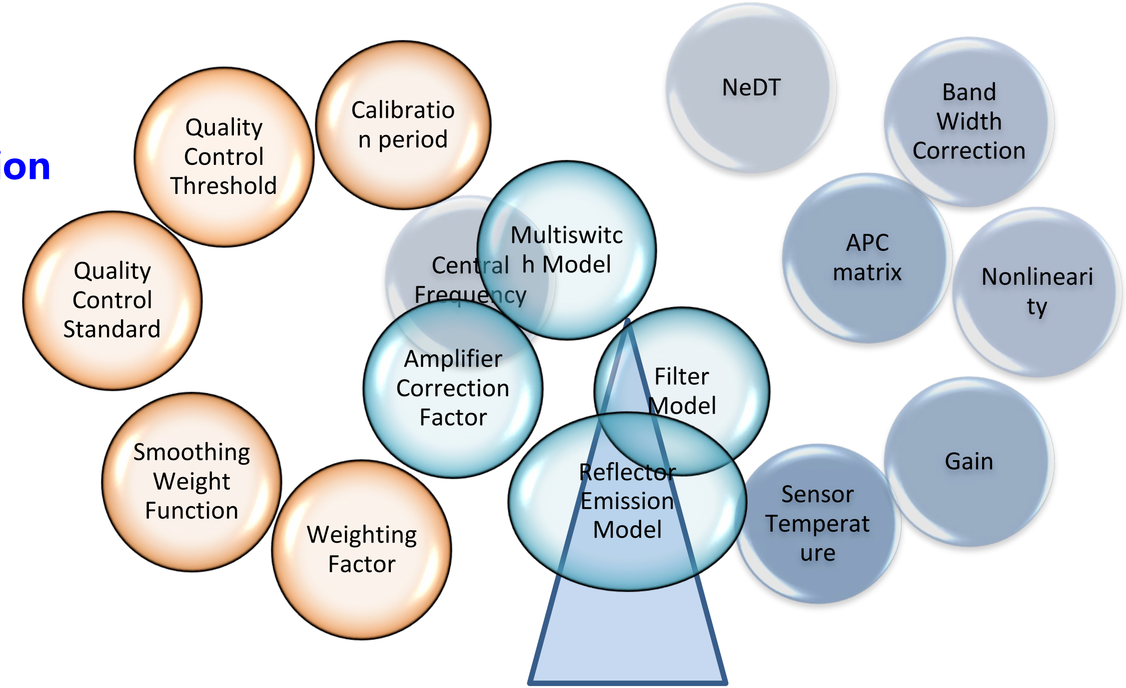
Re-building

Re-procedure

Onboard Calibration Model Re-building

Passive Microwave Sensor

- Theoretical modeling
- Experiment testing
- Application testing and iteration improvement



Passive optical instruments: radiometric reference (1/3)

Calibration Reference	Accuracy	Source
CRCS **(China Remote Sensing Satellite Radiometric Calibration Site)**	Reflectance: 15-30% Stability: 1-2% Directional effect: Yes Spectral: Smooth but not flat Accuracy: 3-5%	**Hu et al, 2010** **Chen et al, 2017**
PICS (Pseudo Invariant Calibration Site)	Reflectance: 15~50% Stability: Directional effect: Yes Spectral: Accuracy: 3%±2%	H. Cosnefroy,1996 Y. M. Govaerts, 2004 G. Chander,2007; P. M. Teillet,2007 **Sun et al., 2012** Mishra et al., 2014 Wang et al., 2018
DCC **(Deep convective cloud)**	Reflectance: 80-90% Stability: 1-2% Directional effect : Yes Spectral: flat Accuracy: 3-5%	B. Fougnie ,2009 B. J. Sohn, 2009
Liquid Water Cloud (LWC)	Reflectance: 20-70% Stability: 3% Directional effect: obvious Spectral: flat Accuracy: 5%	Ham & Sohn， 2010 B.J. Soh， 2013

Passive optical instruments: radiometric reference (2/3)

Calibration Reference	Accuracy	Source
Rayleigh Scattering	Reflectance: 5~10% Stability: 1~2% Directional effect: Yes Accuracy: 3~5%	E. Vermote, 1992 E. Dilligeard， 1997 O. Hagolle,1999
Sun glint	Reflectance: 5~50% Stability: 1% Directional effect : Yes Accuracy: 1~2% High degree of polarization; Fat spectrum; Reflectance depends on observation geometry and sea surface roughness	C. Cox and W. Munk， 1954； B. Toubbé, 1999； O. Hagolle, 2004；
Snow	Reflectance: >90%(300-700 nm) Stability: 1.5% Directional effect: Yes Spectral: flat (<700) Accuracy: 2%	Masonis et al., 2001 Wu et al., 2009 **Wang et al., 2019**
Moon	Reflectance: ~7% Stability: 10^{-8}/year Directional effect: Yes Spectral: flat Uncertainty: 5-10% (ROLO)	Kieffer and Stone, 2005 Miller and Turner, 2009 **Zhang, et al., 2017**

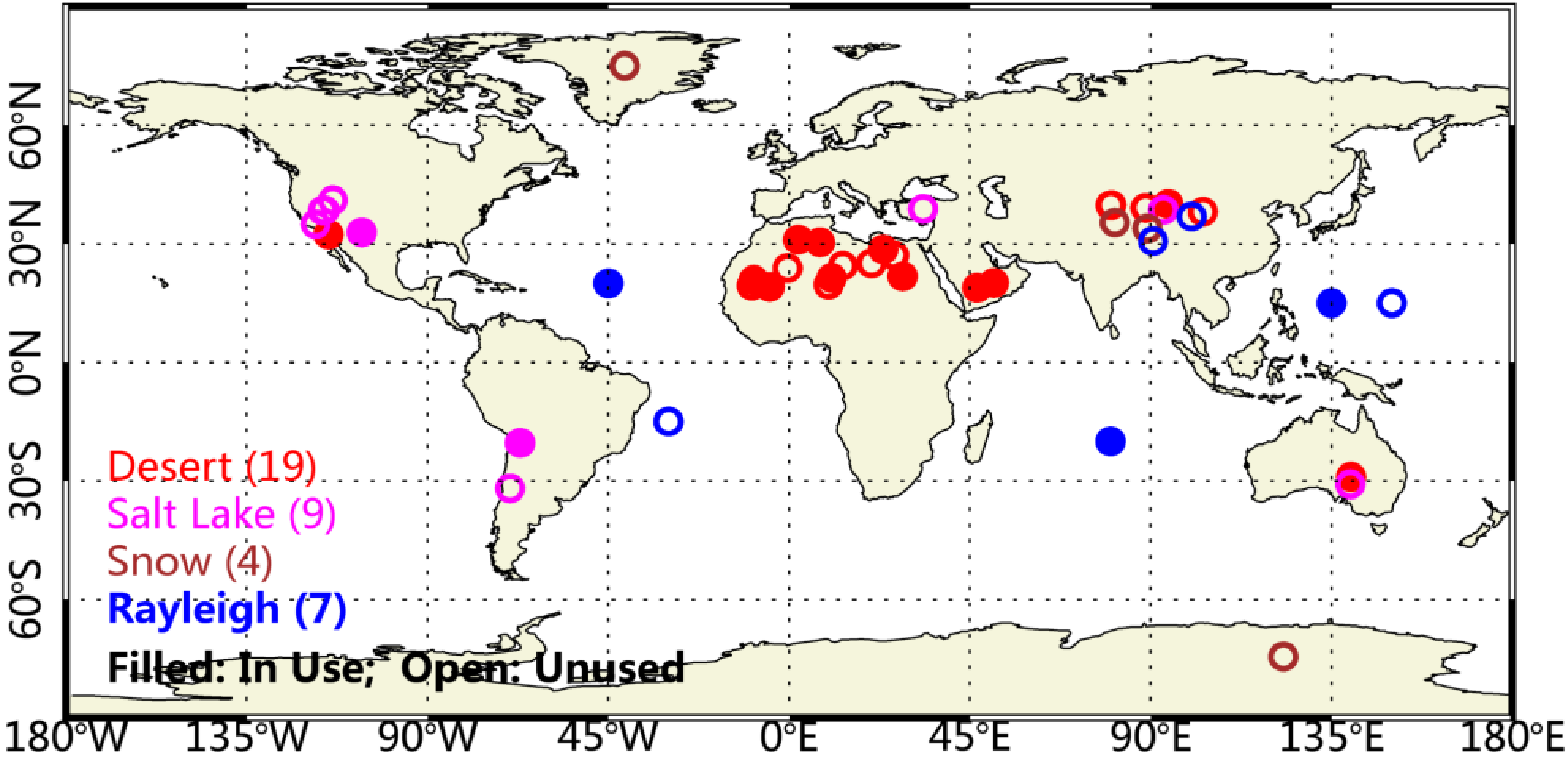
Passive optical instruments: radiometric reference (3/3)

Reference Instrument	Accuracy	Source
HIRS	Stability: 0.2K Number of channels： 20 Accuracy: 0.5K；	L. Shi, 2013
IASI	Stability: 0.2K Spectral resolution: 0.25cm-1 Accuracy: 0.2K；	T. J. Hewison， 2013
AIRS	Stability: 0.2K Spectral resolution: 0.625cm-1 Accuracy: 0.2K；	L. Wang， 2011
CrIS	Stability: 0.2K Spectral resolution: 0.625cm-1 Accuracy: 0.2K；	Hui Xu, 2018 Likun Wang, 2017
MODIS	Stability: 0.1K/1% Number of channels： 36 Accuracy: 0.2K (IR)； 2% (RSB)	A. K. Heidinger， 2002 X. J. Xiong， 2010； C. Cao,2008
VIIRS	Stability: 0.1K/1% Number of channels： 36 Accuracy: 0.2K (IR)； 2% (RSB)	

Passive Microwave Sensor: Radiometric Reference

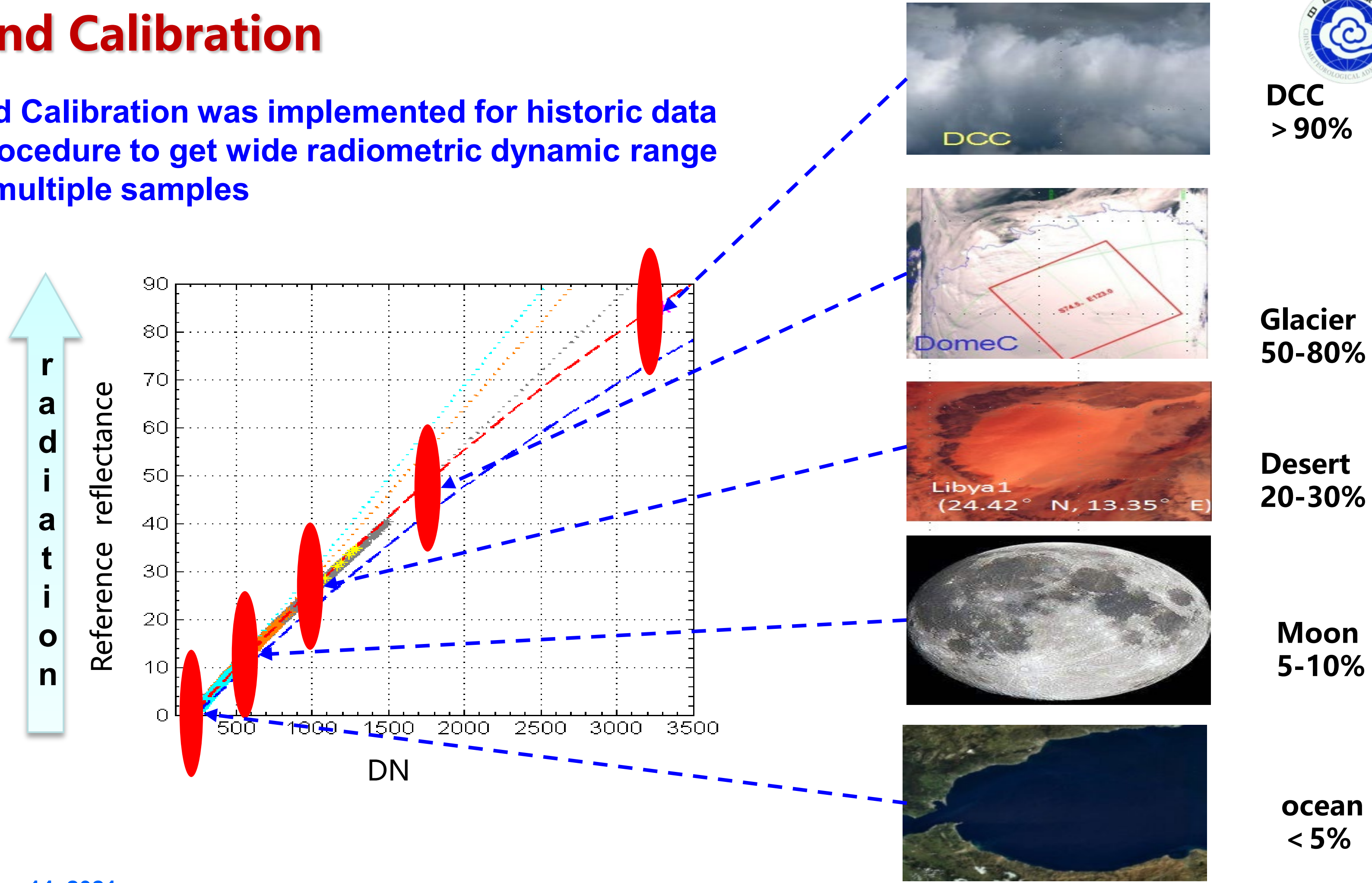
	Accuracy	Source
ERA5	<2.5K	http://www.ecmwf.int/publications
GRUAN	0.6K,6%	http://www.gruan.org
GNSS/OR	0.02%/5 yrs, 0.06 K/5 yrs	Ho, S., et al. 2012: J. Geophys. Res., 117
GMI	Accuracy<0.4K， Stability < 0.2K	Wentz,F.J.and D.Draper, J.Atmos.Oceanic Technol.,33
ATMS	Channel 3-15<0.75K Other Channel <1.0K	Weng, F., et. al. 2013: J. Geophys. Res. Atmos., 118
AMSU	0.5-1K	Cheng-Zhi, et al. 2016: CDR-ATBD
MHS	1K	EUMETSAT， MHS Lecel 1 PGS
SSM/I FCDR	0.5K	Wentz, F. J., 2013. SSM/I Version-7 Calibration Report
Cool Ocean Surface	0.27K/yr （18GHz）	Christopher S. Ruf， 2000. IEEE TGRS 38
Cold Space	2.72548±0.00057K， Peak wavelength 1.063mm， radiation intensity change <0.2%-0.3%	Baike of Baidu
Microwave Calibration Field (Simao)	Bt Change in 30d(Dry season)<0.4K； Horizontal heterogeneity<0.15K 。	“Research on Key Technologies of Microwave Calibration Field” Project closing report， 2009

Pseudo-invariant sites（PICs）

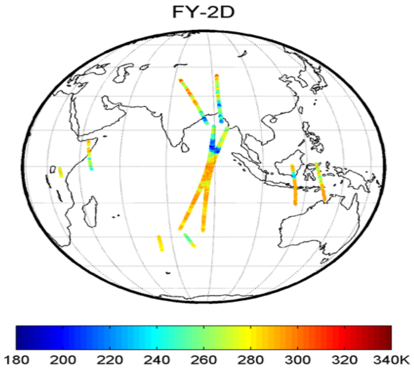


Blend Calibration

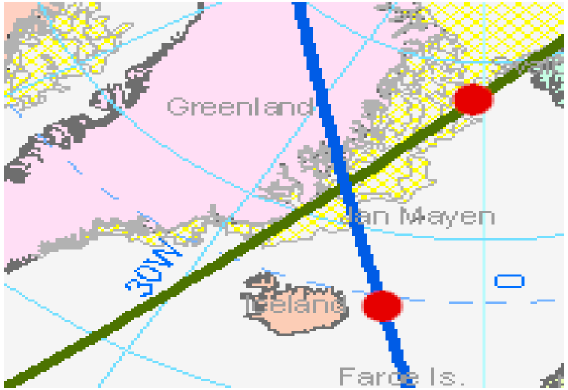
Blend Calibration was implemented for historic data re-procedure to get wide radiometric dynamic range and multiple samples



Inter-calibration with reference sensors



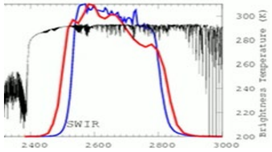
Geo-Leo

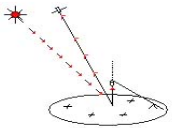


Leo-Leo

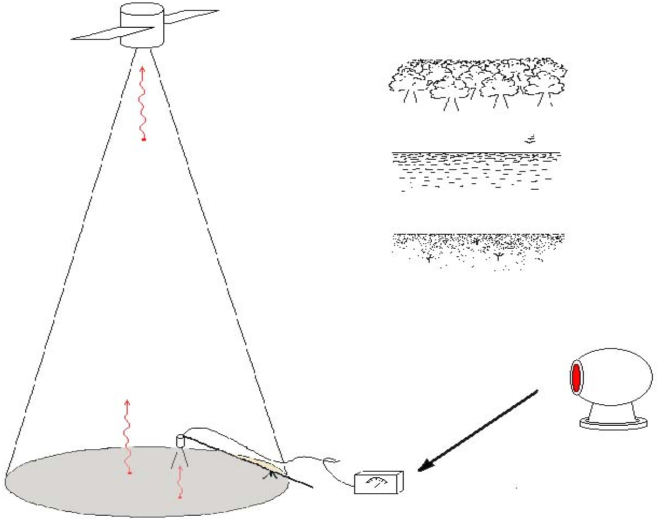
Direct Inter-calibration with global data matching

- Space
- Time
- Geometry
- Spectral

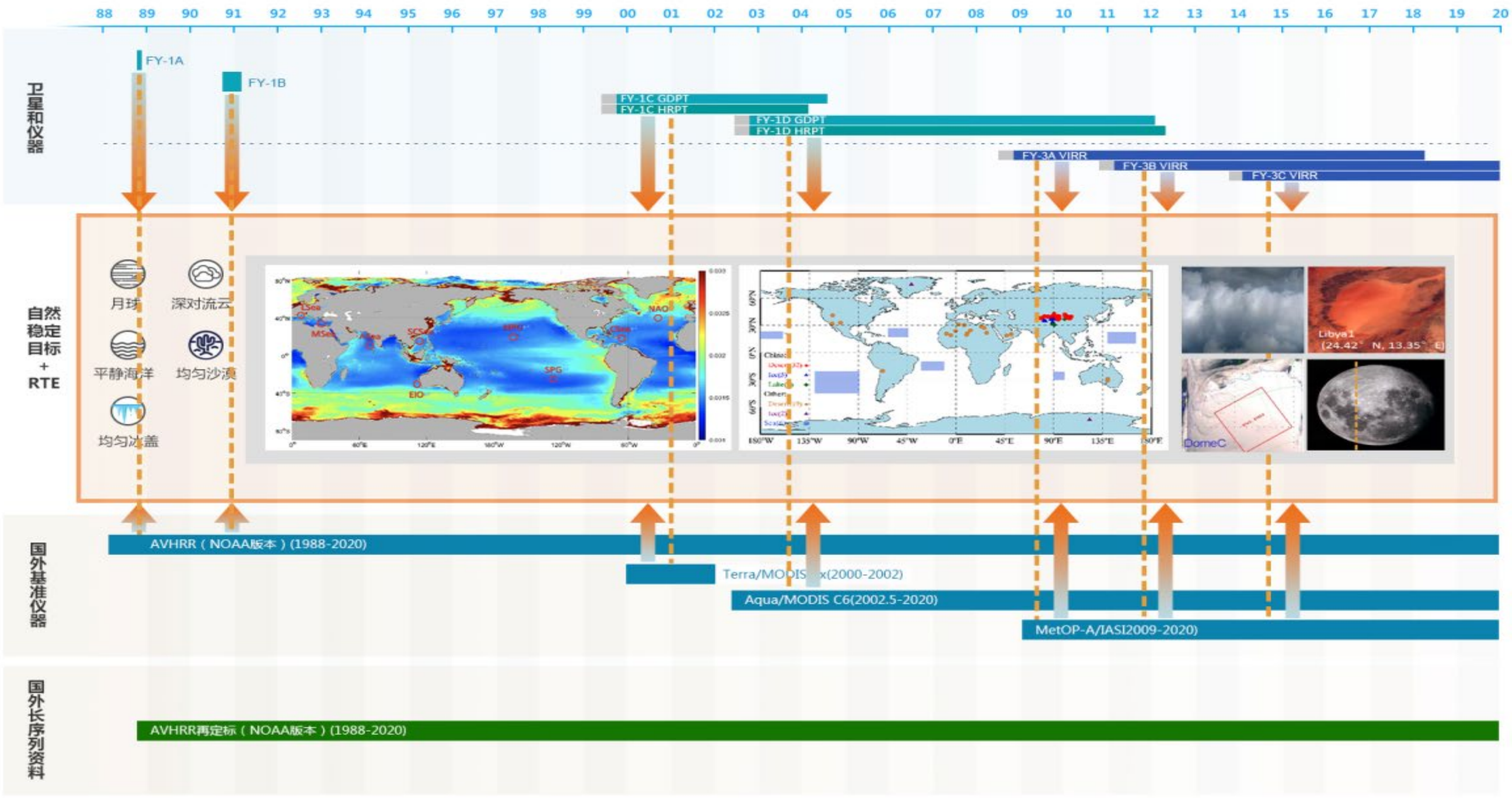




Indirect Inter-calibration with PICS

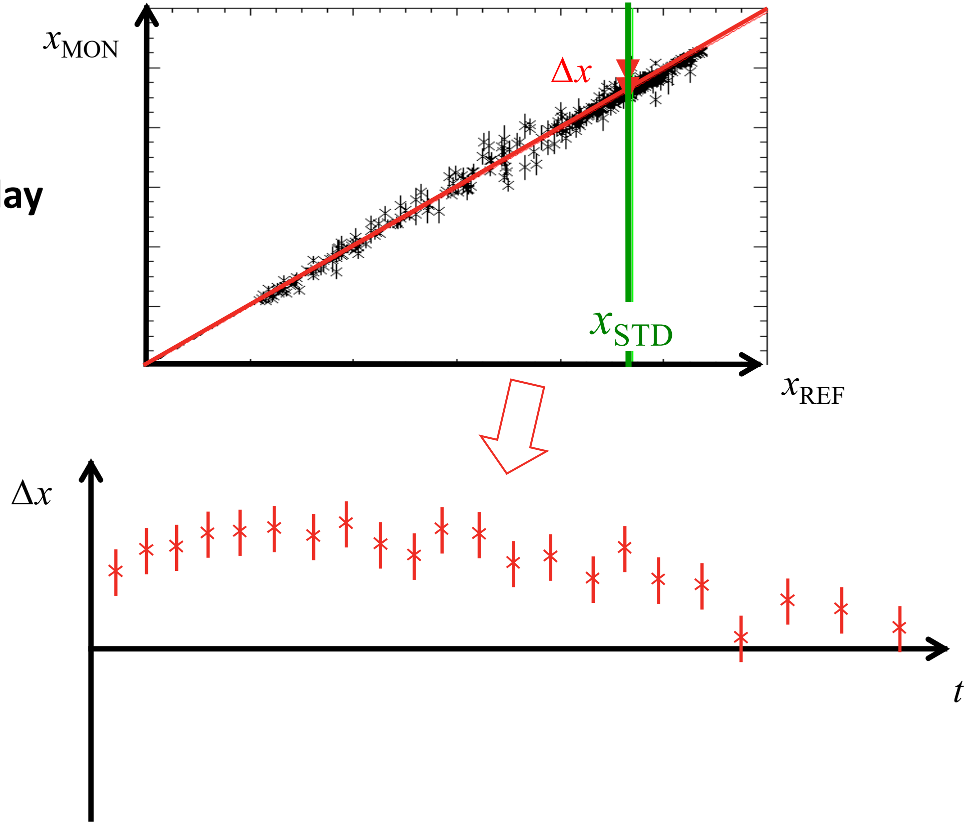


Skeleton Frame of FY Recalibration



Statistical Analysis and Correction

- Comparing samples of x_{MON} , x_{REF}
  - Over fixed domain
  - Period (e.g. 1 orbit/1 day)
  - Typically ~ 1000 comparable samples/day
- Regression
- Calc bias, $\Delta x = x_{\mathrm{MON}} - x_{\mathrm{REF}}$
  - Δx at standard scene, x_{STD}
  - with uncertainty
- Plot time series of bias Δx
  - Compare recent results with long-term trend
  - Valuable for instrument monitoring



Latest Progress

Retrospective Recalibration of Historical Fengyun Satellite Data

Period: 2018.05-2022.04

Sensors included:

- Optical imager: FY-1/3 VIRR, FY-3 MERSI, FY-2 VISSR
- Optical sounder: FY-3/IRAS
- Microwave sounder: FY-3/MWHS&MWTS
- Microwave imager: FY-3/MWRI

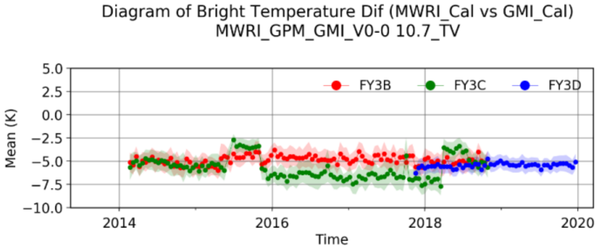
Version	V1 (beta)	V2 (trial)	V3 (formal)
Status	Completed in 2019	Partly completed	To be finished at 2021/12
Main concerns	Lifetime recalibration of each instrument using consistent calibration framework	Focus on the recalibration model improvement to achieve the accuracy and stability	Focus on the inter-instrument consistency, gridded climate dataset

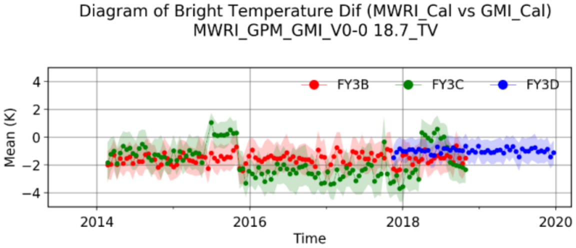
- The beta version (V1) datasets have been finished through the lifetime recalibration of each instrument in 2019.
- At present, the trial version (V2) datasets are finished for MWRI, MWTS and VIRR solar bands, meanwhile others are still ongoing.

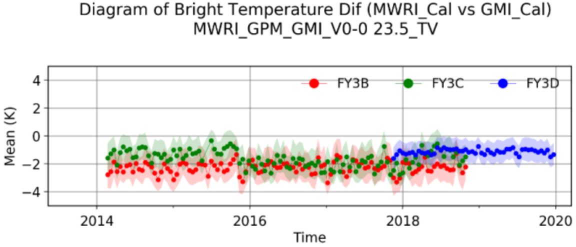
FY-3/MWRI FCDR V1/V2

SNO&DD VS. GMI

Operational





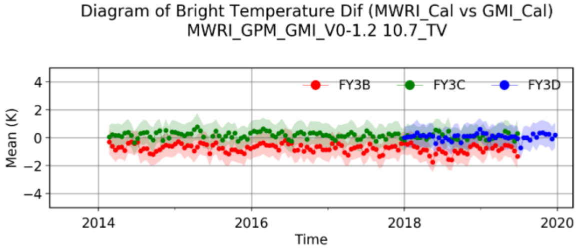


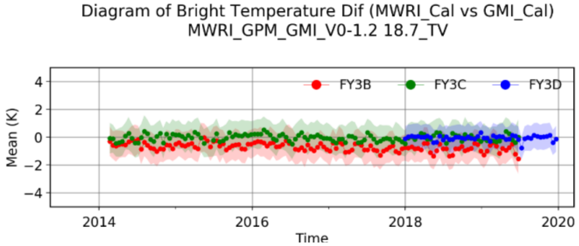
Sensor	Time range
FY-3B/MWRI	2010/11/11-2018/11/30
FY-3C/MWRI	2013/09/29-2019/06/30
FY-3D/MWRI	2017/11/25-present

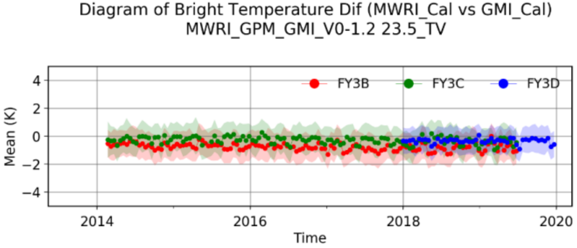
- V2 dataset is finished, covering FY-3B/C/D from 2010 to 2019 .
- 5 major issues improved: hot reflector back lobe correction, hot reflector emissivity correction, hot load efficiency correction, non-linear correction, and cold reflector correction.

V2: Bias mostly within 0.5K;
RMSE all within 1.5K, mostly around 1K.

Re-processed V2







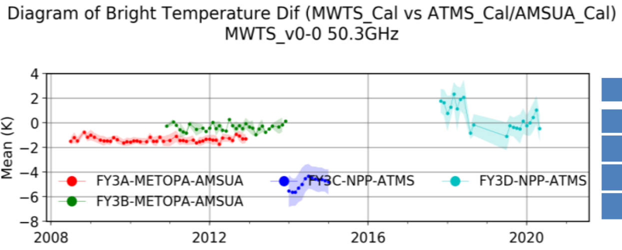
Data DOI: 10.12185/NSMC.RICHCEOS.FCDR.MWRIRecalOrb.FY3.MWRI.L1.GBAL.POAD.NUL.010KM.HDF.2021.2.V1

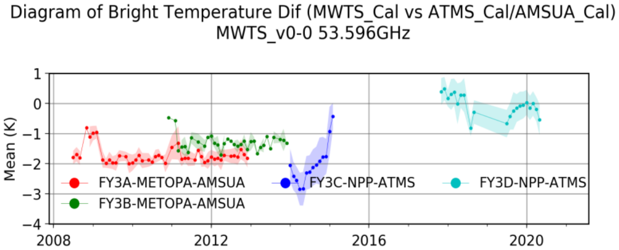
FY-3/MWTS FCDR V2

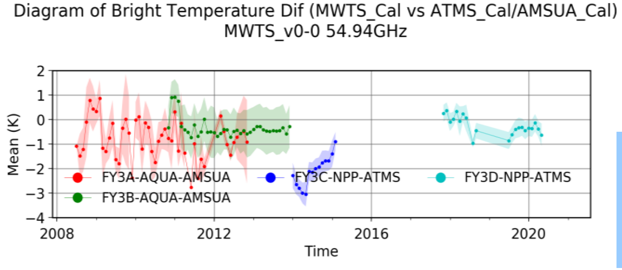
SNO VS. AMSUA/ATMS

Operational

Re-processed V2



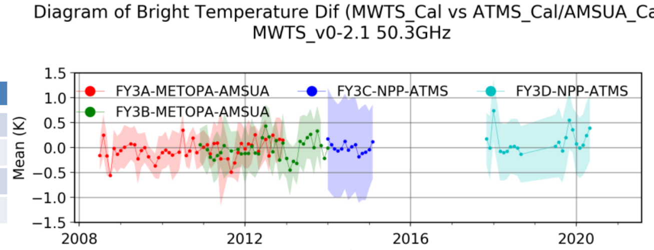


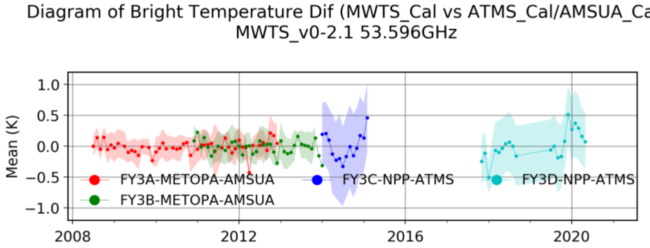


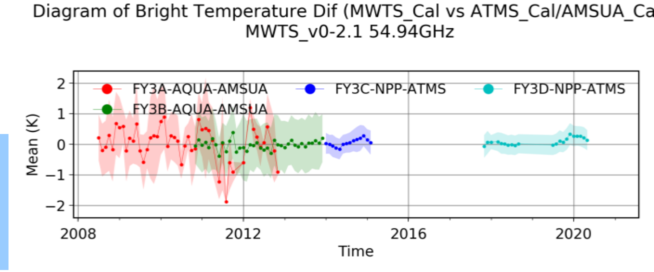
Sensor	Time range
FY-3A/MWTS	2008/07/01-2013/05/06
FY-3B/MWTS	2010/11/11-2014/02/21
FY-3C/MWTS	2013/09/30-2015/02/28
FY-3D/MWTS	2017/11/25-present

- V2 dataset is finished, covering FY-3A/B/C/D from 2008 to 2020.
- Applying new static calibration parameters from pre-launch thermal/vacuum test, data quality control, cold/hot target and nonlinear correction.

V2: RMSE within 1K for channels at 50.3 GHz, 53.596 GHz, 54.94 GHz and 57.29 GHz







FY-3C/IRAS FCDR V2

SNO VS. IASI

Sensor	Dataset coverage
FY-3B/IRAS	2010/11/18-present
FY-3C/IRAS	2013/09/30-2019/10/19

Operational

Diagram of Bright Temperature Dif(IRAS vs IASI)
IRASX_METOP-A_IASI_V0-0-DAY CH_01

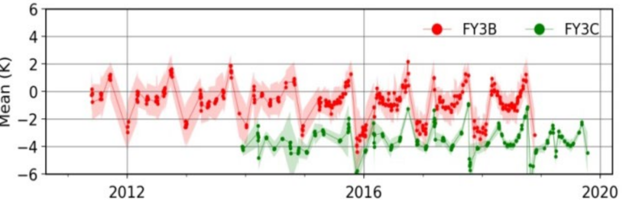


Diagram of Bright Temperature Dif(IRAS vs IASI)
IRASX_METOP-A_IASI_V0-0-DAY CH_14

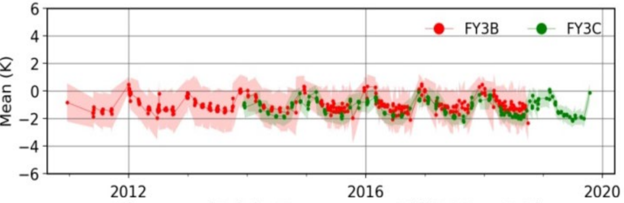
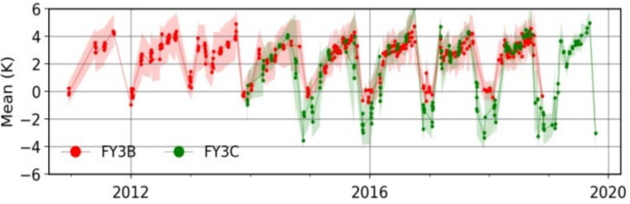


Diagram of Bright Temperature Dif(IRAS vs IASI)
IRASX_METOP-A_IASI_V0-0-DAY CH_18



- V1 dataset covers FY-3B/C from 2010 to 2019, by system bias correction with referenced to IASI.
- V2 dataset is finished with refined model for FY-3C.

- **System biases are corrected for most channels, RMSE in range of 0.5~1.0 K.**
- **Seasonal fluctuation of FY-3C are corrected using V2 refined model .**

Re-processed V2

Diagram of Bright Temperature Dif(IRAS vs IASI)
IRASX_METOP-A_IASI CH_01

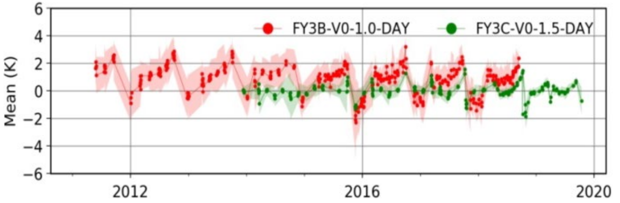


Diagram of Bright Temperature Dif(IRAS vs IASI)
IRASX_METOP-A_IASI CH_14

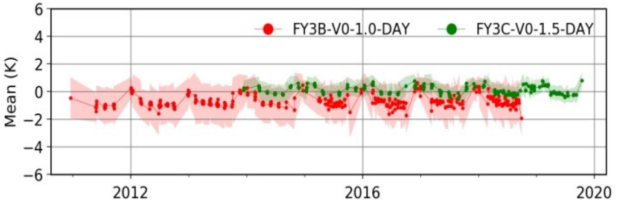
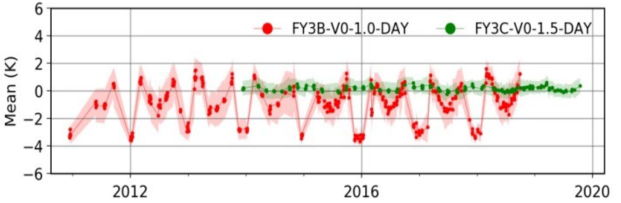


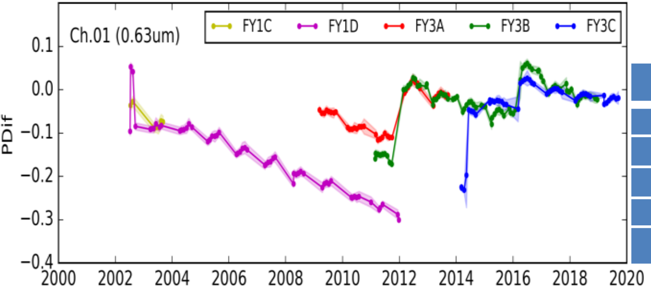
Diagram of Bright Temperature Dif(IRAS vs IASI)
IRASX_METOP-A_IASI CH_18

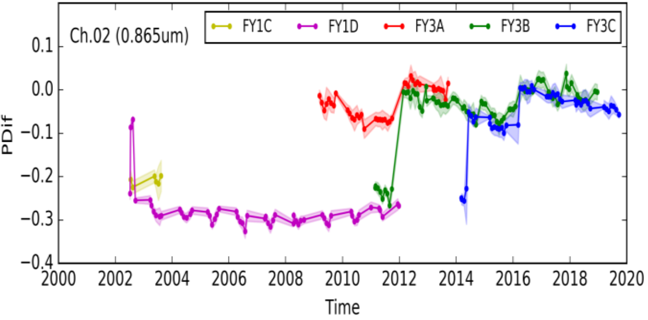


FY/VIRR FCDR V2 (RSBs)

SNO VS. MODIS

Operational

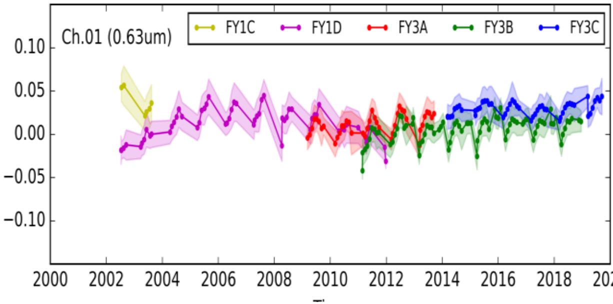


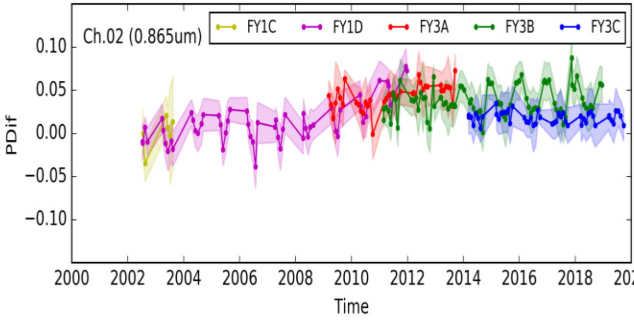


Sensor	Time range
FY-1C/VIRR2	2000/01/21–2004/06/30
FY-1D/VIRR2	2002/07/11–2012/01/13
FY-3A/VIRR3	2008/07/01–2015/01/04
FY-3B/VIRR3	2010/11/14–present
FY-3C/VIRR3	2013/10/01–present

- V2 dataset is finished, covering the time span from 2000 to 2019, using daily gains derived by vicarious calibration approach and the record calibration reference is further traced to Aqua MODIS C6.1 by a systematic correction derived from Libya desert.

Re-processed V2

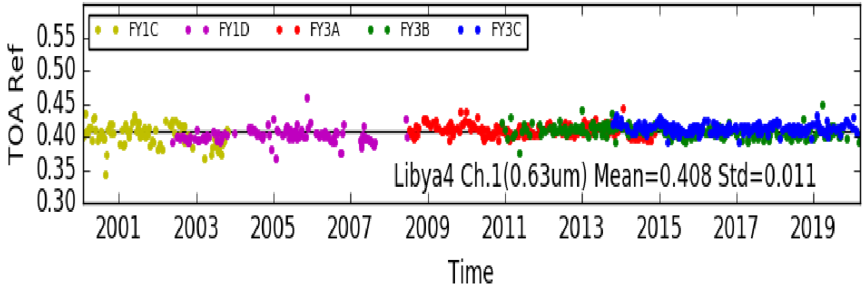


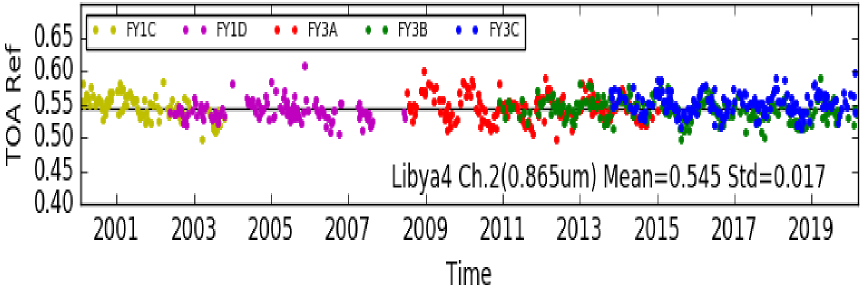


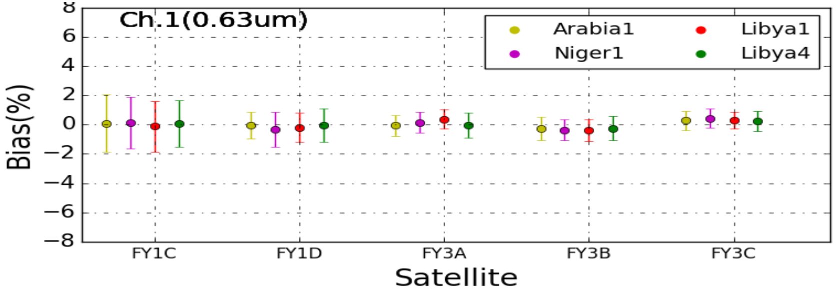
- **Variation of sensor radiometric response both gradual and sudden degradation is corrected, and the radiometric stability and inter-platform consistency is improved after recalibration.**
- **Life-time RMS of the relative difference is within 5% for Ch1, 2, 6, 7, 8, while relatively larger for Ch9 at low signal.**

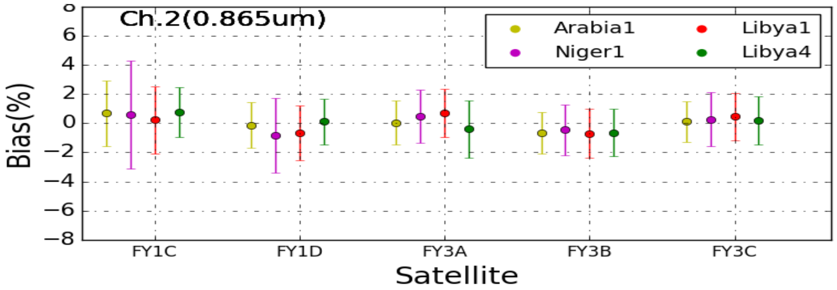
FY/VIRR FCDR V2 (RSBs)

Clear-sky normalized reflectance of invariant deserts



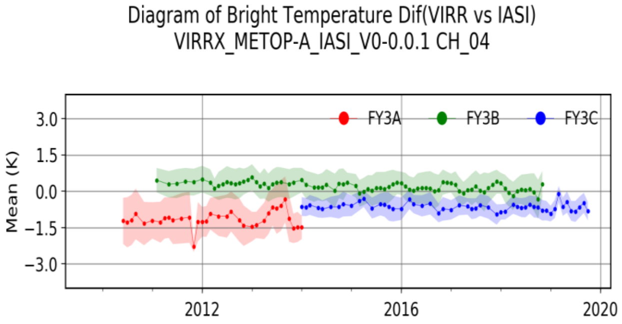


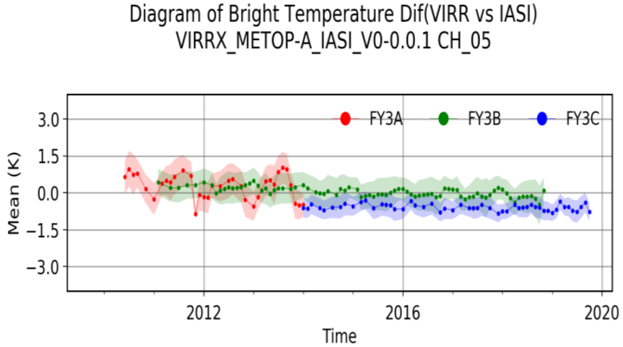




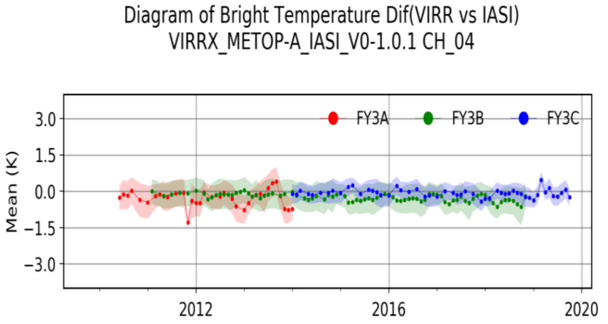
In general, after anisotropic and spectral correction, the TOA reflectance means for each instrument are within 1% of the 20-yr average for channels 1 and 2.

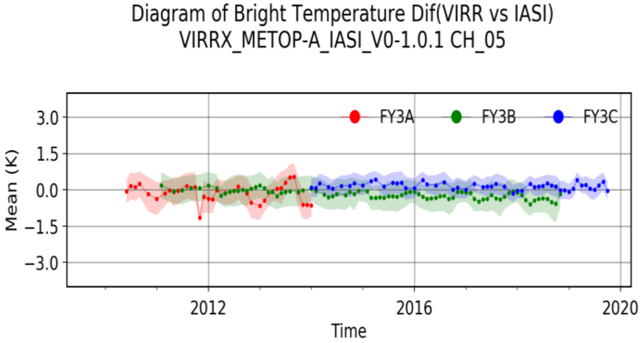
FY/VIRR FCDR V1（TEBs)





- In V1, the IR recalibration focuses on the correction of the nonlinear response derived by SNO analysis using IASI.
- The deviation time series shows that the inter-platform consistency is improved after recalibration, while the seasonal variation still exists.
- The lifetime mean biases of 3 instruments are less than 0.4K, and the RMSE is less than 0.65K， 0.6K and 0.5K for FY-3A, FY-3B, FY-3C, respectively.





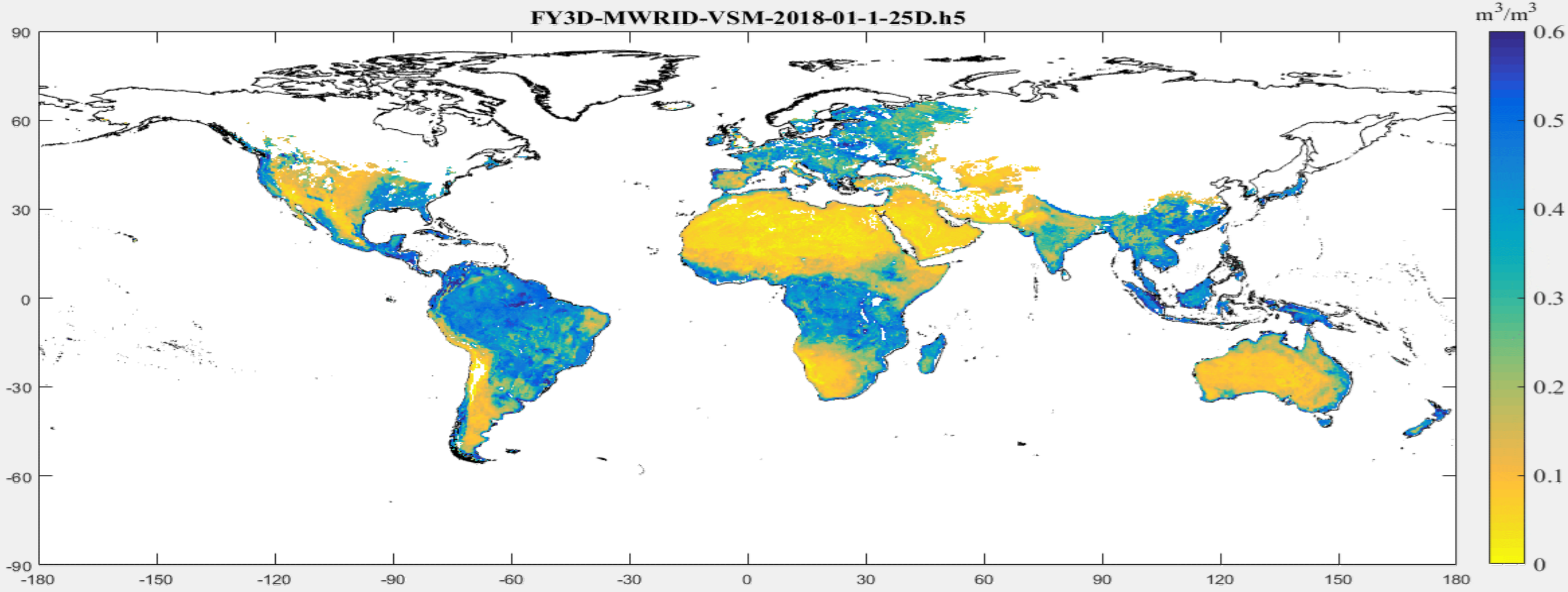
- In V2, the refined TEB onboard recalibration model is developed,which corrects the radiance from the internal blackbody and the effects of instrument temperature. The evaluation of V2 VIRR TEB dataset is ongoing.

FY Recalibration Summarization

- The beta version (V1) datasets have been finished through the lifetime recalibration of each instrument in 2019.
- The trial version (V2) datasets are completed for MWRI, MWTS and VIRR solar bands, meanwhile others are still ongoing and scheduled to be completed in June, 2021.
- Reprocessed dataset will be publicly released with registered DOI. (www.richceos.cn)
- User feedbacks are expected through using the recalibrated FCDR.

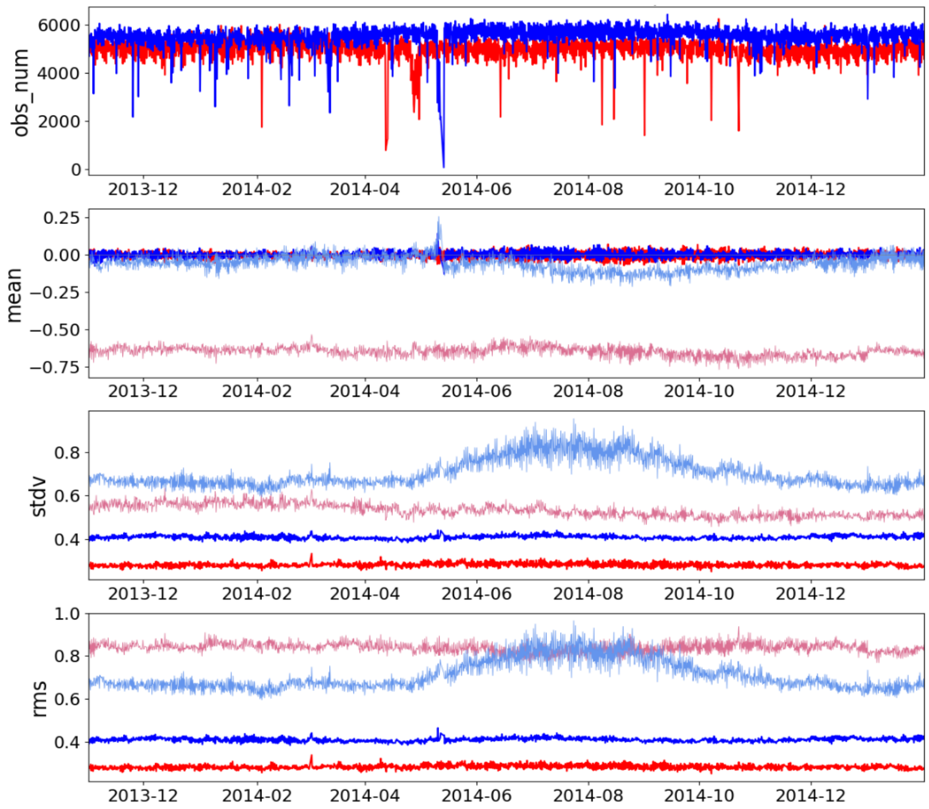
Some Demonstrations

FY-3D 10-days SM of 2018

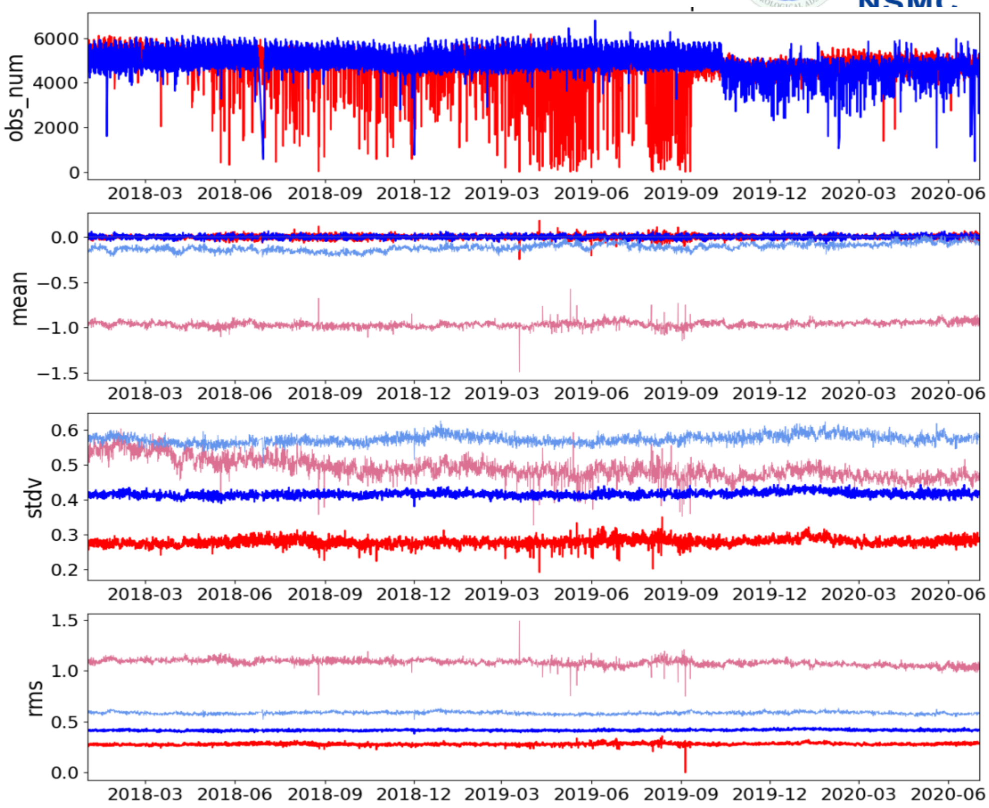


Kang, C. S. , Zhao, T. , Shi, J. , et al. 2020, Global soil moisture retrievals from the chinese FY-3D microwave radiation imager. IEEE Transactions on Geoscience and Remote Sensing

Evaluation of Reprocessed FY-3C/D MWTS against CRA



— MWTS2/FY3C CH3 OMB (with bias correction)
— MWTS2/FY3C CH3 OMB (without bias correction)
—ATMS/SNPP CH5 OMB (with bias correction)
—ATMS/SNPP CH5 OMB (without bias correction)



— MWTS2/FY3D CH3 OMB (with bias correction)
— MWTS2/FY3D CH3 OMB (without bias correction)
—ATMS/SNPP CH5 OMB (with bias correction)
—ATMS/SNPP CH5 OMB (without bias correction)

Special Issue in Preparing

Home | Just Accepted | Issue in Progress | *Current Issue* | All Issues | Special Co

Fengyun Meteorological Satellite Climate Data Records (CDR) Reprocessing: Methods, Products, and Applications

Special Issue on Fengyun Meteorological Satellite Climate Data Records (CDR) Reprocessing: Methods, Products, and Applications

(Abbreviated title: Fengyun Meteorological Satellite Historical Data Reprocessing)

Call for Papers

Constructing Climate Data Records (CDR) from satellite historic data is a fundamental work advocated by the Global Climate Observation System (GCOS) programme. Since the launch of the first Fengyun (FY) satellite in 1988, we have collected FY satellite data with a 20-year-long record.

Because of the upgrading of the instruments to the same category of instruments, the degradation of the instrument during its lifetime, and the unstable status of the data quality in the early commissioning stage, FY satellite data quality exhibits significant temporal and spatial variations. So far, the archived FY satellite data have never been reprocessed with the state-of-the-art sciences of calibration, cross calibration, and the product algorithms. As a result, neither Fundamental Climate Data Records (FCDR) nor Thematic Climate Data Records (TCDR) have been developed from FY satellites to support the user communities in data reanalysis, and climate and climate change research. In reprocessing the archived data, we need to analyze the historic data quality, characterize the spectral and radiometric response, trace the radiometric benchmark, and harmonize the observations from a series of FY instruments.

This special issue will summarize the activities of FY satellite data reprocessing and introduce the current accuracy of FCDR and TCDR. We do hope that this special issue can promote the Chinese satellite data quality and advance their applications in data reanalysis and research on climate and climate change.

Papers for this special issue are solicited for, although not limited to, the following topics:

1. The methods and products to generate the FCDR through reprocessing of the archived FY satellite data;
2. The methods and products to generate the TCDR through reprocessing of the archivedFY satellite data;
3. The natural and man-made stable calibration references in optical/microwave spectrum and their spatial and temporal characteristics;
4. Application of the FY satellite data to data reanalysis and research on climate and climate change.

Responsible Lead Editors for the Special Issue:

Peng Zhang, National Satellite Meteorological Center, zhangp@cma.gov.cn

Dr. Peng Zhang is Senior Scientist and Deputy Director-General of National Satellite Meteorological Center (NSMC/CMA) since 2013, Chief Director of FY-3 ground segment since 2013, Chair of Global Space Inter-Calibration System (GSICS) Executive Panel from 2014 to 2017, Chief Director of Chinese TanSat satellite ground segment since 2015, and IEEE Senior Member since 2016. Dr. Zhang obtained his PhD from IAP/CAS (Institute of Atmospheric Physics, Chinese Academy of Sciences) in 1998. He has been intensively involved in conceiving, developing, and operating FY-3 satellite ground segment. With his leadership, Chinese meteorological polar orbiting satellite FY-3 data have been used worldwide, and the radiance calibration accuracy of the instruments has been improved progressively. His research experience covers the atmospheric remote sensing, satellite calibration and validation, and atmospheric radiative transfer calculation, etc. He has authored and coauthored over 100 papers in refereed scientific journals.

Fuzhong Weng, Chinese Academy of Meteorological Sciences, wengfz@cma.gov.cn

Dr. Fuzhong Weng received his PhD in 1992 from Department of Atmospheric Sciences, Colorado State University. He is a fellow of the American Meteorological Society and a professor in Chinese Academy of Meteorological Sciences, Co-Chief Editor of Journal of Meteorological Research and Associate Editor of Journal of IEEE Geoscience Remote Sensing. His major research areas include radiative transfer, satellite remote sensing, satellite data assimilation, and instrument calibration. He was a physical scientist at NOAA, USA during 1992–2017 and received many awards including NOAA David Johnson award in 2000, US Department of Commerce Gold Medal in 2005, and NOAA Administrator Award on Science and Technology in 2009. He has published more than 300 peer-reviewed articles and 9 book chapters on remote sensing sciences. In 2017, he also published a book on passive microwave remote sensing of the earth for meteorological applications in Wiley Series in Atmospheric Physics and Remote Sensing.

Jun Li, University of Wisconsin-Madison, jun.li@ssec.wisc.edu

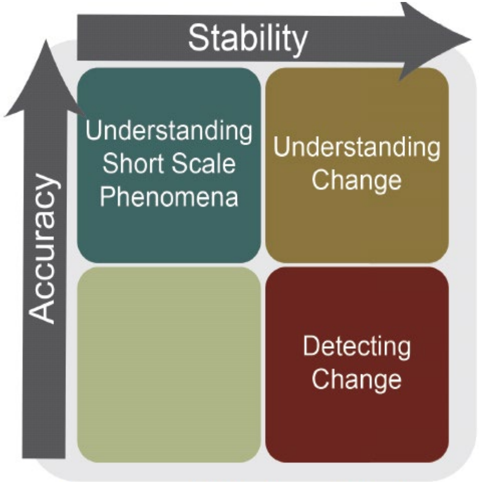
Dr. Jun Li received his B.S. degree in mathematics from Peking University in 1987, and M.S. and Ph.D. degrees in atmospheric science from the Institute of Atmospheric Physics, Chinese Academy of Sciences in 1990 and 1996, respectively. His research area includes retrieval of geophysical parameters from both geostationary and polar-orbiting satellite measurements; applications of satellite data in nowcasting, weather forecasting, and numerical weather prediction; and future observing system simulation and impact assessment. He has authored and co-authored more than 200 peer-reviewed journal publications, and has been granted permanent principal investigator status, promoted to Distinguished Scientist, and awarded the Chancellor's Award for Excellence in Research by University of Wisconsin-Madison.

Johannes Schmetz, EUMETSAT former Chief Scientist, johannesschmetz@gmail.com

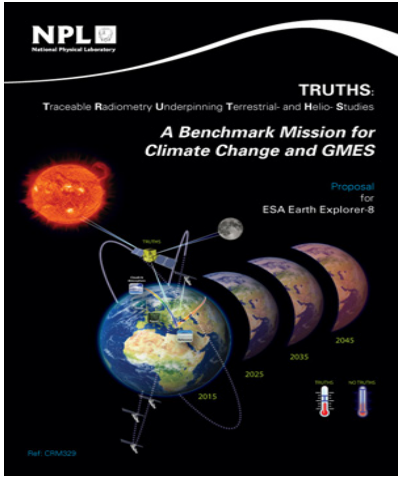
Dr. Johannes Schmetz received his PhD in 1981 from the University of Cologne (Germany) and his habilitation from the University of Frankfurt (UF, Germany). As a researcher, he worked at UF inter alia on cloud–radiation interaction based on research aircraft experiments. He joined the European Space Agency (ESA) to work in the Meteosat programme as senior researcher and Head of the Science Section. He changed to EUMETSAT as Division Head where he built up the Meteorological Division. Then he became the first Chief Scientist of EUMETSAT. He is retired and continues working as advisor and member of various advisory boards. He is a fellow of the American Meteorological Society (AMS) and received the award of the AMS Committee on Satellite Meteorology, Oceanography, and Climatology. He has published more than 90 papers in peer-reviewed journals and books. He served on various international committees and has led scientific cooperation between operational satellite agencies over nearly three decades.

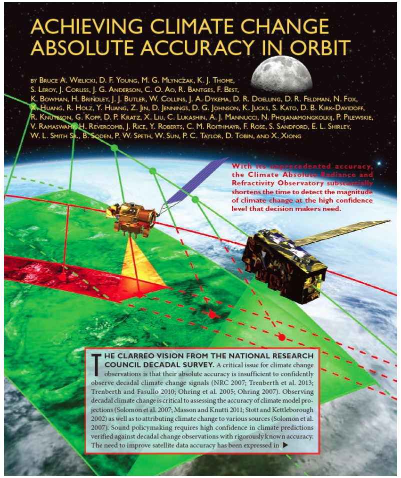
6. Future: Radiometric Benchmark Satellite to SI Traceability

SI-Traceable Space-based Climate Observing System



Accuracy vs. stability diagram following Ohring et al. (2004)



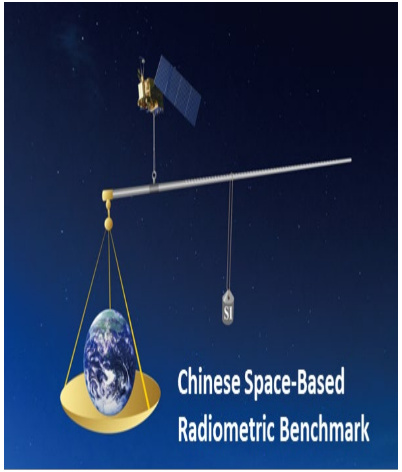


ACHIEVING CLIMATE CHANGE ABSOLUTE ACCURACY IN ORBIT

BY BRUCE A. WIELICKI, D. F. YOUNG, M. G. MLYNCZAK, K. J. THOME, S. LEROY, J. CORLISS, J. G. ANDERSON, C. O. AO, R. BANTGES, F. BEST, K. BOWMAN, H. BRINDLEY, J. J. BUTLER, W. COLLINS, J. A. DYKEMA, D. R. DOELLING, D. R. FELDMAN, N. FOX, X. HUANG, R. HOLZ, Y. HUANG, Z. JIN, D. JENNINGS, D. G. JOHNSON, K. JUCKS, S. KATO, D. B. KIRK-DAVIDOFF, R. KNUTESON, G. KOPP, D. P. KRATZ, X. LIU, C. LUKASHIN, A. J. MANNUCCI, N. PHOJANAMONGKOLKIJ, P. PILEWSKIE, V. RAMASWAMY, H. REVERCOMB, J. RICE, Y. ROBERTS, C. M. ROITHMAYR, F. ROSE, S. SANDFORD, E. L. SHIRLEY, W. L. SMITH SR., B. SODEN, P. W. SPETH, W. SUN, P. C. TAYLOR, D. TOBIN, AND X. XIONG

With its unprecedented accuracy, the Climate Absolute Radiance and Refractivity Observatory substantially shortens the time to detect the magnitude of climate change at the high confidence level that decision makers need.

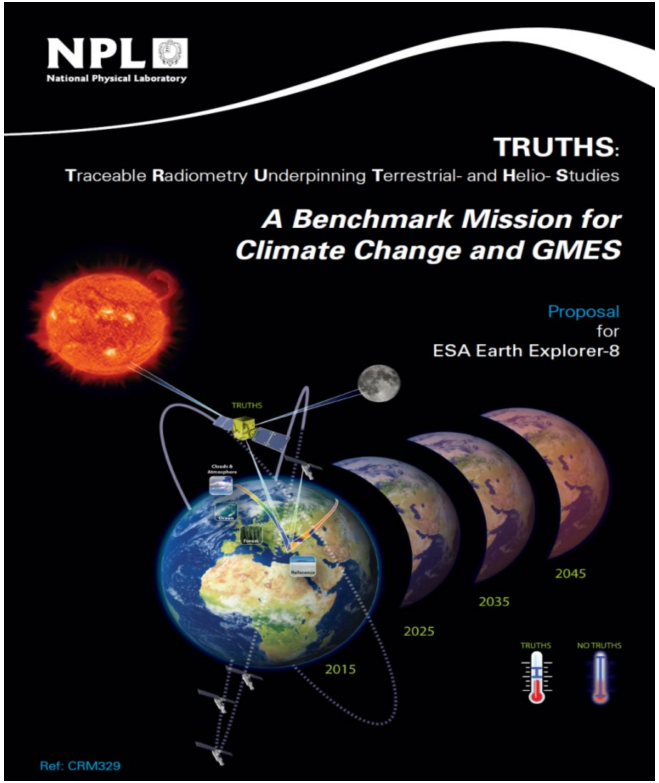
THE CLARREO VISION FROM THE NATIONAL RESEARCH COUNCIL DECADAL SURVEY. A critical issue for climate change observations is that their absolute accuracy is insufficient to confidently observe decadal climate change signals (NRC 2007; Trenberth et al. 2013; Trenberth and Fasullo 2010; Ohring et al. 2005; Ohring 2007). Observing decadal climate change is critical to assessing the accuracy of climate model projections (Solomon et al. 2007; Masson and Knutti 2011; Stott and Kettleborough 2002) as well as to attributing climate change to various sources (Solomon et al. 2007). Sound policymaking requires high confidence in climate predictions verified against decadal change observations with rigorously known accuracy. The need to improve satellite data accuracy has been expressed in ▶



TRUTHS

Climate Mission：ESA，2016

Traceable Radiometry Underpinning Terrestrial- and Helio-Studies



Measurand	Spectral resolution nm	Spatial resolution m	Accuracy %
Total Solar Irradiance	Total	-	0.01
Solar Spectral Irradiance	200 – 2500 (0.5 - 1)	-	0.1
Lunar Spectral Irradiance and Radiance	380 – 2500 (10)	-	<0.3
Earth Spectral Radiance (five angles per target)	380 – 2500 (10)	~ 25 (20 x 20 km)	<0.3
via filter radiometers for Aerosols / E Rad Bud	TBD	20 km (TBD)	<0.3

Observing conditions (near polar 700 km)

Solar viewing - ~ 10 mins per orbit

Earth viewing ~ 10 sites (20 * 20 km) at 5 angles per orbit

N. Fox, et al, 2003: Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS). Adv. Space Res.

N. Fox and P. Green, 2020: TRUTHS, An Element of a Space-Based Climate and Calibration Observatory. Remote Sensing.

CLARREO

CLARREO Pathfinder on ISS: NASA, 2023

Climate Absolute Radiance and Refractivity Observatory

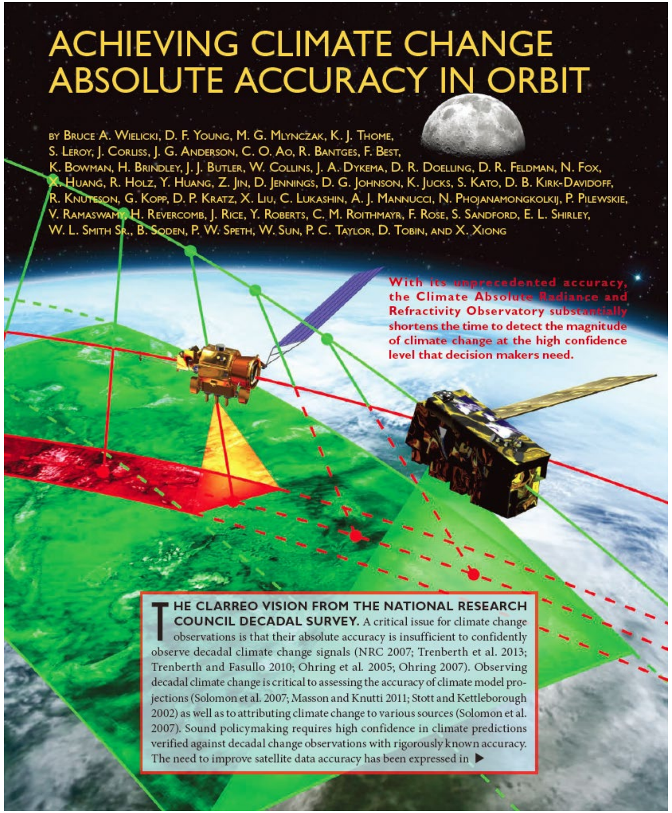


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TABLE 1. Instrument and mission requirements. NEDT = noise equivalent differential temperature. FTS = Fourier transform spectrometer. S/N = signal-to-noise ratio. TRIG = Tri GPS GNSS RO Sensor. RAAN = right ascension of ascending node.

IR spectrometer	RS spectrometer	GNSS radio occultation	Spacecraft orbit
Systematic error <0.06 K (k = 2)	Systematic error <0.3% (k = 2) of Earth mean reflectance	Systematic error <0.06% refractivity (k = 2) for 5–20 km	90° ± 0.1° orbit for full diurnal sampling twice per year
200–2000 cm^{-1} spectral coverage	320–2300-nm spectral coverage	GPS and Galileo GNSS frequencies	Global coverage 90° inclination
0.5 cm^{-1} unapodized spectral resolution	4-nm spectral samples; 8-nm resolution	5–20-km altitude range refractivity	609 ± 0.2-km altitude, 61-day repeat
NEDT < 10 K for 200–600 cm^{-1}, and >1600 cm^{-1}, all others <2 K	S/N > 33 for 0.3 scene reflectance, at a solar zenith angle of 75°. S/N > 25 for λ > 900 nm	>1000 occultations per day to control sampling noise	RAAN of 0° or 180° to optimize reference intercalibration
25–100-km nadir FOV	0.5-km nadir FOVs for a 100-km-wide swath		5-yr initial mission record length
<200 km between successive spectra along the ground track	Polarization sensitivity <0.5% (k = 2) for λ < 1000 nm, <0.75% (k = 2) for λ > 1000 nm		Orbits repeat exactly each year to avoid diurnal/seasonal cycle aliasing
Nadir pointing, with systematic error <0.2°	Pointable in azimuth and elevation for solar, lunar, reference intercalibration views		RS and IR fly on same spacecraft or in close formation
Prototype design: 4-port FTS, 76-kg mass, 124-W avg power, 2.5 GB day^{-1}	Prototype design: Dual Grating Spectrometer, 69-kg total mass, 96-W avg power, 30 GB day^{-1}	Prototype design: TRIG receiver, 18-kg mass, 35-W avg. power, 1.2 GB day^{-1}	IR/RO- or RS-fueled spacecraft mass 370 kg, can fit on small launch vehicles

Bruce A. Wielicki, et al, 2013: Achieving Climate Change Absolute Accuracy in Orbit. BAMS

LIBRA

Chinese Space-based Radiometric Benchmark Mission

Table 1. Detailed payloads specifications of the LIBRA prototype model.

Instrument Name	Payload Requirements	Key Technology
IRS	Spectral range: 600–2700 cm^{-1} Spectral resolution: 0.5 cm^{-1} IFOV: 24 mrad Sensitivity: 0.1 K@270 K Emissivity of BB: ≥0.999 Measurement uncertainty: 0.15 K (k = 2)	Miniature fixed-temperature phase-change cells
EMIS	Spectral range: 380–2350 nm, Spectral resolution: 10 nm, Spectral precision: 0.5 nm, Spatial resolution: 100 m, Coverage: 50 km, Measurement uncertainty: 1% (k = 2)	Space Cryogenic Absolute Radiometer
TSI	Spectral range: 0.2–35 µm, Measurement uncertainty: 0.05% (k = 2) Long-term stability:0.005%	Space Cryogenic Absolute Radiometer
SITQ	Spectral range: 380–2500 nm, Spectral resolution: 3 nm (380–1000 nm), 8 nm (1000–2500 nm) Spectral precision: 0.1–0.3 nm, Self-calibration uncertainty: 0.2%, Measurement uncertainty: 0.35% (k = 2)	Spontaneous Parametric Down-Conversion

remote sensing

MDPI

Article

Development of the Chinese Space-Based Radiometric Benchmark Mission LIBRA

Peng Zhang [1,2], Naimeng Lu [1,2], Chuanrong Li [3,*], Lei Ding [4], Xiaobing Zheng [5], Xuejun Zhang [6], Xiuqing Hu [1,2], Xin Ye [6], Lingling Ma [3], Na Xu [1,2], Lin Chen [1,2] and Johannes Schmetz [7]

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P. Zhang et al., 2020: Development of the Chinese Space-Based Radiometric Benchmark Mission LIBRA. Remote Sensing

Comparison among LIBRA, CLARREO, TRUTHS

Table 2. Comparison among radiometric benchmark satellite.

Satellite	Libra				Clarreo		Truths		
Instrument Type *	IR	RS	TS	SS	IR	RS	RS	TS	SS
Spectral Coverage	600–2700 cm^{-1}	380–2350 nm	0.2–35 µm	380–2500 nm	200–2000 cm^{-1}	320–2300 nm	380–2300 nm	0.2–35 µm	320–2450 nm
Spectral Resolution	0.5 cm^{-1}	10 nm	–	3~8 nm	0.5 cm^{-1}	8 nm	5~10 nm	–	1~10 nm
Measurement Uncertainty	0.15 K (k = 2)	1% (k = 2)	0.05% (k = 2)	0.35% (k = 2)	0.065 K (k = 2)	0.3% (k = 2)	0.1% (k = 2)	0.02% (k = 2)	0.2% (k = 2)
SI-traceability	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

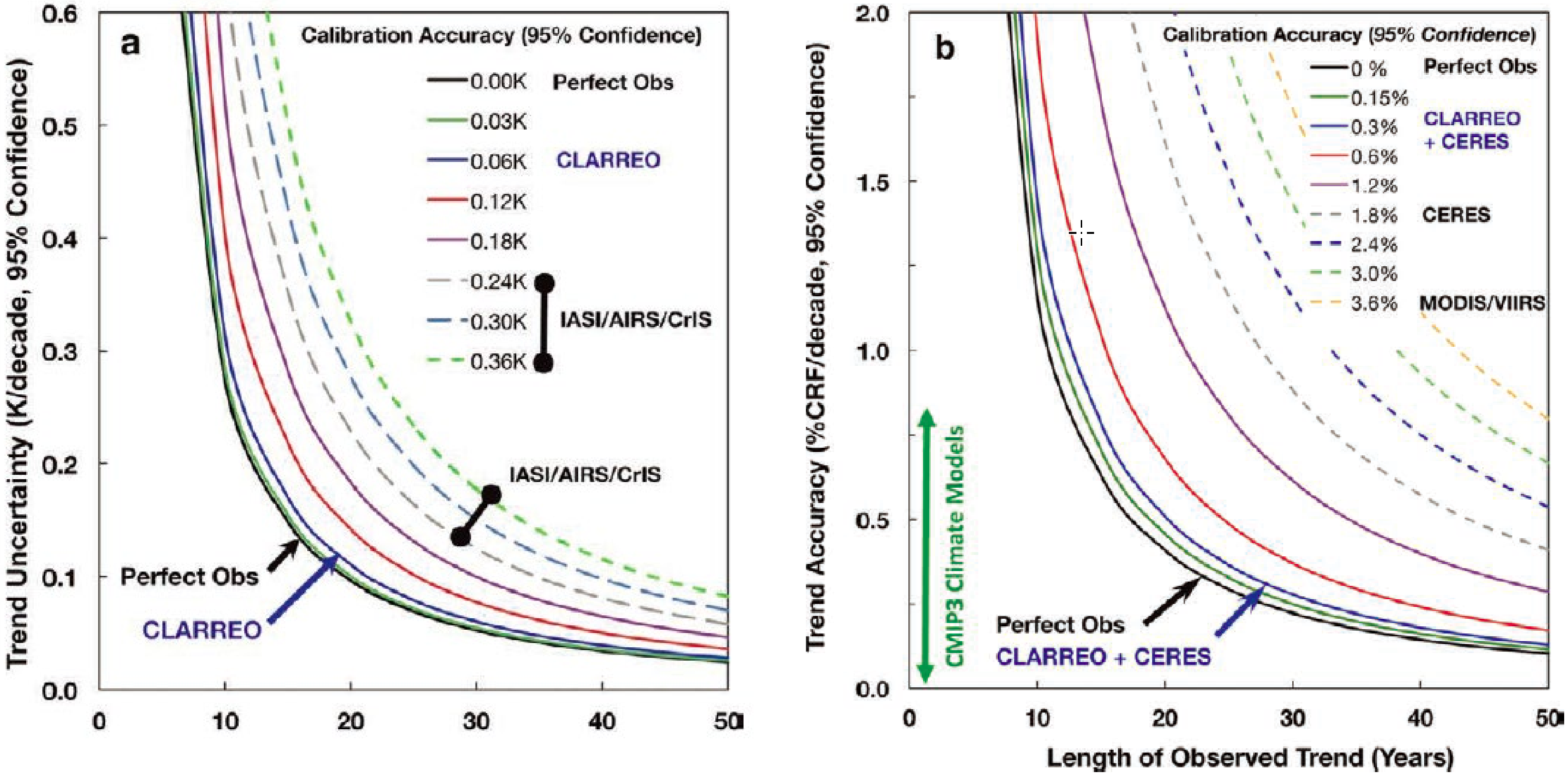
* In the line 'Instrument type', IR represents the instrument to measure the spectrally resolved infrared radiance, RS represents the instrument to measure the spectrally resolved reflectance of solar radiation, TS represents the instrument to measure the total solar irradiance, and SS represents the instrument to measure the spectrally resolved solar irradiance.

Benefit to satellite measurement unifying

Table 3. Products to support intercalibration with radiometric traceability.

Instruments	Products	Intercalibration Method	Example
IRS	Spectrally-resolved infrared radiance	Quasi-synchronous intercalibration	[16]
		LEO-LEO SNO	[30,31]
		GEO-LEO SNO	[32,33]
EMIS	Spectrally-resolved reflectance of solar radiation	Quasi-synchronous intercalibration	[34]
		LEO-LEO SNO	[35,36]
		GEO-LEO SNO	[37]
	Selected DCC reflectance	DCC	[38,39]
	Selected PICS reflectance	PICS	[40]
	Selected Lunar reflectance	Lunar	[41,42]

Benefit to climate change monitoring



Bruce A. Wielicki, et al, 2013: Achieving Climate Change Absolute Accuracy in Orbit. BAMS

Latest Progress

CEOS

GSICS Global Space-based Inter-Calibration System

An SI-Traceable Space-based Climate Observing System

A CEOS, GSICS Workshop
hosted by the UK Space Agency at National Physical Laboratory, London, UK,

September 9-11, 2019

Final ANNOUNCEMENT AND CALL FOR CONTRIBUTIONS

Recent years have seen an increasing urgency from international coordinating bodies such as CEOS, WMO-GSICS, GCOS, climate researchers, and policy makers to establish *a space-based climate observing system* capable of unambiguously monitoring indicators of change in the Earth's climate, as needed for international mitigation strategies such as the 2015 Paris climate accord. Such an observing system requires the combined and coordinated efforts of the world's space agencies. To deliver data that can be considered unequivocal on decadal timescales, facilitating policy makers to make decisions in a timely manner, requires improvements to heritage, existing, and in-development space assets. In particular, observations spanning the electromagnetic spectrum from the near-UV to microwave need to be of sufficient accuracy and duration, traceable to the International System of Units (SI), and sampled to ensure global representation in order to detect change in as short a timescale as possible. The harshness of launch and the space environment has to date limited any satellite mission's ability to robustly demonstrate SI traceability on-orbit at the accuracy and confidence levels needed. *An order of magnitude improvement is typically required for robust climate observations.*

Although not as demanding in terms of long-term accuracies, implementing such a system also facilitates improvements to *operational applications*, particularly where data harmonisation enables 'information on-demand' for a wider range of applications such as health, a sustainable food supply, and pollution.

Bringing together experts from space agencies, industry, academia, and policy makers, the intent of this international workshop is a community strategy to quantify the *benefits and consequential specifications of a space-based climate observing system* along with a roadmap to implementation. **Discussion topics include**:

- Potential scientific and economic benefits,
- The state-of-the-art in establishing traceability in orbit: current technologies, methods, and missions (e.g. CLARREO and its Pathfinder, TRUTHS, and Chinese and Indian counterparts)
- New observation and climate-sensitivity detection capabilities and concepts

Stimulated by invited and contributed presentations, the workshop will be structured to ensure ample discussions on all topics. An introductory session will be suitable for a broad audience. This will be followed by more detailed technical discussions, and conclude with a final session focussing on defining observing-system requirements and a draft implementation strategy, see attached outline. The latter will require pre-workshop preparations.

Although the final oral program is now defined in the attached agenda additional formal contributions in the form of poster are solicited related to any of the workshop topics summarised in the following themes:

- *Science and societal drivers for the climate and operational communities (including economic benefits)*
- *Observations and datasets needed (measurements, timescales, and accuracies)*
- *Reference calibrations (facilities/targets, approaches, capabilities, and uncertainties)*
- *Mission/technologies/concepts under development or conceived (status, technical capabilities)*
- *Develop community 'white paper' on benefits, needs, and a proposed implementation architecture*

Pre-registration for this open workshop is required for the venue

https://ceoswmogsicsworkshop.eventbrite.co.uk . To submit an additional poster please provide a short *300- to 500-word abstract* online for any proposed additional poster presentations by **August 31st, 2019** stating clearly how it addresses the scope and themes of the workshop. All submissions will be reviewed by the Scientific Organizing Committee.

Papers based on contributions to this workshop will be published in a special edition of 'Remote Sensing https://www.mdpi.com/journal/remotesensing/special_issues/Space-based_COS

Scientific Organising Committee: Nigel Fox (NPL, CEOS WGCV), Bruce Wielicki (NASA), Greg Kopp (U.Colorado/LASP), Xiuqing ("Scott") Hu (CMA, GSICS), Tim Hewison (EUMETSAT, GSICS)

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IMPACT FACTOR 4.118

The Needs and Path Toward an SI-Traceable Space-based Climate Observing System

Guest Editors:

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Deadline for manuscript submissions:
15 December 2019

Message from the Guest Editors

Recent years have seen increasing urgency from international coordinating bodies for establishing a space-based climate observing system capable of unambiguously monitoring indicators of change in the Earth's climate, as needed for international mitigation strategies. The harshness of the launch and the space environment has, to date, limited many satellite missions' abilities to robustly demonstrate SI traceability on-orbit at the accuracy and confidence levels needed. An order of magnitude of improvement is typically required for robust climate observations.

The intent of this Special Issue is to present a community strategy on the benefits and consequential specifications of a space-based climate observing system along with a roadmap to implementation. Articles for this Special Issue are solicited on the following:

- Societal need and economic benefits
- Applications benefitting from higher-accuracy space-based observations
- Reflected-solar observations
- Thermal infrared observations
- Broadband radiation-budget measurements
- Microwave, radio-occultation, radar, and lidar observations
- Concepts to improve the global inter-calibration of space-based assets

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Special Issue

- 2019: NPL, An SI-Traceable Space-based Climate Observing System (SITSCOS)
- 2020: Special Issue on The Needs and Path Toward an SI-Traceable Space-based Climate Observing System
- 2021: SITSCOS White Paper

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