Future evolution of satellite observing systems

Stephen English

1. Recap on the current Satellite GOS
2. The WMO Integrated Global Observing System (WIGOS)
3. Future operational missions: EPS-SG, MTG
4. Future research missions: Sentinels and Copernicus, EarthCARE, TROPICS, Polarimetric RO

Stephen.English@ecmwf.int

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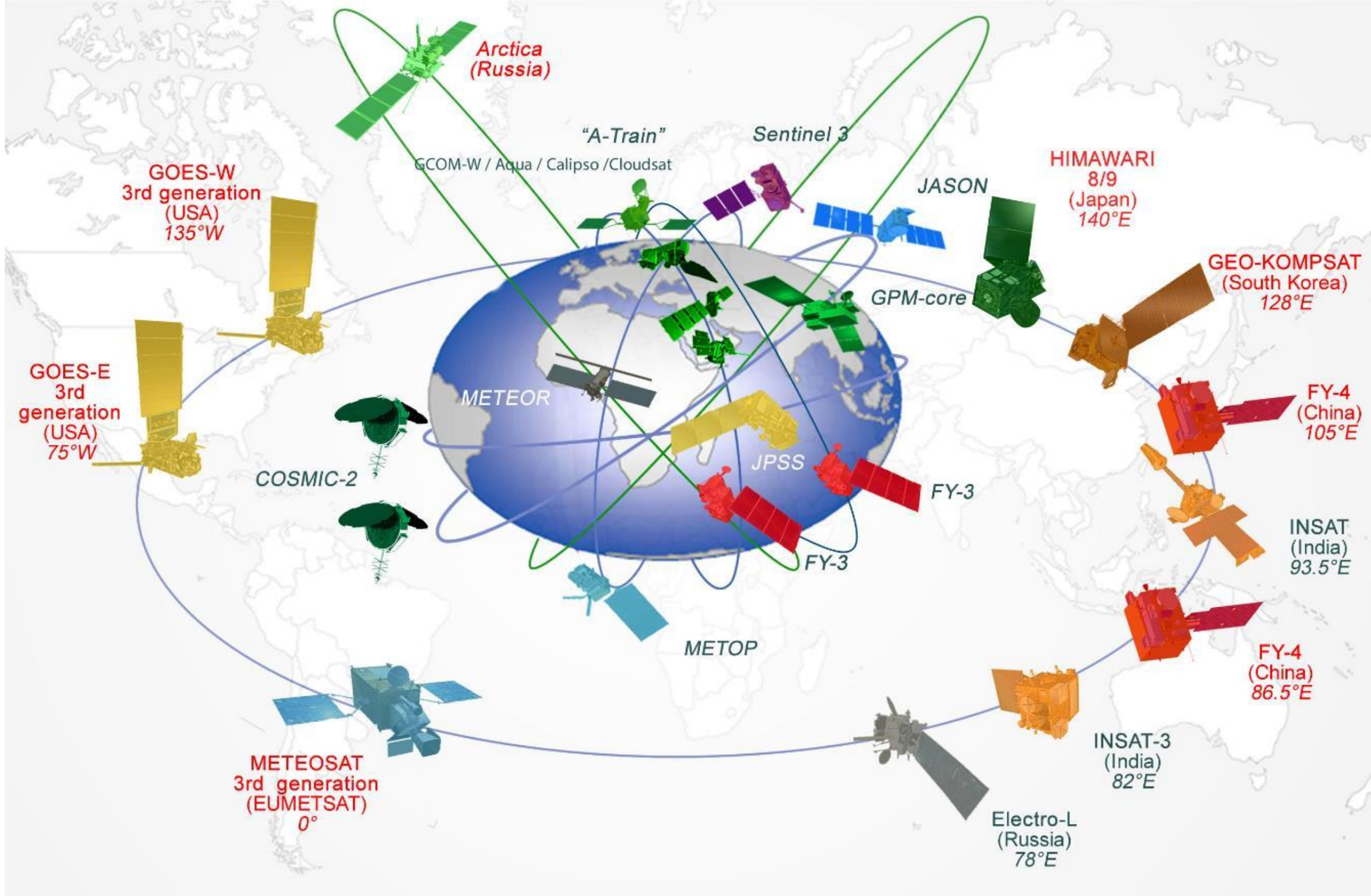
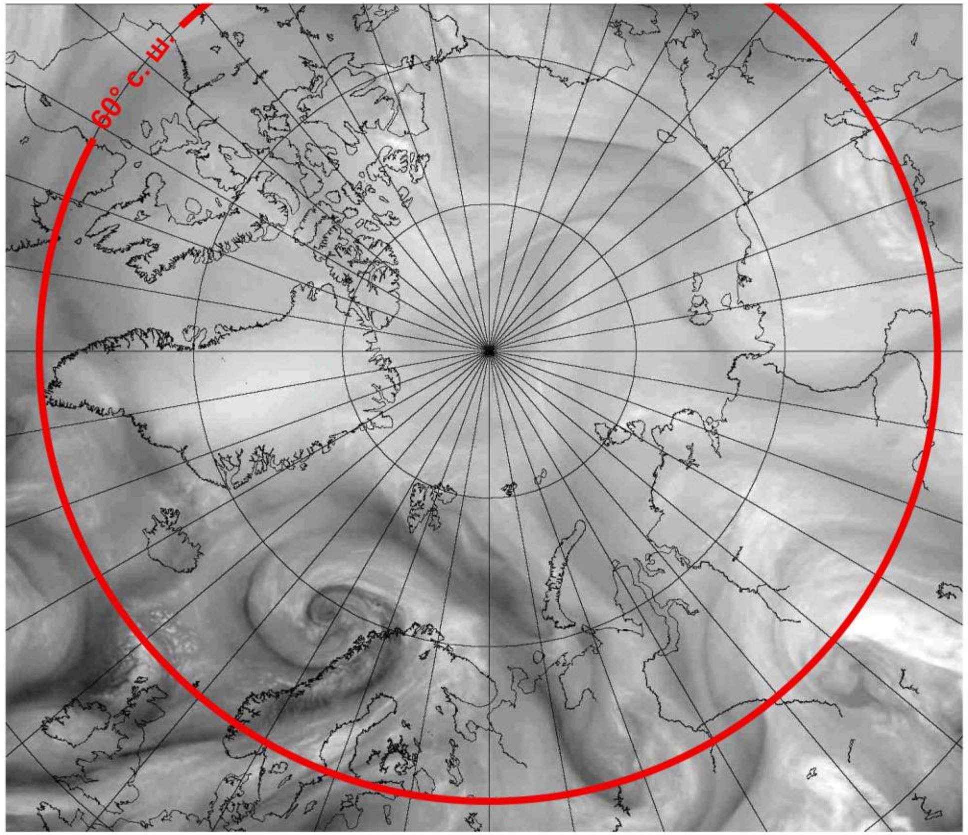
Thanks to WMO

WIGOS: WMO Integrated Global Observing System



In 2023 there are ~200 active satellites supporting weather, climate, earth system and space weather and another ~100 doing relevant Earth Observation



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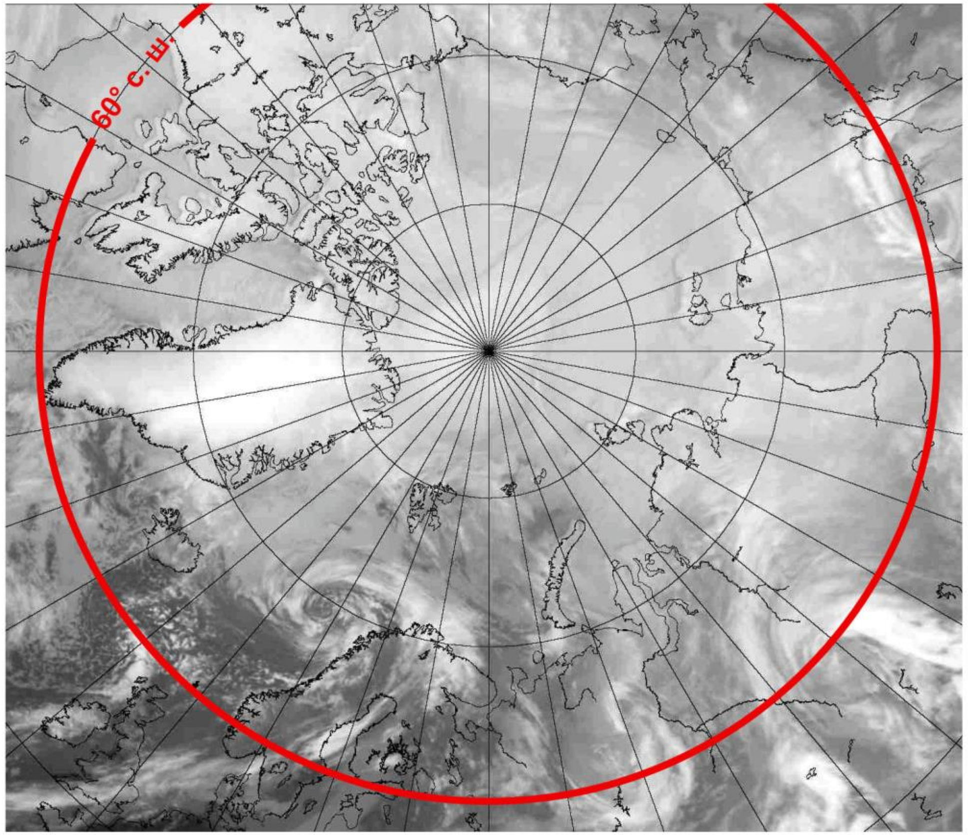
net.iitp.ru

Анимация изображений с МСУ-ГС/ВЭ КА «Арктика-М» №1

5 канал (5,7 - 7,0 мкм)

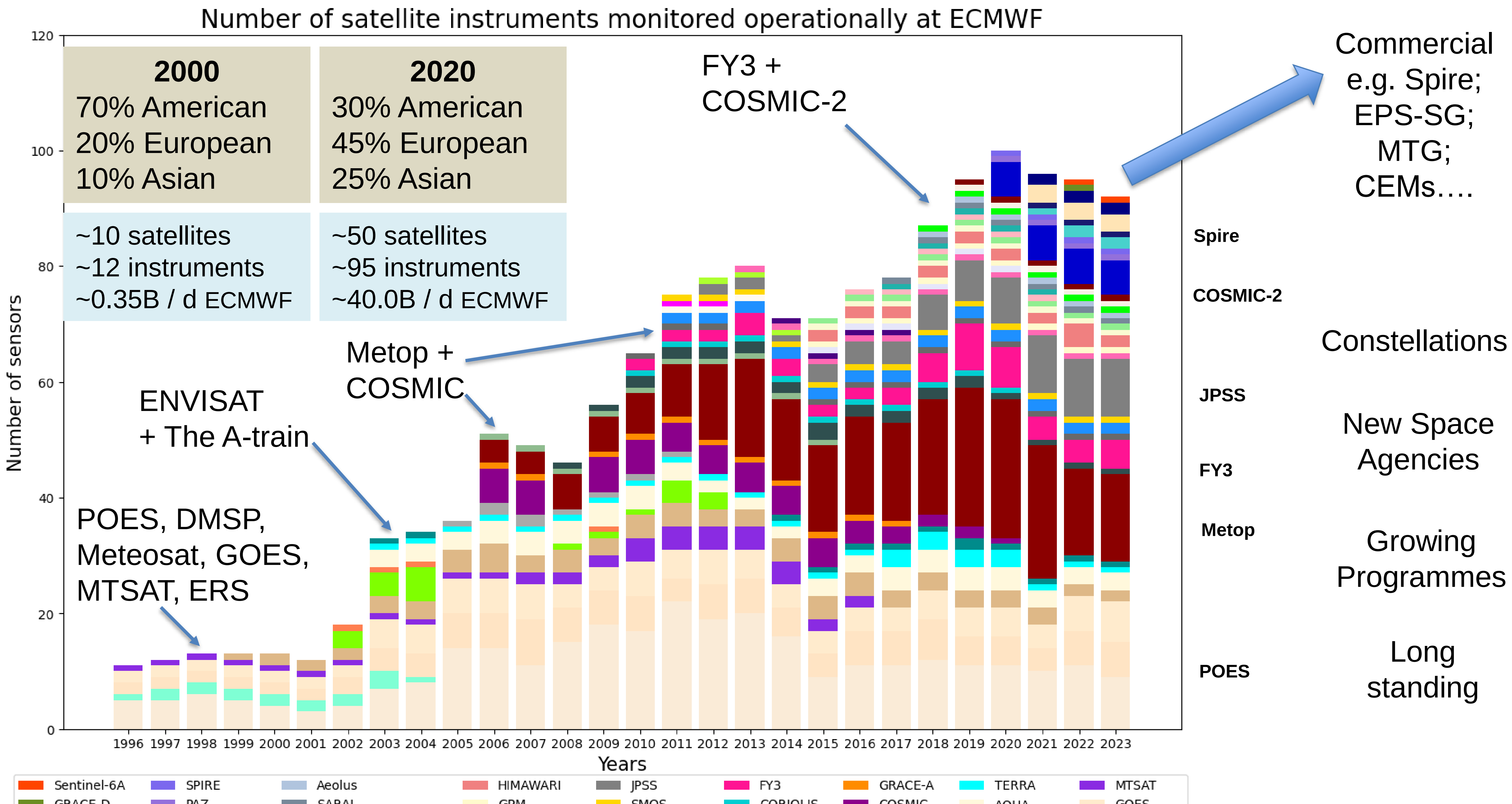
Рабочий участок орбиты - 6,5 часов, частота съёмки - 30 минут



Анимация изображений с МСУ-ГС/ВЭ КА «Арктика-М» №1

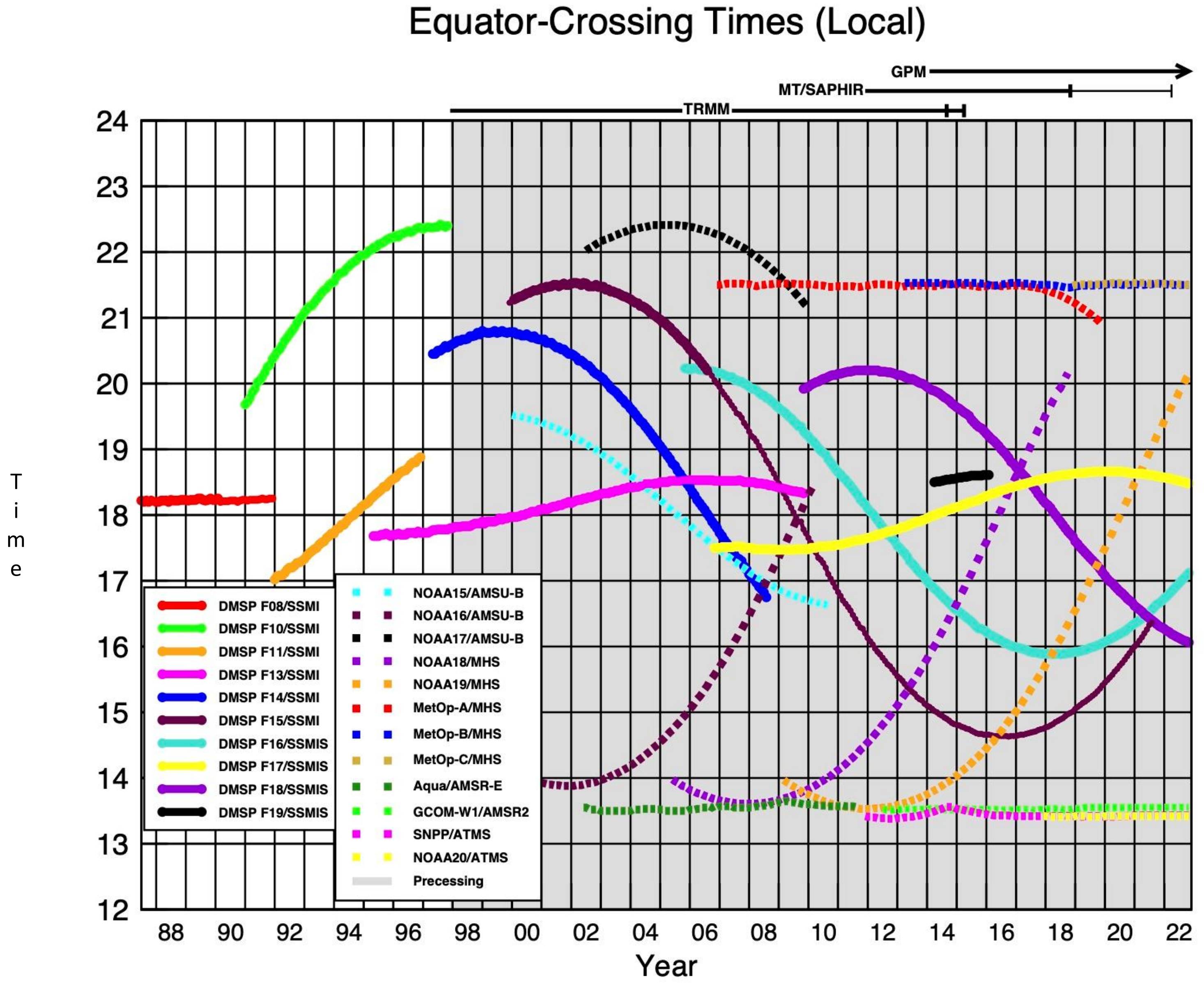
9 канал (10,2 - 11,2 мкм)

Рабочий участок орбиты - 6,5 часов, частота съёмки - 30 минут



Graph provided by
Mohamed Dahoui

Satellite Equatorial Crossing Times (Courtesy of Eric Nelkin, NASA/GSFC)



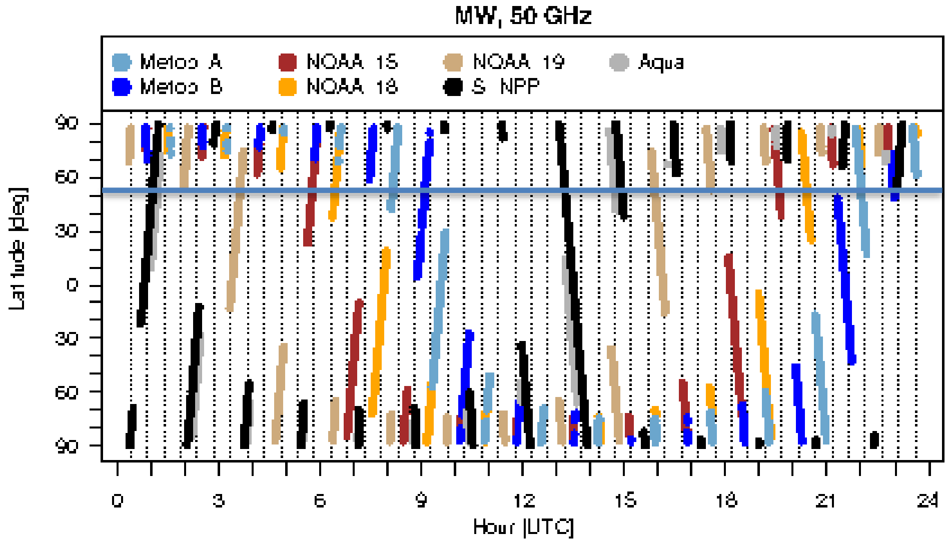
Ascending passes (F08 descending); satellites depicted above graph precess throughout the day.
Image by Eric Nelkin (SSAI), 29 November 2022, NASA/Goddard Space Flight Center, Greenbelt, MD.

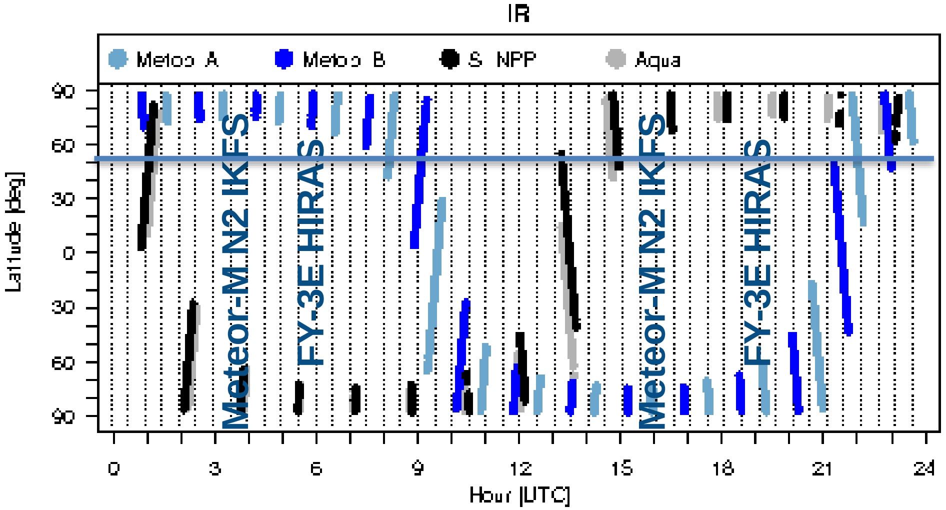
AM **e.g. MetOp**	**Europe** **China**
Early AM **e.g. FY-3E**	**China** **South Korea**
Mid PM **e.g. Meteor-M N2**	**Russia?**
PM **e.g. JPSS**	**US** **China**

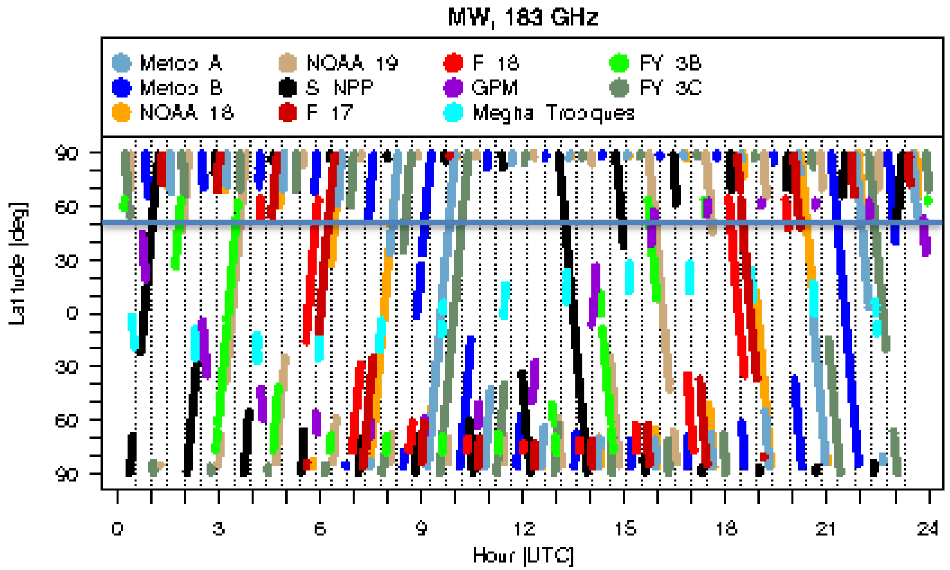
Thanks to Tony McNally

Temporal coverage of satellite data by type

In some bands e.g. 183 GHz excellent temporal coverage
In some bands e.g. 50 GHz gaps
In some bands e.g. IR major gaps in 2021







Future evolution of satellite observing systems

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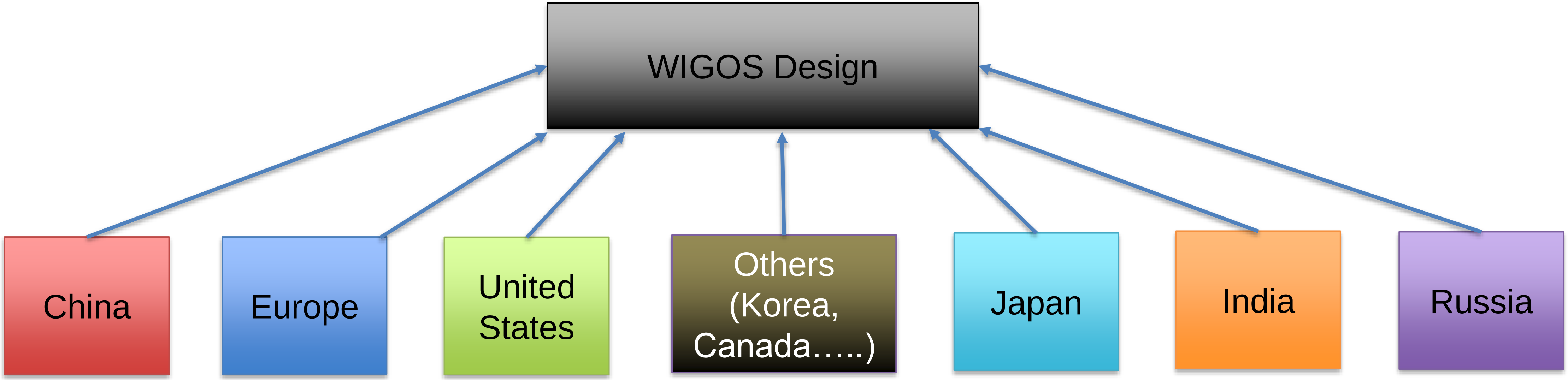
WMO Coordination and WIGOS

WMO is striving towards a coordinated global observing system

(**WMO Integrated Global Observing System** – WIGOS)



Trying to make sure national efforts are complementary

Surface and space components

WIGOS – what is our/your role in this?

Monitoring performance of current WIGOS → WIGOS Data Quality Monitoring System
Sharing monitoring at ECMWF etc.

Rolling Requirements Review
WIGOS gap analysis → How will this be met? Vision 2040.
https://community.wmo.int/vision2040

Preserving WIGOS
Eg Spectrum Management → Responding to threats e.g. 5G
Efforts by CGMS
(Coordinating Group for Meteorological Satellites)

Tools to support WIGOS

WMO Space provide detailed support for satellite data from https://space.oscar.wmo.int

OSCAR lists what exists, what is planned, what it can do, how this compares to requirements

OSCAR
Observing Systems Capability Analysis and Review Tool

Home | Observation Requirements | Space-based Capabilities | Surface-based Capabilities | Analysis | Quick Search...

Overview | Programmes | Satellites | **Instruments** | Frequencies | Agencies | Satellite Status | Gap Analyses

Instrument: IASI-NG

Instrument details

Acronym	IASI-NG
Full name	Infrared Atmospheric Sounder Interferometer - New Generation
Purpose	Temperature/humidity sounding, ozone profile and total-column or profiles of green-house gases (C2H2, C2H4, C2H6, CFC-11, CFC-12, CH3OH, CH4, CO, H2CO2, HCN, HNO2, HNO3, N2O, NH3, PAN, SO2)
Short description	16,921 channels, range 645-2760 cm-1 (3.62-15.50 µm) split in 12 bands [see detailed characteristics below]. Spectral resolution 0.125 cm-1 (unapodised)
Background	Evolution of IASI on Metop A, Metop-B, Metop-C
Scanning Technique	Cross-track: 16 steps of 100 km (14 earth-viewing FOV's, one for cold space, one for blackbody) step-and-dwell scanned, for a swath of 2000 km. Along-track: one scan line every 100 km every 16 s.
Resolution	4 x 4 12-km IFOV's regularly spread within the 100 x 100 km2 FOV (average sampling distance: 24 km).
Coverage / Cycle	Near-global coverage twice/day
Mass	360 kg — **Power** 500 W — **Data Rate** 6 Mbps

Providing Agency	CNES
Instrument Maturity	Backed by strong heritage
Utilization Period:	2025 to 2045
Last update:	2021-06-02

Satellites this instrument is flying on

Note: a red tag indicates satellites no longer operational, a green tag indicates operational satellites, a blue tag indicates future satellites

- EPS Second Generation (EUMETSAT)
  - Metop-SG-A1 (see instrument status) 2025 - 2032
  - Metop-SG-A2 (see instrument status) 2031 - 2038
  - Metop-SG-A3 (see instrument status) 2038 - 2045

Instrument classification

- Earth observation instrument
  - Passive optical radiometer or spectrometer
    - Cross-nadir infrared sounder, possibly including VIS channels

WIGOS Subcomponents

- Subcomponent 1
  - IR hyperspectral sounders [in SSO]
    - IR hyperspectral sounder [in SSO]

Mission objectives

Primary mission objectives

- Atmospheric temperature
- Height of the top of PBL
- Integrated Water Vapour (IWV)
- O3 Total Column
- Specific humidity
- Temperature of the tropopause

Evaluation of Measurements

Detailed characteristics

Band	Wavelength	Wavenumber	NEΔT after apodisation
IAS-1	15.50 µm	645 cm^{-1}	0.39 K @ 280 K
	15.27 µm	655 cm^{-1}	0.26 K @ 280 K
	15.08 µm	663 cm^{-1}	0.225 K @ 280 K
	14.49 µm	690 cm^{-1}	0.225 K @ 280 K
IAS-2	12.99-14.49 µm	690-770 cm^{-1}	0.130 K @ 280 K
IAS-3	10.00-12.99 µm	770-1000 cm^{-1}	0.130 K @ 280 K
IAS-4	9.35-10.00 µm	1000-1070 cm^{-1}	0.195 K @ 280 K
IAS-5	8.70-10.00 µm	1070-1150 cm^{-1}	0.195 K @ 280 K
IAS-6	6.06-8.70 µm	1150-1650 cm^{-1}	0.130 K @ 280 K
IAS-7	4.76-6.06 µm	1650-2100 cm^{-1}	0.449 K @ 280 K
IAS-8	4.59-4.76 µm	2100-2180 cm^{-1}	0.156 K @ 280 K
IAS-9	4.44-4.59 µm	2180-2250 cm^{-1}	0.26 K @ 280 K
IAS-10	4.13-4.44 µm	2250-2420 cm^{-1}	0.26 K @ 280 K
IAS-11	4.13 µm	2420 cm^{-1}	0.26 K @ 280 K
	4.08 µm	2450 cm^{-1}	0.26 K @ 280 K
	3.85 µm	2600 cm^{-1}	0.65 K @ 280 K
	3.70 µm	2700 cm^{-1}	1.138 K @ 280 K
IAS-12	3.70 µm	2700 cm^{-1}	1.138 K @ 280 K
	3.62 µm	2760 cm^{-1}	1.43 K @ 280 K

Additional related information

Information and links relating data access are integrated in OSCAR. Access to low-level data is described on the Data access page. Satellite imagery and derived products can be accessed

ECMWF


The Guardian
5G signal could jam satellites that he
with weather forecasting
New mobile system to be launched this year 'will put lives at risk'
THE HILL
Mixing 5G and w
could skew forecas
storm
INION CONTRIBUTOR — 07/01/19 06:30 PM EDT
BY CONTRIBUTORS ARE THEIR OWN
26 APRIL 2019
nature
International journal of science
Global 5G wireless networks threaten weather forecasts
Why we need to protect weather prediction from radio frequency interference
PHYSICS TODAY
NOAA warns of threat to weather forecasts from 5G spectrum
THE Sun
NEWS WEBSITE OF THE YEAR
Recent posts
Why we need to protect weather prediction from radio frequency interference
ECMWF over the Moon
FOGGY OUTLOOK UK weather forecasts could get even WORSE as 5G 'risks confusing satellite networks'
ccuracy of forecasts could drop
ITUNews MAGAZINE
Monitoring our changing planet
Critical spectrum for Earth observation from space
Read the full edit
Le Point Tech & Net
Les prévisions météo menacées par la 5G ?
"For these numerical weather prediction applications, radio-frequency spectrum is crucial for satellite weather observations as well as communications."
Stephen English
Head of the Earth System Assimilation Section, European Centre for Medium-Range Weather Forecasts (ECMWF)

Frequency management and why this is critical to NWP

- Passive microwave contribute around 40% of the impact of all observations in NWP:
  - 50-60 GHz and 176-190 GHz provide largest direct impact
  - 18.7, 23.8, 31.4, 37, 89, 166 have lower direct impact but support use of 50-60 and 176-190 GHz
  - 1.4, 6.8, 10.7, 209, 229 important for emerging applications
  - Active bands, notably radar, also suffer interference.
- Satellite up + down link + control frequencies and data dissemination e.g. 400-406 MHz for radiosondes.
- Committee on Radio Frequencies (CORF), USA
- European Scientists on Spectrum for Earth Observation (ESSEO), Europe (Chair = S English so if you want to know more, ask me!)

ECMWF RFI Workshop, ECMWF, UK 13-14 September 2018

URSI-ECMWF RFI Workshop, Online 14-18 February 2022

URSI RFI Workshop, Argentina (TBC) August 2024

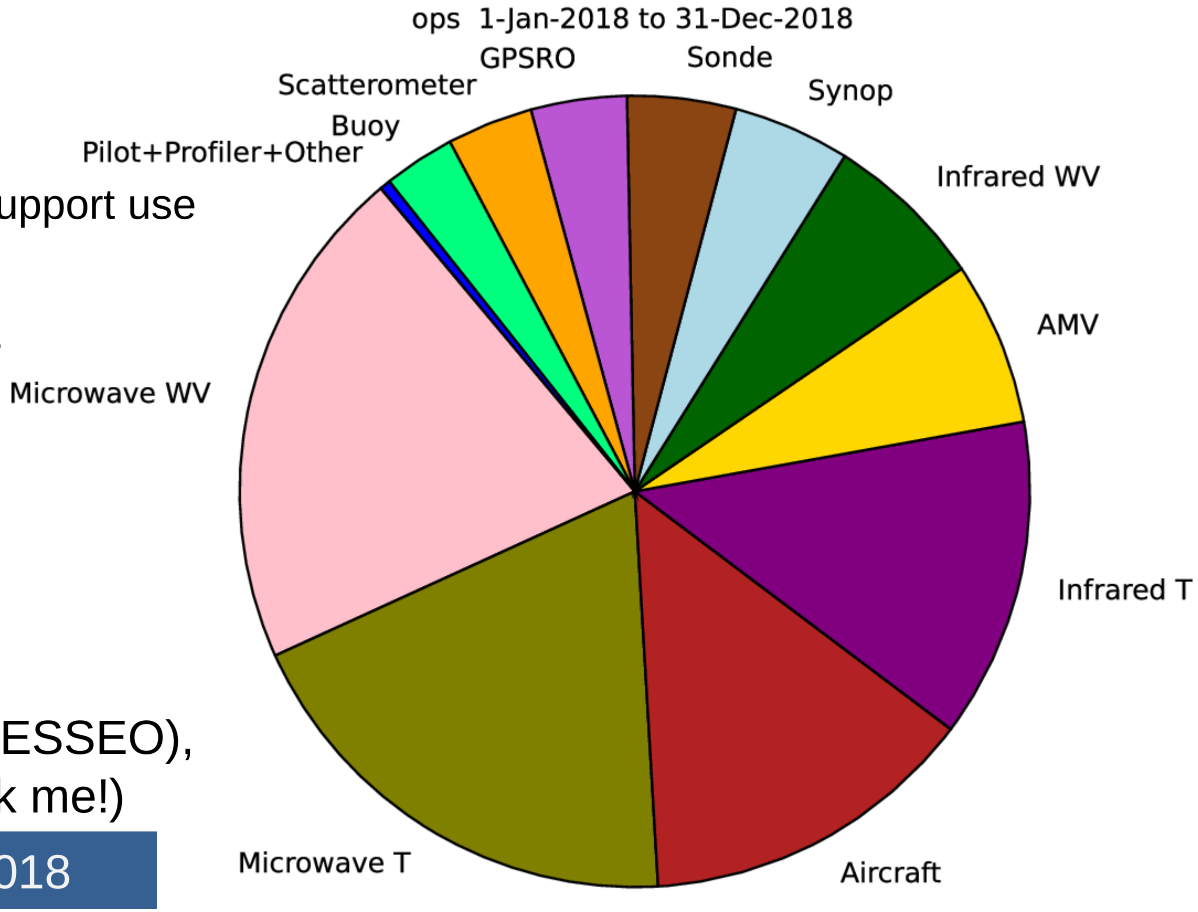
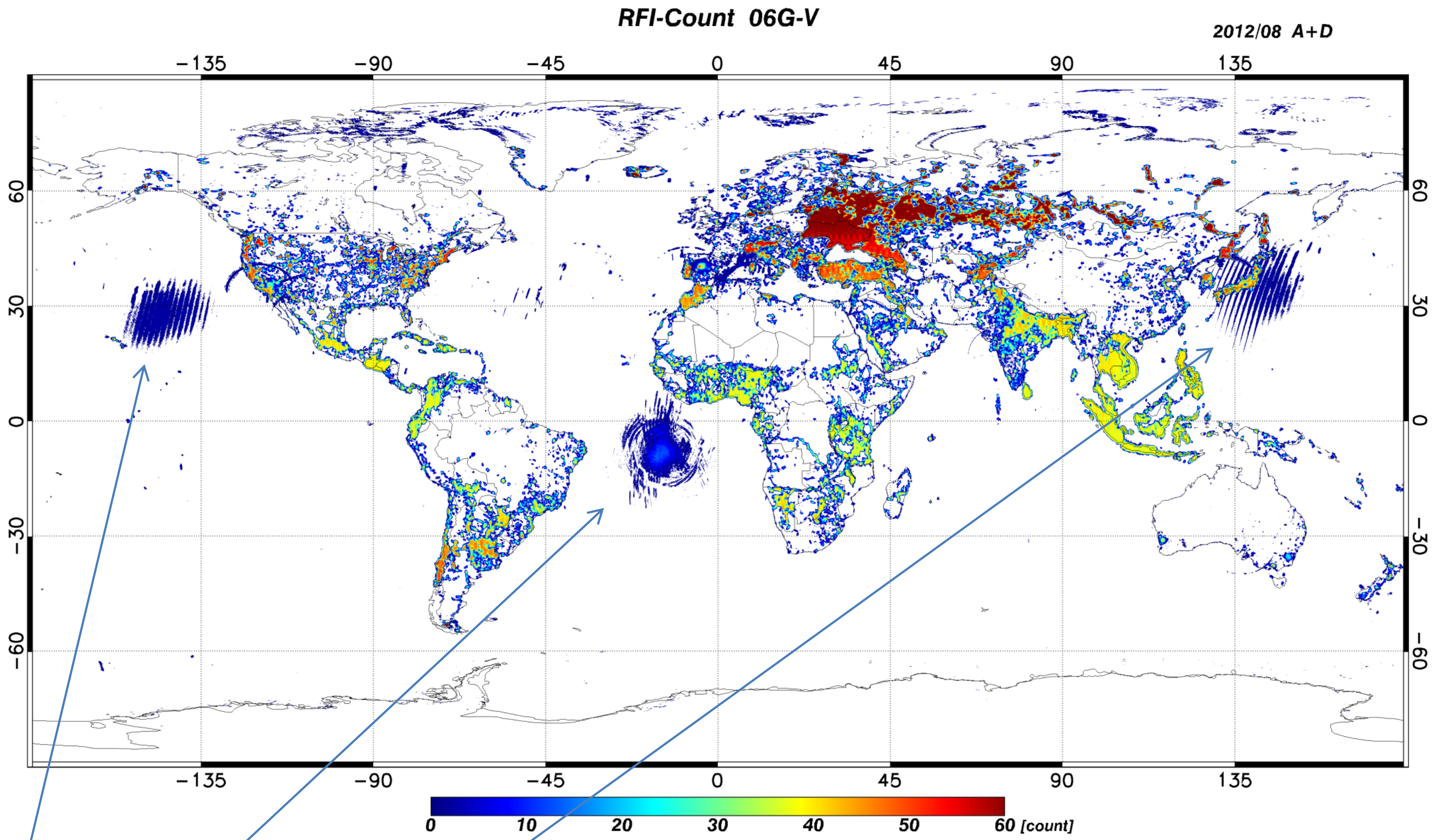


Figure from Alan Geer, ECMWF

Example of current RFI shown by JMA (Japan) in C band (unprotected)

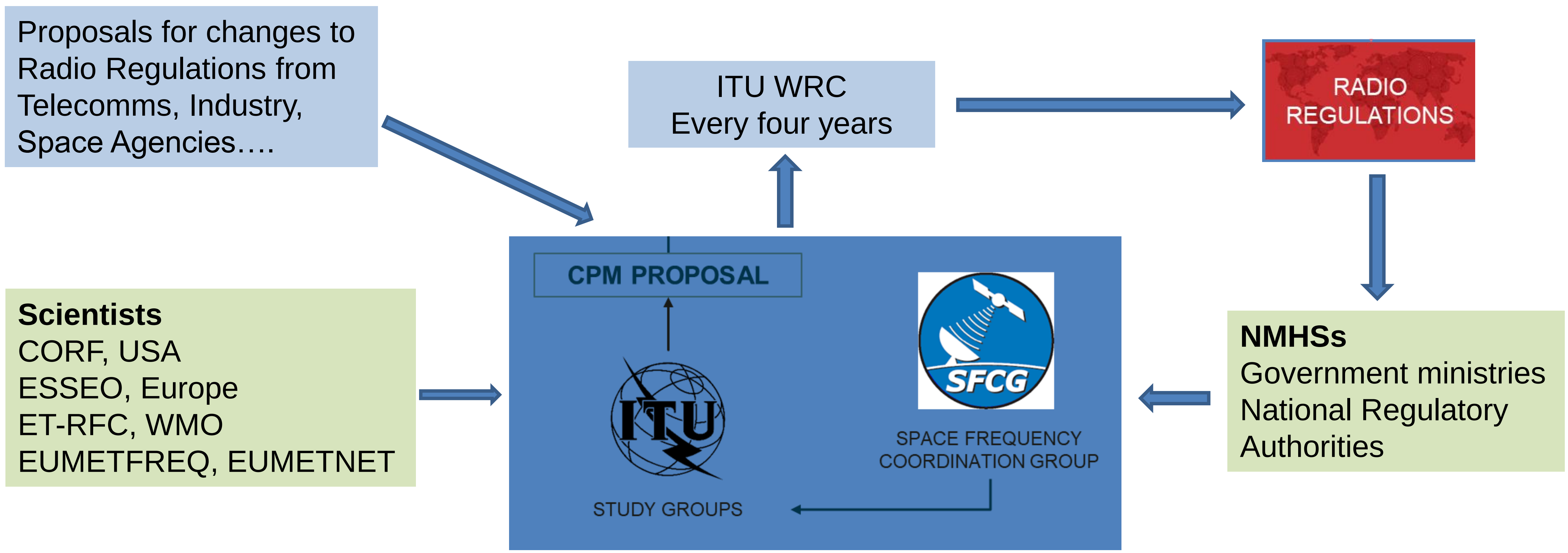


RFI sources:

1. Globalstar (satellite phone)
2. Ascension island(Ground-Satellite communication)
3. Japan, South-east Asia (ground-ground communication)

M. Seki, presented by M Kazumori at ECMWF RFI workshop, 2018

ITU WRCs


Proposals for changes to Radio Regulations from Telecomms, Industry, Space Agencies….
ITU WRC
Every four years
RADIO REGULATIONS
Scientists
CORF, USA
ESSEO, Europe
ET-RFC, WMO
EUMETFREQ, EUMETNET
CPM PROPOSAL
ITU
STUDY GROUPS
SFCG
SPACE FREQUENCY COORDINATION GROUP
NMHSs
Government ministries
National Regulatory Authorities

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The history that led to EPS-SG

Europe

US research satellites in 1960s and 1970s led to what we have now

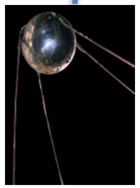
We are approaching a new leap forward (EPS-SG, FY-5, Post-JPSS)

2007 Metop
MHS
IASI
ASCAT
GRAS
GOME-2
HIRS/4
AMSU-A
AVHRR

2023/4 Metop-SG
MWS
MWI
ICI
IASI-NG
SCA
RO
MetImage
3MI
Sentinel-5

1957 1960 1970 1980 1990 2000 2010 2020 2030

Rest of the World



1964 NIMBUS-1
HRIR
APT
ACVS

1968 NIMBUS-B
SIRS

1972 NIMBUS-5
ITPR
NEMS
ESMR

NOAA-2
VTPR
VHRR

1979 TOVS
HIRS/2
MSU
AVHRR
SSU

1998 ATOVS
HIRS/4
AMSU-A
AVHRR
AMSU-B

2003 A-train
AIRS
MODIS
MLS
CloudSat
Calipso

2011 JPSS (S-NPP)
ATMS
CrIS
VIIRS
OMPS

2014 China FY3-C
MWHS-2
MWTS-2
MWRI
IRAS
GNOS

2017 Russia Meteor-M N2
MTVZA-GY
IKFS

EPS Second Generation

1. Updated counterparts to Metop 1st generation

ATOVS + AVHRR/MODIS → MWS + MetImage

IASI → IASI-NG

ASCAT → SCA (on EPS-SG-B)

GOME-2 → Sentinel-5 UVNS

GRAS → RO

2. New capability

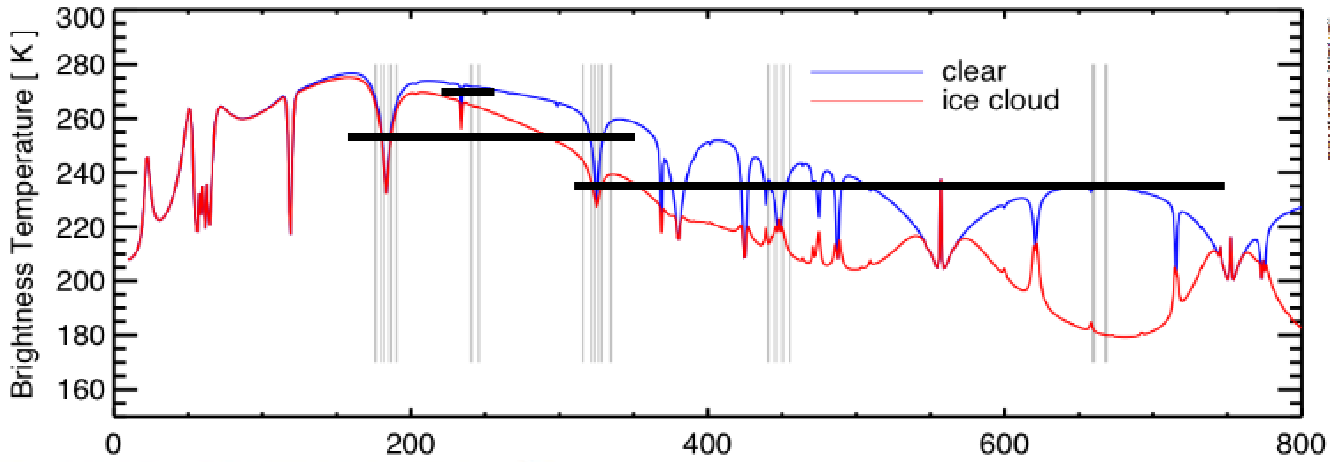
MWI: based on SSM/I

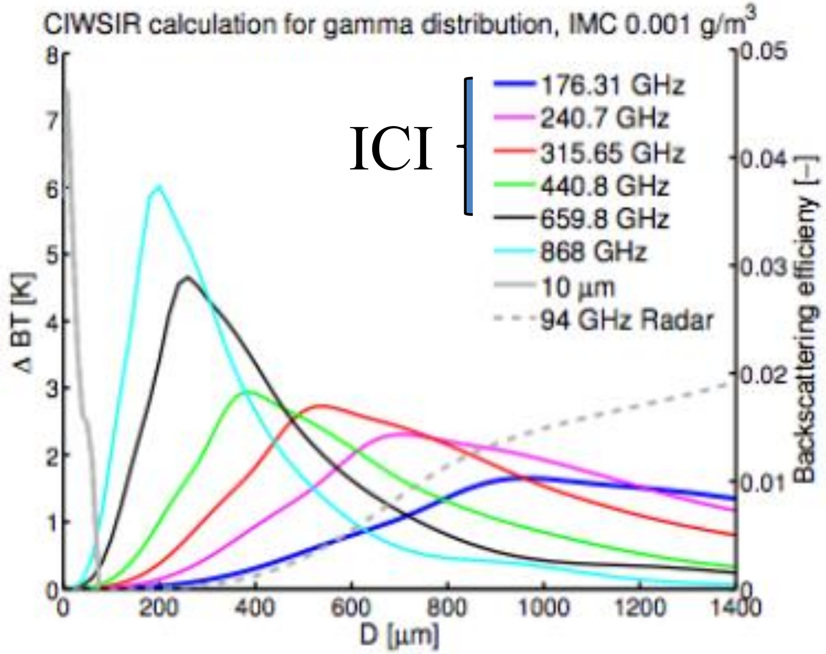
3MI: based on POLDER and PARASOL (VIS/NIR/SWIR)

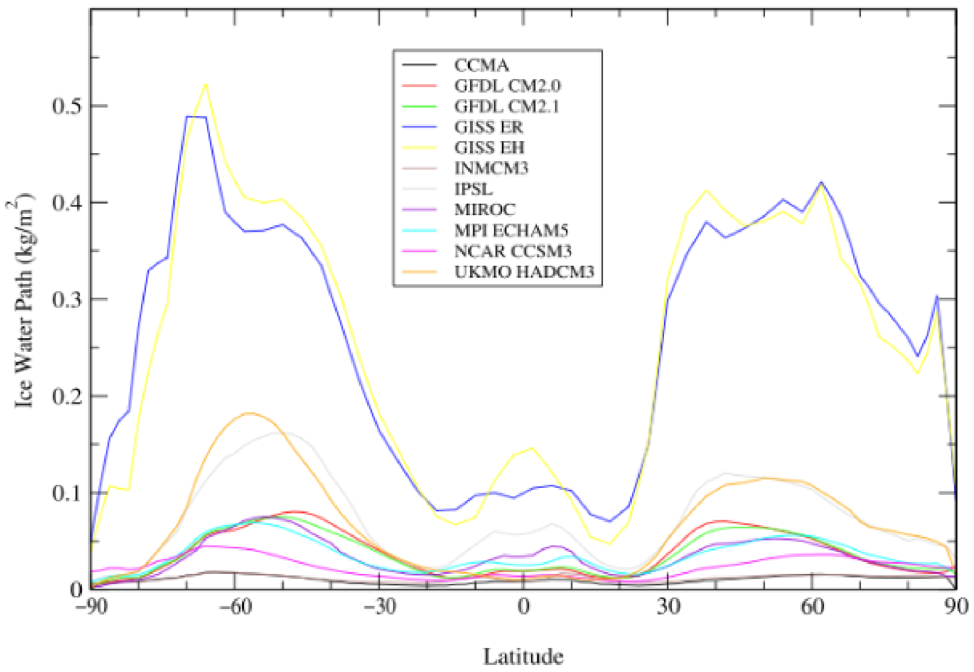
ICI: completely new! Sub-mm imager for cloud ice

EPS-SG: Ice Cloud Imager - ICI

From CloudIce proposal (Buehler et al.)







From John and Soden (2006)

Ice water path

+

Some information on particles (size, shape, orientation….)

The history that led to MTG

Europe

1977
Meteosat-1
MVIRI = 3 channel imager
(research)

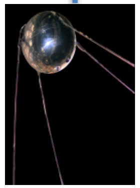
1989
Meteosat-4
MVIRI = 3 channel imager
(operational)

2005
MSG-1
SEVIRI =12 channel imager

2023-4
MTG-I1
FCI
LI
MTG-S1
IRS
Sentinel-4

1957 1960 1970 1980 1990 2000 2010 2020 2030

Rest of the World



1975
USA
GOES-1
VISSR

1994
USA
GOES-8
IMAGER
SOUNDER

2006
Japan
Himawari-6
IMAGER

2014
Japan
Himawari-8
AHI

2016
USA
GOES-16
ABI
GLM

2016
China
FY-4A
GIIRS
LMI
AGRI

India and South Korea have also developed similar programmes e.g. INSAT-3D 2013, GEOKOMPSAT 2018

Meteosat Third Generation

1. Updated counterparts to Meteosat second generation

SEVIRI → FCI 16 channel imager

European rapid scan 2.5 minutes, full disk 10 minutes.

2. New instruments

IRS: IR interferometer

LI: Lightning imager (777.4nm)

UVN: Ultraviolet, Visible and Near IR imager

First MTG Imager satellite launched
13 Dec 2022

MTG: Infrared Sounder - IRS

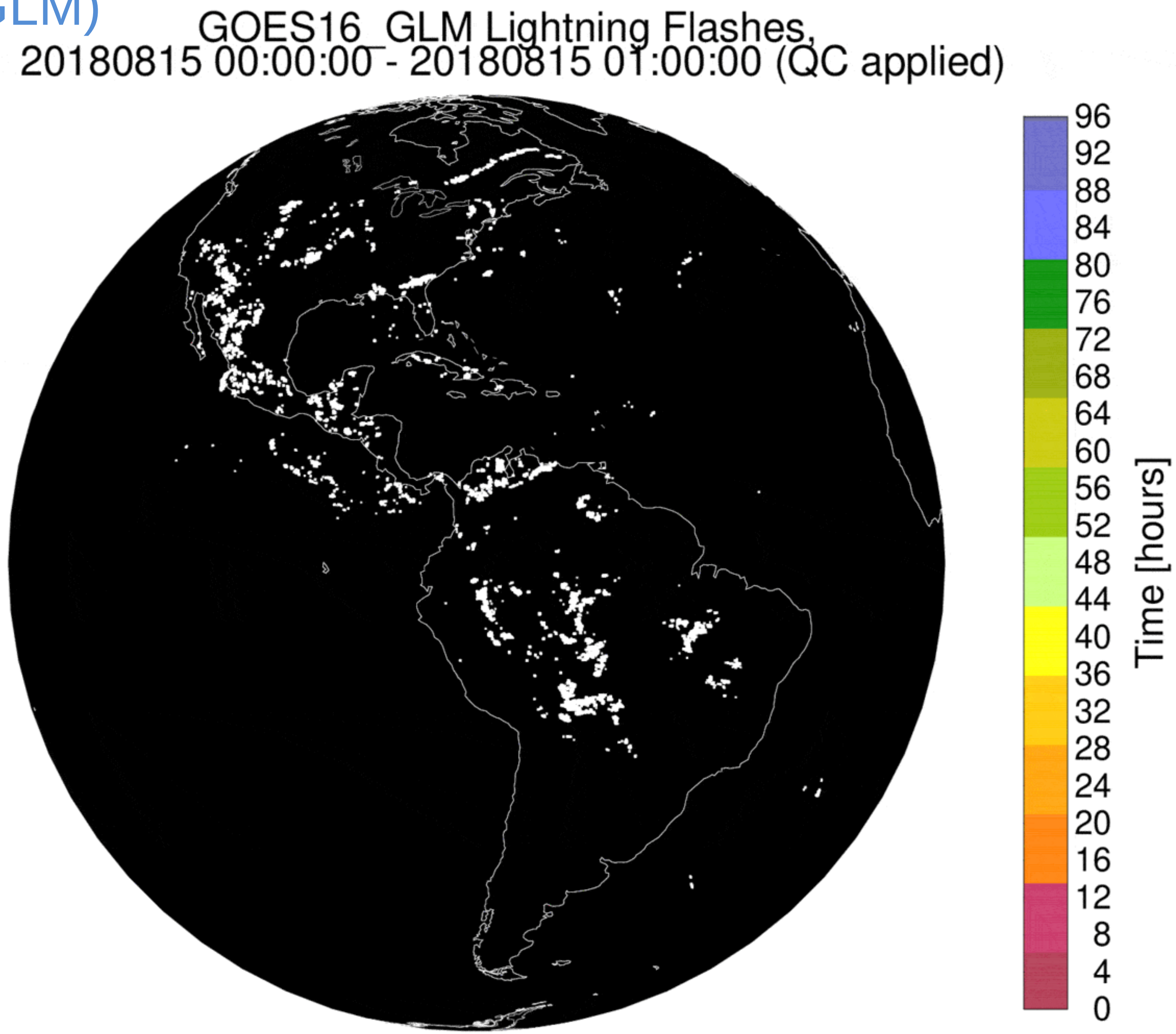
- An imaging Fourier-interferometer
- Resolution of 0.625 cm^{-1}
- Two bands
  - 700–1210 cm^{-1} Long-Wave InfraRed (LWIR)
  - 1600–2175 cm^{-1} Mid-Wave InfraRed (MWIR)
- Spatial resolution of 4 km.
- Full Disk basic repeat cycle of 60 min.

- Note China’s FY4 series also carries an interferometer in Geo orbit
- FY4-A launched 2017

- *ECMWF workshop in January 2017 dedicated to exploitation of high temporal Advanced IR Sounder information.*

GOES-16 GLM Lightning Mapper (GLM)

- **The Geostationary Lightning Mapper (GLM) on board the NOAA GOES-R series satellites provides continuous full-disk lightning observations at 8 km resolution (nadir) and in quasi-real-time.**
- **Lightning pulses are detected through their signature in the 777.4 nm oxygen band (lightning peak emission).**

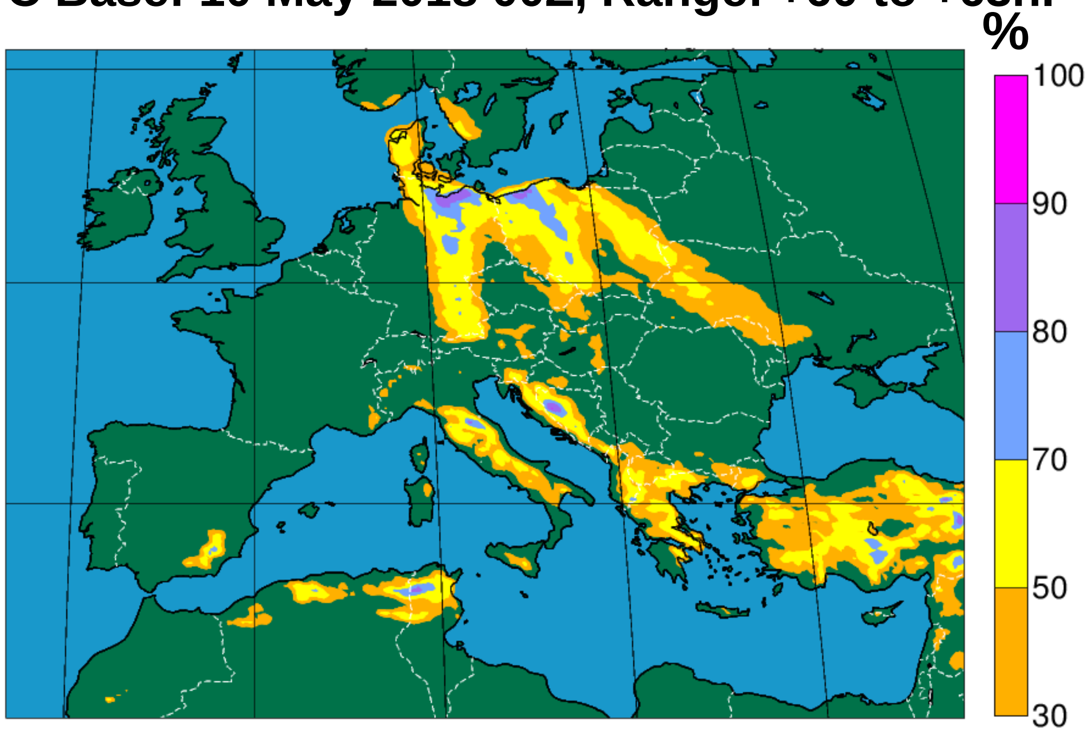


Animation of GOES-16 GLM lightning flashes over 4 days.

Thanks to Philippe Lopez for this slide

Towards lightning imager assimilation

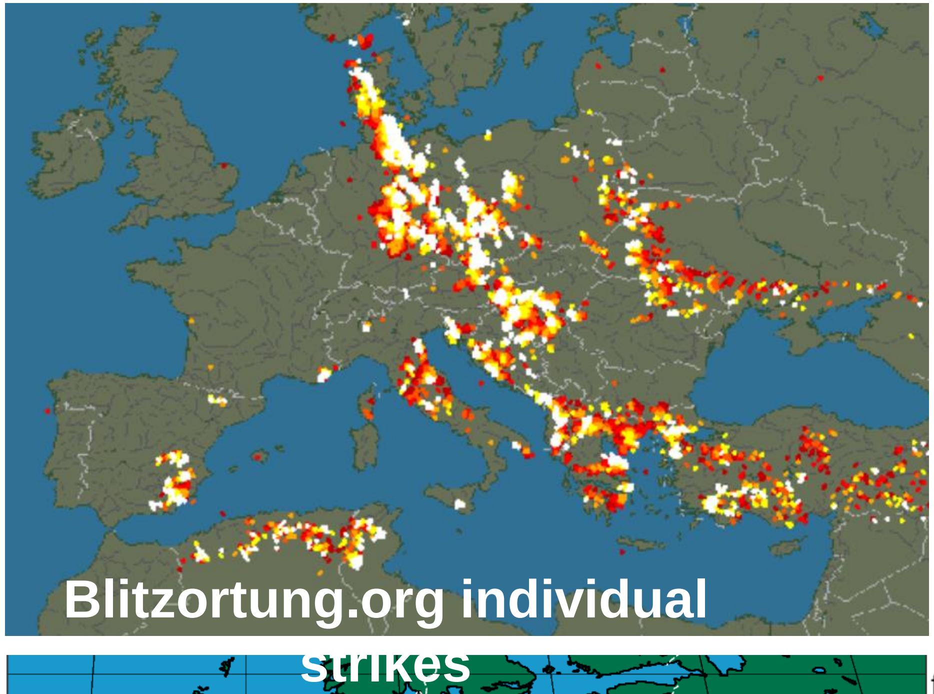
ECMWF ensemble forecast
Probability[flash density > 0.1 fl/100km^2/h]
FC Base: 10 May 2018 00Z, Range: +60 to +63h.

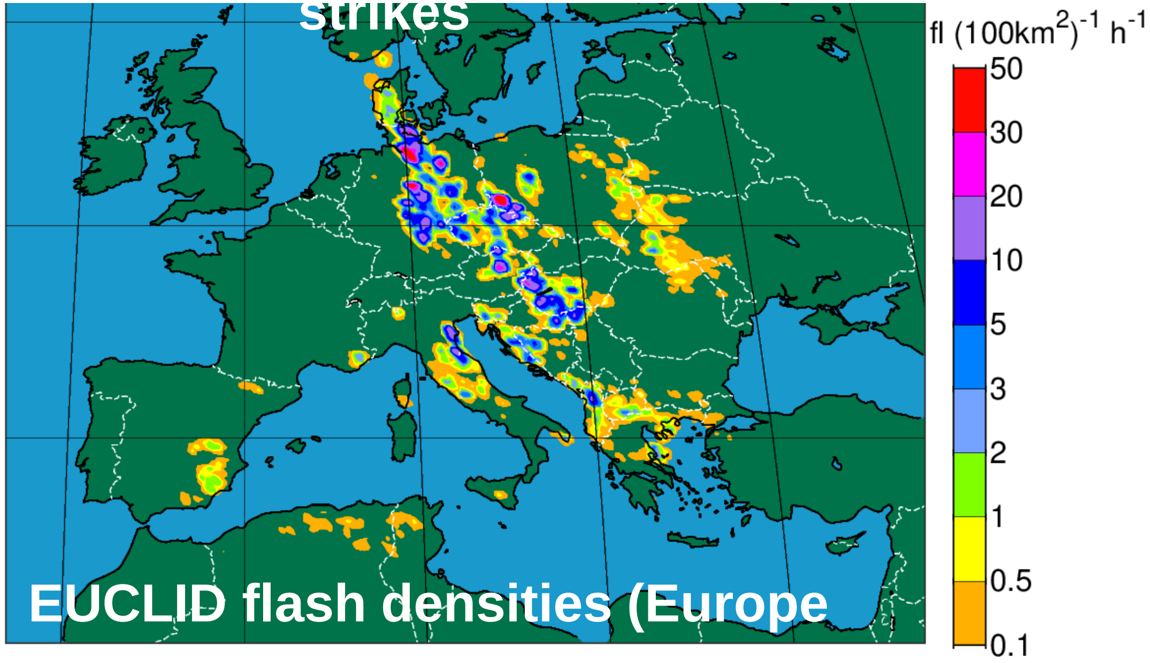


→ Ensemble lightning forecasts can offer useful guidance to forecasters up to day 3 (in mid-latitude regions).

Thanks to Philippe Lopez for this slide

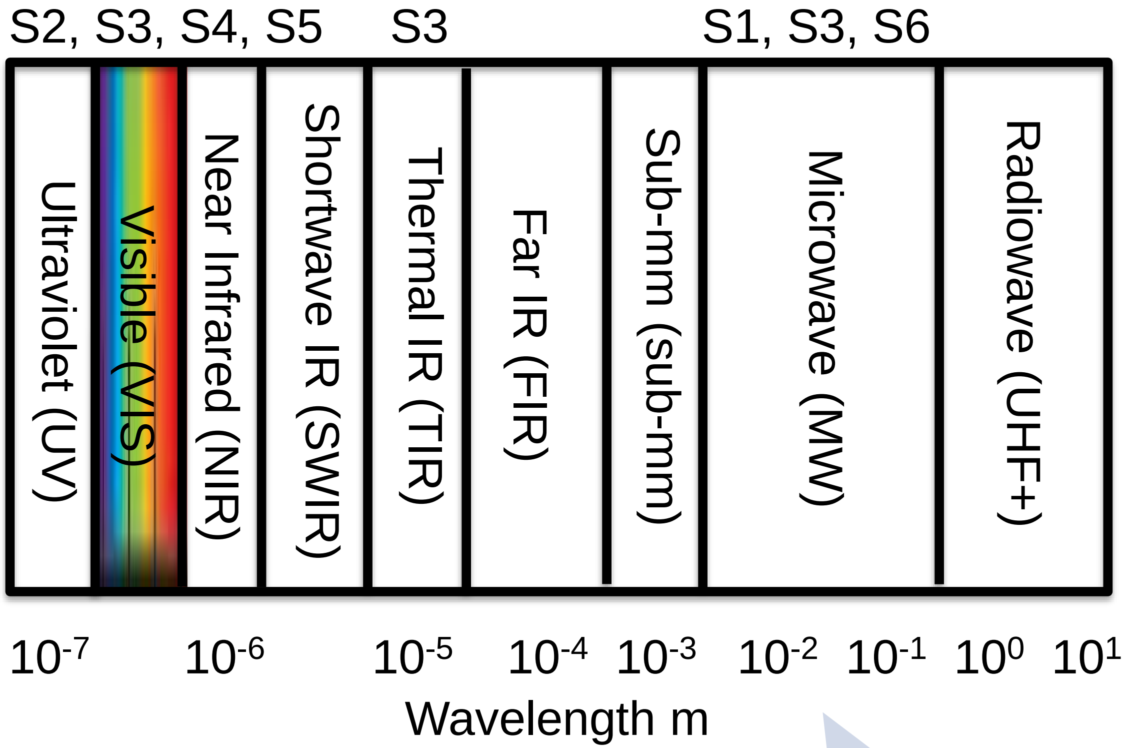
Ground-based obs., 10 May 2018 15Z

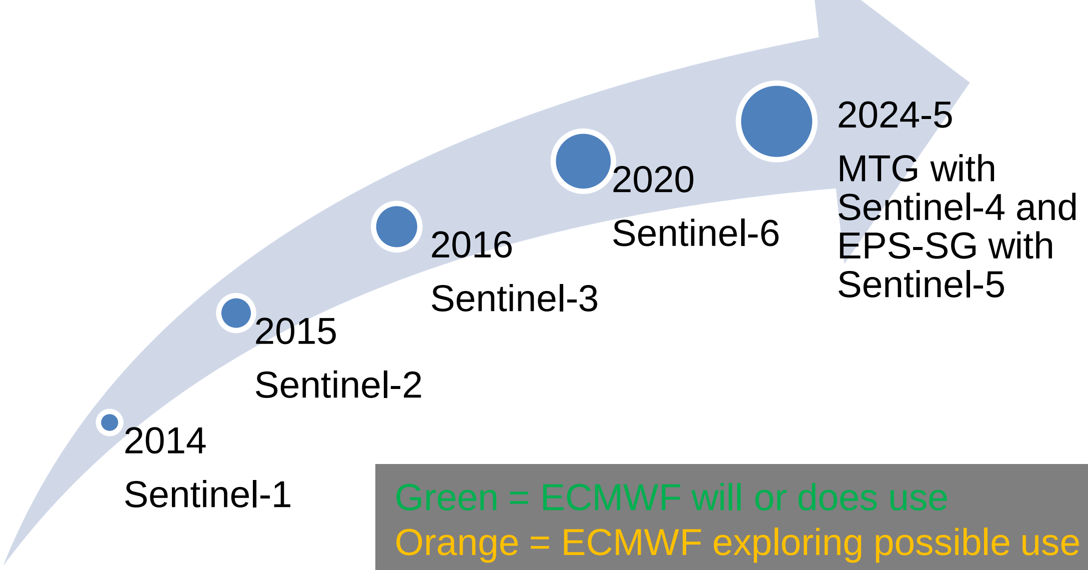




Copernicus Missions: Sentinel 1-6

- **Sentinel-1: 4-80m resolution C-band SAR (5.405 GHz): Discussion on possible new collaboration on wave spectrum assimilation**
- **Sentinel-2: 10-60m resolution NIR/VIS/UV imager 13 bands 443-2190nm**
- **Sentinel-3: Altimeter (SRAL), IR imager (SLSTR), Visible imager (OLCI), MW radiometer (MWR) and others.**
- **Sentinel-4: 8km resolution NIR/VIS/UV grating spectrometer for atmospheric chemistry flying on MTG**
- *Sentinel-5/UVNS* (**and Sentinel-5p/TROPOMI**)*: 7km resolution NIR/VIS/UV grating spectrometer for atmospheric chemistry flying on EPS-SG*
- **Sentinel-6: Poseidon-4 altimeter 5.4 and 13.58 GHz**





Green = ECMWF will or does use
Orange = ECMWF exploring possible use
Red = ECMWF has no current plans to use

Copernicus Expansion Missions

Green = ECMWF will or does use
Orange = ECMWF exploring possible use
Red = ECMWF has no current plans to use

- **CO2M 2026**
  - **0.8-1km VIS/NIR/SWIR for CO2 monitoring**
- **CRISTAL 2027**
  - **10km dual frequency (Ku, Q-band) radar for cryosphere and ocean. Heritage from Cryosat-2 SIRAL.**
- **CIMR 2028**
  - **3-64 km resolution L, C, X, K and Ka-band MW radiometer supporting all-sky, all-surface data assimilation and surface and atmospheric L2 products. Heritage from SMOS, AMSR and the ”MIMR concept”**
- **ROSE-L 2028**
  - **5m resolution L-band SAR for land and ocean applications; complements C-band SAR of Sentinel-1**
- **LSTM 2029**
  - **30-50m resolution VIS/NIR/SWIR/TIR 24 channel imager (follow on to Sentinel-3 SLSTR)**
- **CHIME 2029**
  - **20-30m resolution VIS/NIR/SWIR imager for land and ocean applications (follow on to Sentinel-2 MSI)**

Band	L	C	X	Ku	K	Ka	Q
Freqs GHz	1.4	5.4 6.9	10.7	13.5	18.7 23.8	31	35.75 36.5

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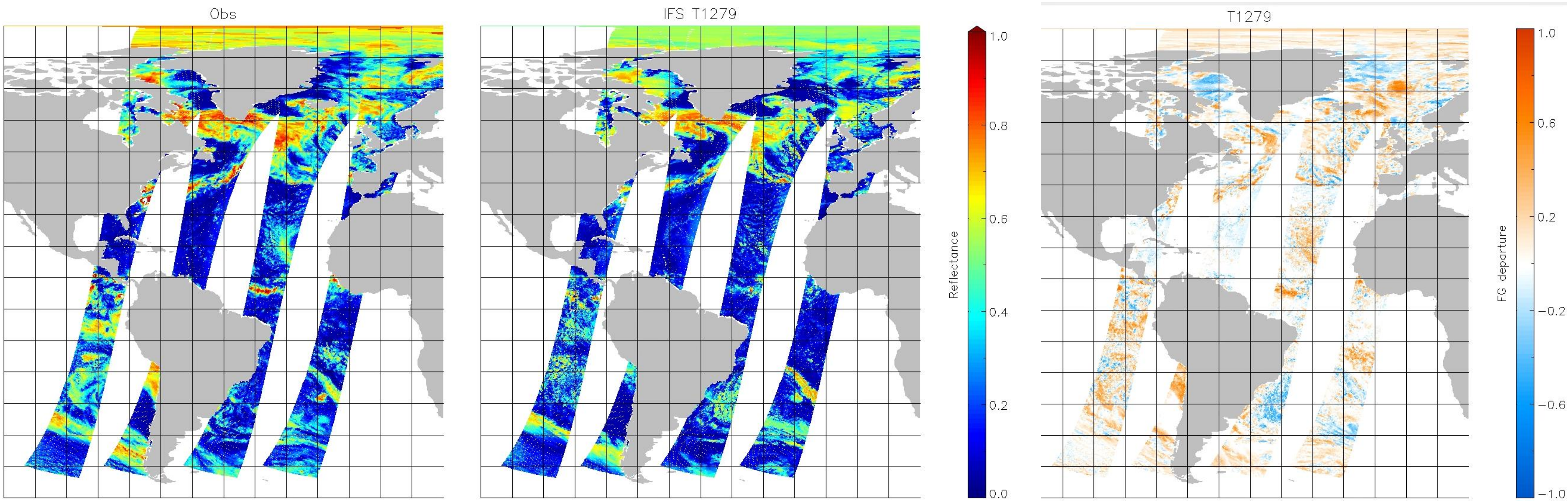
Research Missions

- ESA Earth Explorers
  - SMOS and Aeolus (Patricia de Rosnay, Mike Rennie talks)
  - **EarthCARE**
- GPM
  - GMI – best calibrated radiometer ever and DPR (Alan Geer)
  - Building on TRMM experience
- Small sats / Cubesats
  - **TROPICS,** TEMPEST-D
  - Also RO constellations (e.g. Spire, Katrin Lonitz and Chris Burrows talks)
- Novel radio occultation techniques
  - ROHP-PAZ – Polarimetric RO (Katrin Lonitz talk)
  - RO at higher frequencies e.g. ATOMMS

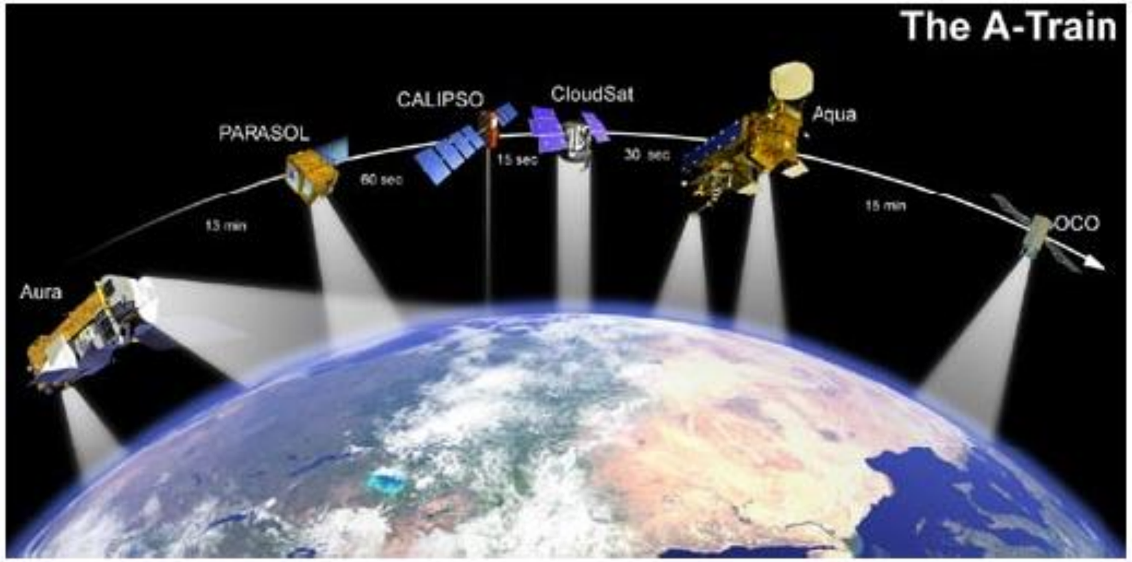
OLCI: Towards direct assimilation of visible observations

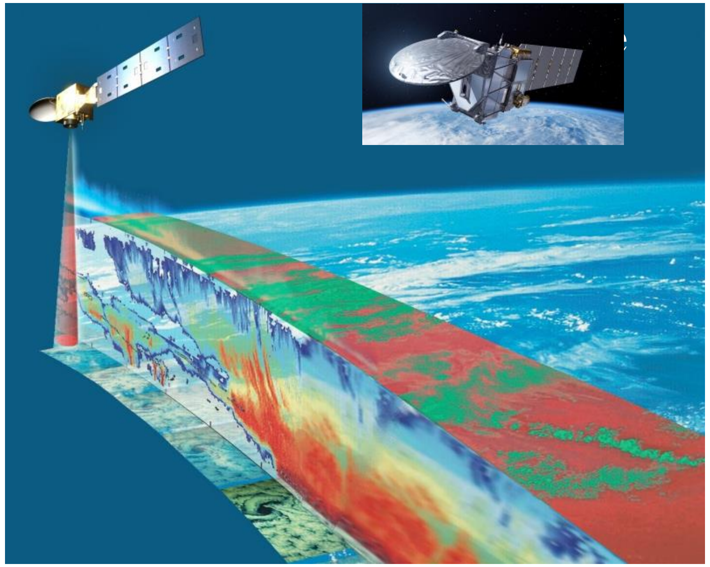


Observations | Model | Obs-Model

Thanks to Liam Steele and Angela Benedetti (CLOVIS project)

EarthCARE: cloud radar and lidar





<u>A-Train</u>

Launched 2006

NASA

700-km orbit

CloudSat 94-GHz radar

CALIPSO 532/1064-nm lidar

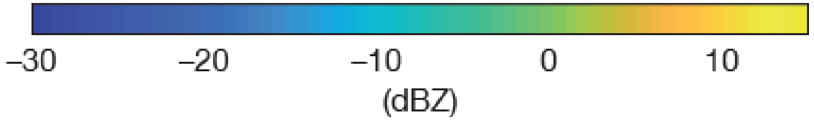
MODIS, CERES and AMSR-E radiometers

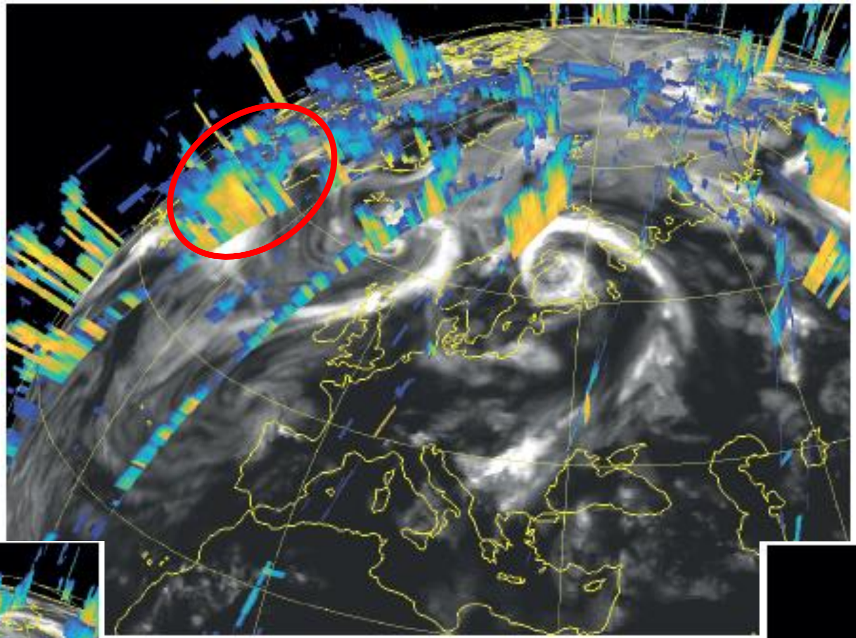
<u>EarthCARE</u>

- **Expected launch late 2024?**
- **ESA+JAXA**
- **400-km orbit (more sensitive)**
- **CPR: 94-GHz Doppler radar**
- **ATLID: 355-nm lidar**
- **MSI and BBR radiometers**

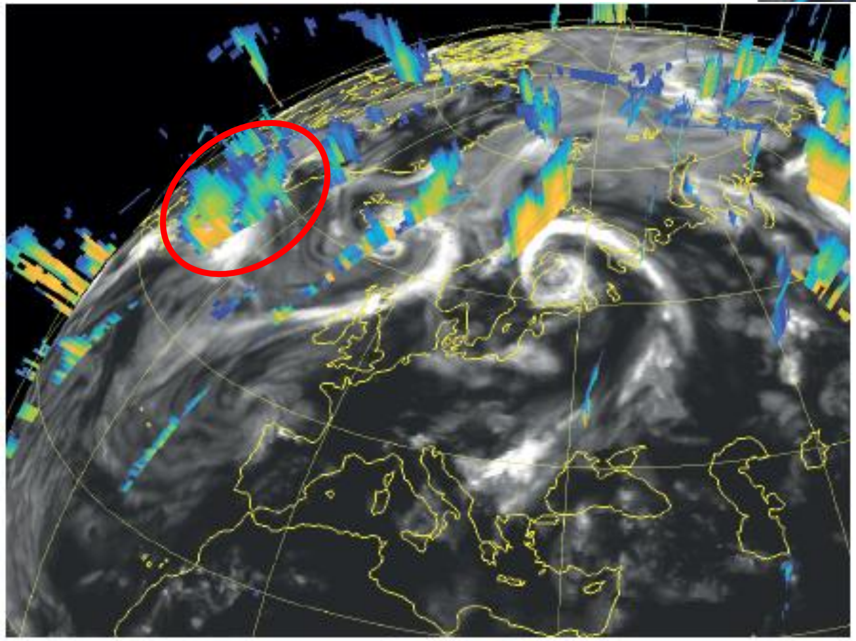
EarthCARE: 3D cloud structure from combined radar and lidar

CloudSat
radar



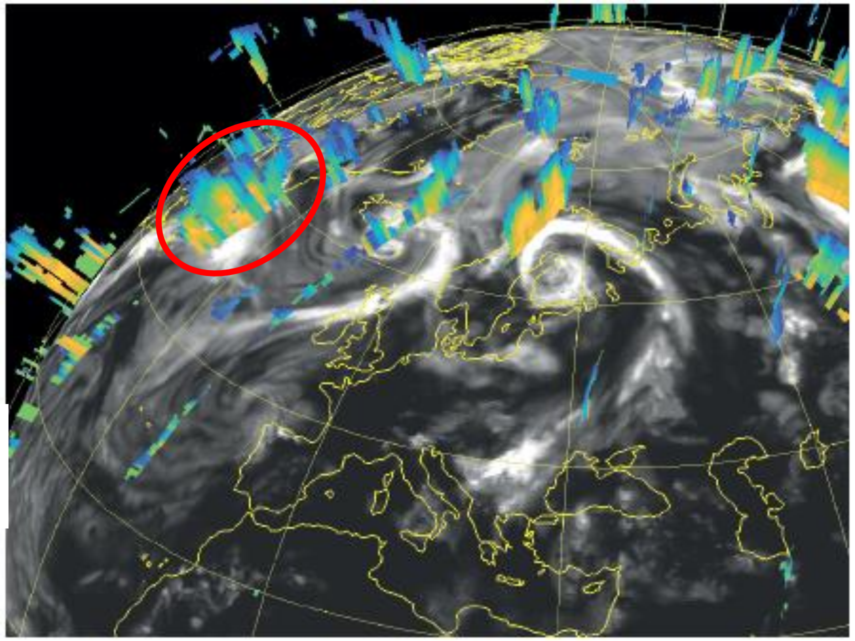


Experiments assimilating Cloudsat radar reflectivity (94 GHz) and CALIPSO lidar backscatter (532 nm)



First guess
(FG)

Analysis
(AN)

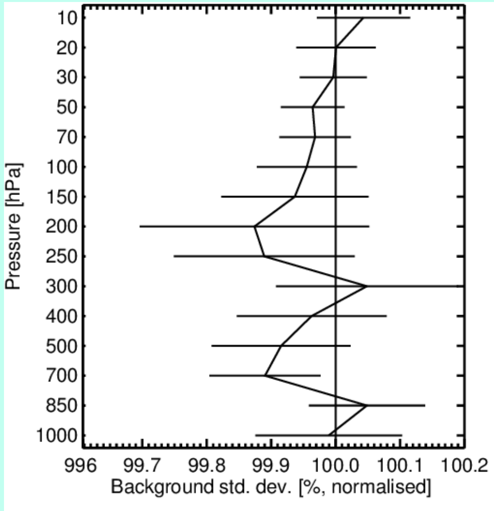


Situation: 20070731 21:00 UTC – 20070801 09:00 UTC

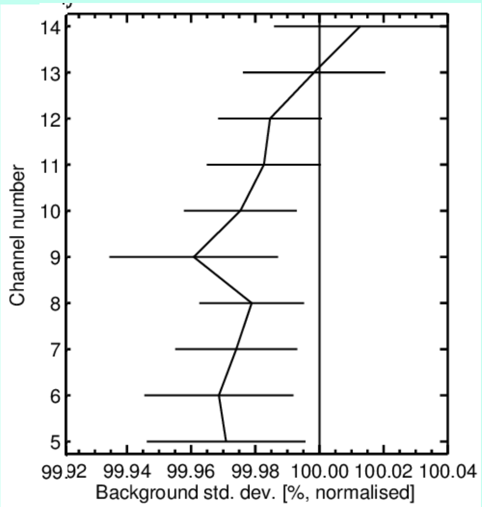
Courtesy of M. Janiskova

EarthCARE: Positive impact assimilating CloudSat and Calipso in all-sky framework

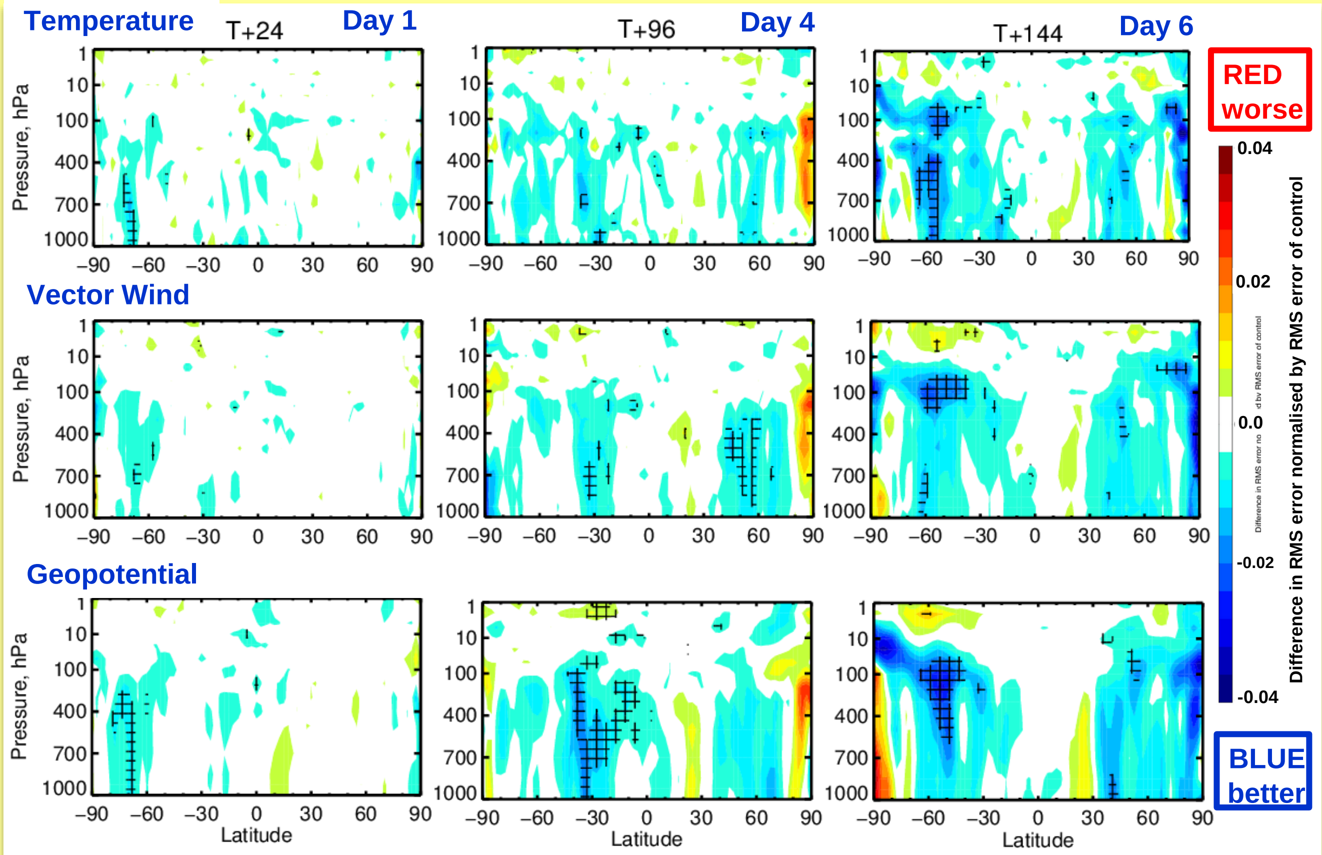
In-situ wind - Global



AMSUA - Global



Improved fit to other assimilated observations

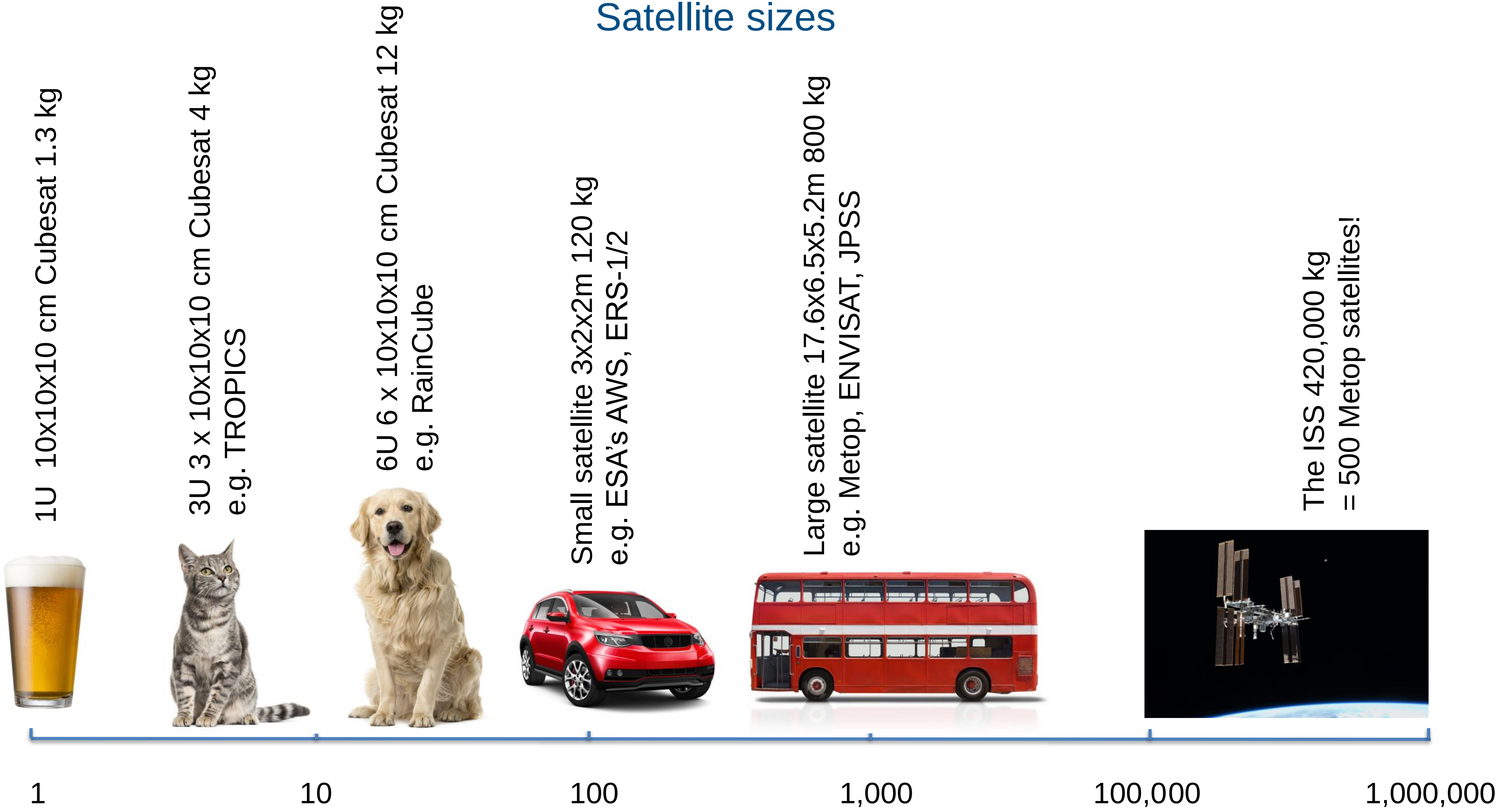


11-month period: 1 August 2007 – 31 October 2008

Thanks to Marta Janiskova and Mark Fielding (EarthCARE project)

ECMWF

Satellite sizes



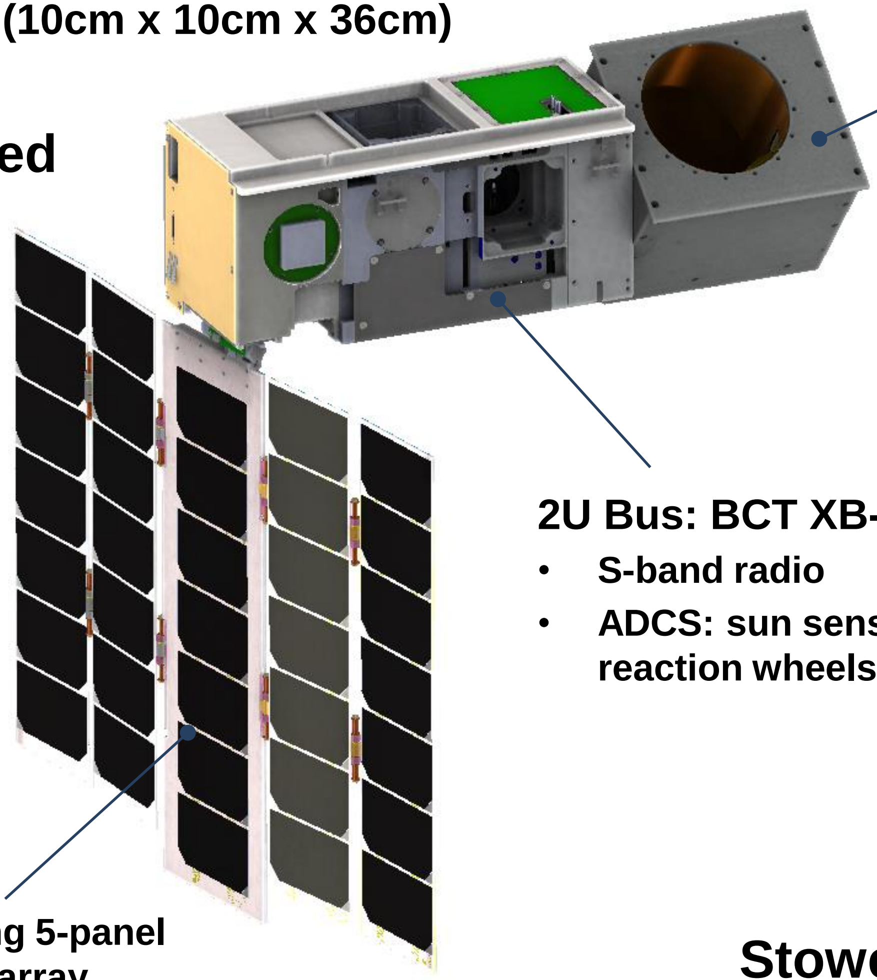
Car and bus indicate size not weight of these satellites!

Future Observations: Small MW satellite constellations, e.g. TROPICS

TROPICS CubeSat Overview

3U CubeSat
(10cm x 10cm x 36cm)

Deployed



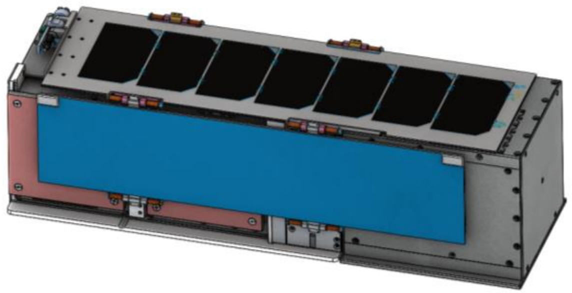
1U Payload
- Rotating microwave radiometer
- Scanner assembly
- 83 mm aperture
- Noise-diode / sky calibration

Ultra-compact W / F / G radiometer
- W band 92 GHz
- F band 7 ch (114-119 GHz)
- G band 4 ch (183±1, 3, 7), 204 GHz

2U Bus: BCT XB-1
- S-band radio
- ADCS: sun sensor(s), star-camera, reaction wheels, torque rods

Articulating 5-panel solar array

Stowed



Courtesy of B.Blackwell TROPICS PI MIT

TROPICS Channel Set

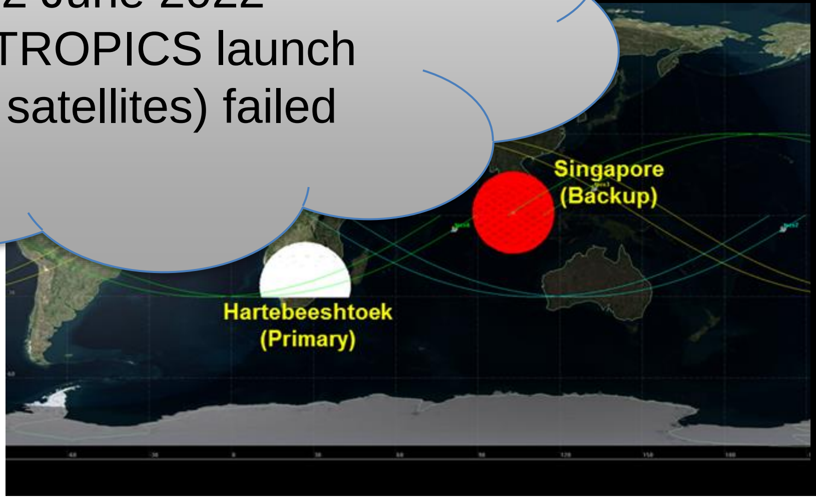
TROPICS Chan.	Center Freq. (GHz)	Bandwidth (GHz)	RF Span (GHz)	Beamwidth (degrees) Down/Cross	Nadir Footprint Geometric Mean (km)*	Measured NEdT (K)
1	91.656 ± 1.4	1.000	89.756-90.756 92.556-93.556	3.0/3.17	29.6	0.66
2	114.50	1.000	114.00-115.00	2.4/2.62	24.1	0.96
3	115.95	0.800	115.55-116.35	2.4/2.62	24.1	0.82
4	116.65	0.600	116.35-116.95	2.4/2.62	24.1	0.86
5	117.25	0.600	116.95-117.55	2.4/2.62	24.1	0.79
6	117.80	0.500	117.55-118.05	2.4/2.62	24.1	0.81
7	118.24	0.380	118.05-118.43	2.4/2.62	24.1	0.90
8	118.58	0.300	118.43-118.73	2.4/2.62	24.1	1.03
9	184.41	2.000	183.41-185.41	1.5/1.87	16.9	0.58
10	186.51	2.000	185.51-187.51	1.5/1.87	16.9	0.55
11	190.31	2.000	189.31-191.31	1.5/1.87	16.9	0.53
12	204.8	2.000	203.8-205.8	1.35/1.76	15.2	0.52

Courtesy of B.Blackwell TROPICS PI MIT

TROPICS Mission Overview

12 June 2022
First TROPICS launch
(two satellites) failed

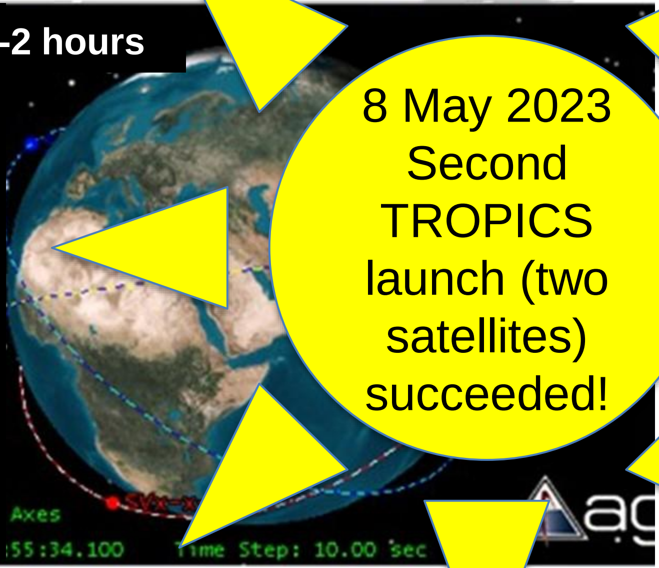
significant % of data will arrive in 1-2 hours



Six CubeSats
Three orbital planes
15-month lifetime

Better than 60-min
median revisit rate
over most of globe

State-of-the-art
temperature and
moisture sounding



8 May 2023
Second
TROPICS
launch (two
satellites)
succeeded!

KSAT

Ground Station Network

BCT

Mission Operations Center

MIT LL

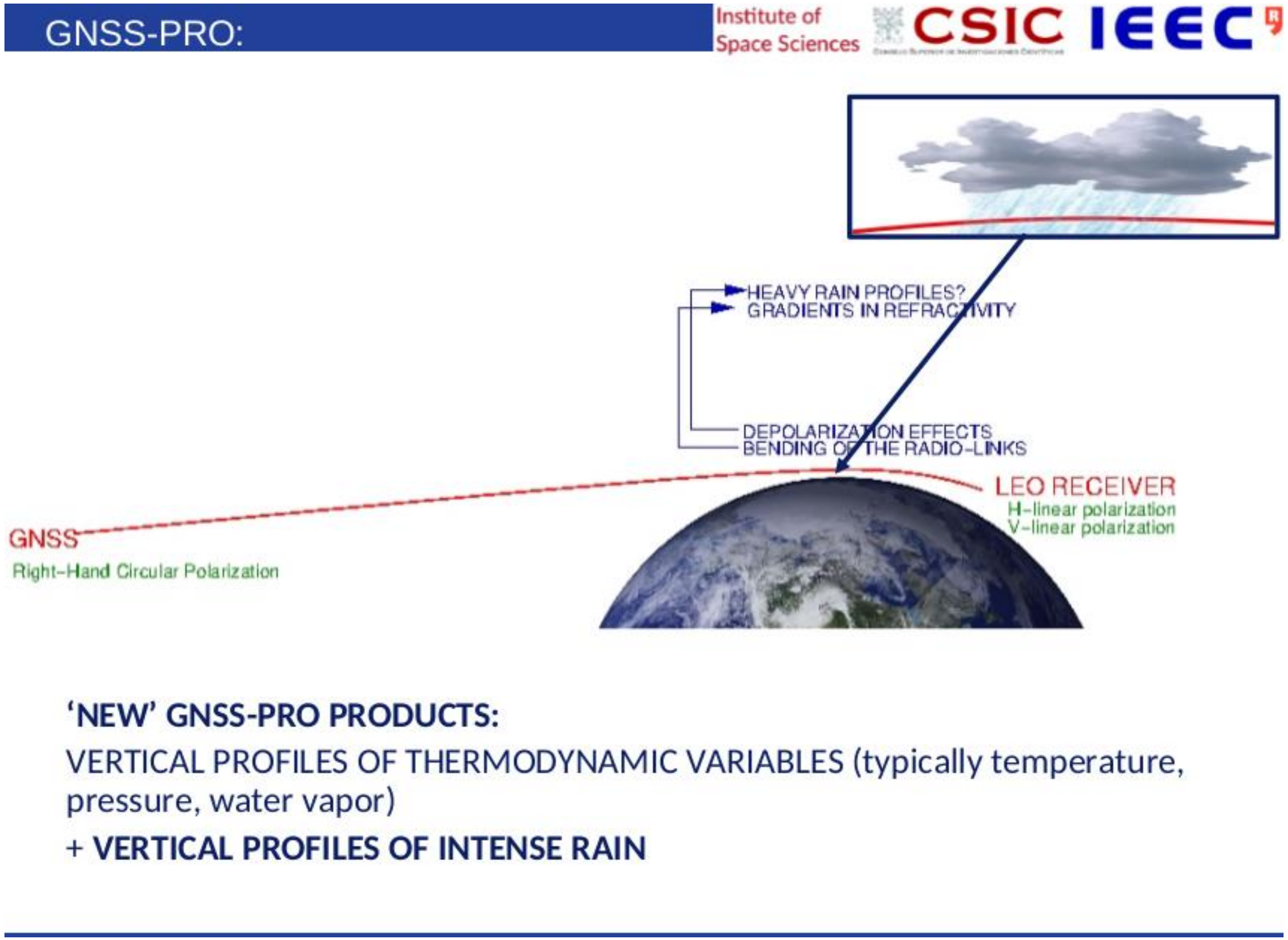
Science Operations Center

UW-SSEC

Data Processing Center

Courtesy of B.Blackwell TROPICS PI MIT

GNSS Phase



Note: There is also a lot of interest in RO reflections, so called GNSS-R to provide surface fields (wind over ocean, soil moisture for land).

The Radio Occultation and Heavy Precipitation aboard PAZ experiment (ROHP-PAZ)

https://paz.ice.csic.es

Demonstrating sensitivity to rain and frozen hydrometeors.

Shown with kind permission of Estel Cardellach (ICE, CSIC, IEEC)

Other future programmes

- USA: LEO Post-JPSS mid 2030s - being planned
- China: LEO FY-5 late 2020s: likely to be mix of core satellite(s) plus free-flyers potentially making a constellation
- Commercial: constellations, MW and other ideas, especially from USA (Spire, Planetiq, Tomorrow.io etc)
- STERNA – potential European constellation of microwave small satellites
- Aeolus-2 – Follow on Doppler Wind Lidar to Aeolus
- ESA's Earth Explorer programme
  - EE11 on going (CAIRT, WIVERN, NITROSAT, SEASTAR) on-going
  - EE12 has several bids of interest to operational meteorology

Take home messages

- We live in an incredible era for earth observation!!! Fantastic scope for research, innovation, impact.
- Good balance of operational programmes from America, Europe, Asia, coordination needed (WMO); Europe is leading with EPS, MTG and Sentinel programmes, plus some great Earth Explorers and other one-off research missions (e.g. SMOS, Cryosat, Aeolus in past; EarthCARE in near future)
- Large constellations of cheap CubeSats may be a game changer if quality is there and data is available
- WMO OSCAR tool is a fantastic way to keep on top of size and complexity of WIGOS.
- There is a threat to essential radiofrequencies from economic pressure on spectrum.