2019 International Workshop on Radiative Transfer Models for Satellite Data Assimilation

Global Satellite Programs and Requirements for Radiative Transfer Models

Peng Zhang

Co-chair of CGMS WG III

Co-chair of ITWG IIFS

zhangp@cma.gov.cn

National Satellite Meteorology Center （NSMC）
China Meteorological Administration （CMA）

Outline

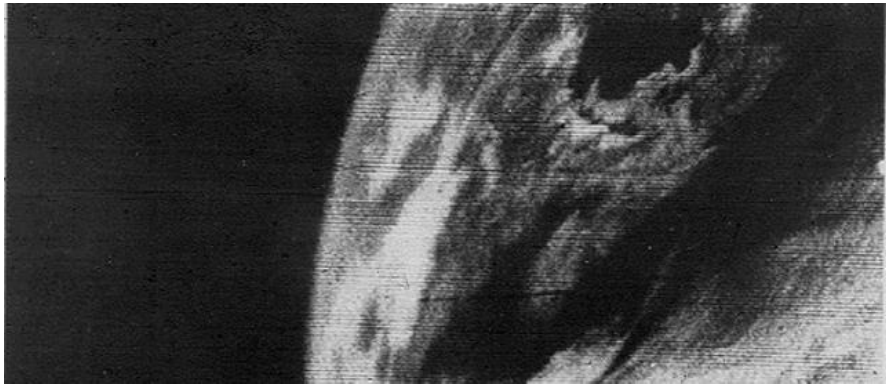
- Satellite and NWP
- RTM for Satellite Data Assimilation
- Global Satellite Program
- Issues to be Discussed

1. Satellite and NWP

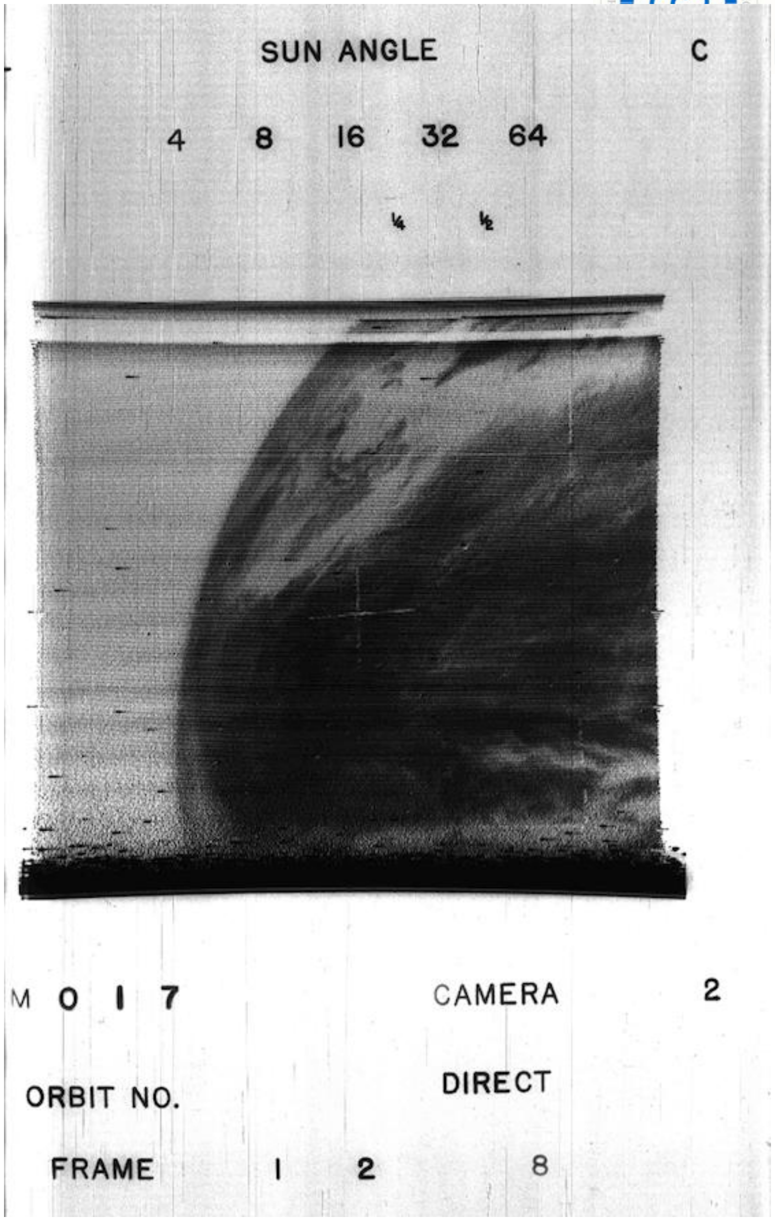
Retrospect

- 1896, Kite meteorological instrument, Weather Bureau of US
- 1940s, Radiosonde observation, US
- 1943, Airplane-based Typhoon eye detection, US Air Force
- 1950s, NWP and high performance electronic computer (global forecast field required)

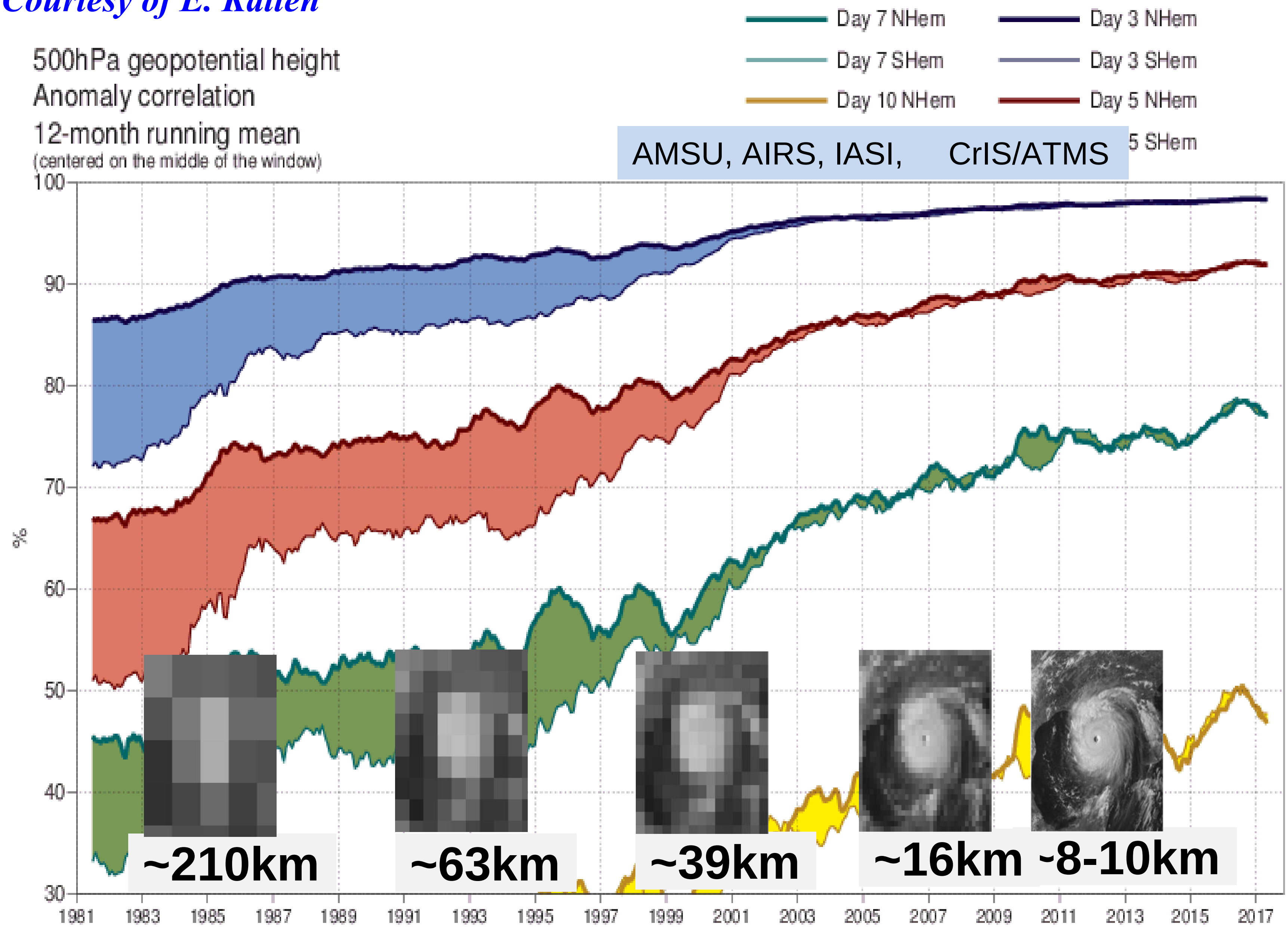
- 1940s, Rocket with camera (the first image from space)
- 1957, Sputnik (the first man-made satellite, former Soviet Union)
- 1959, Vanguard 2 (the first meteorological instrument, US)
- 1959, Explorer 7 (the first successful meteorological instrument, US)
- 1960, TIROS-1 (the first meteorological satellite, US)



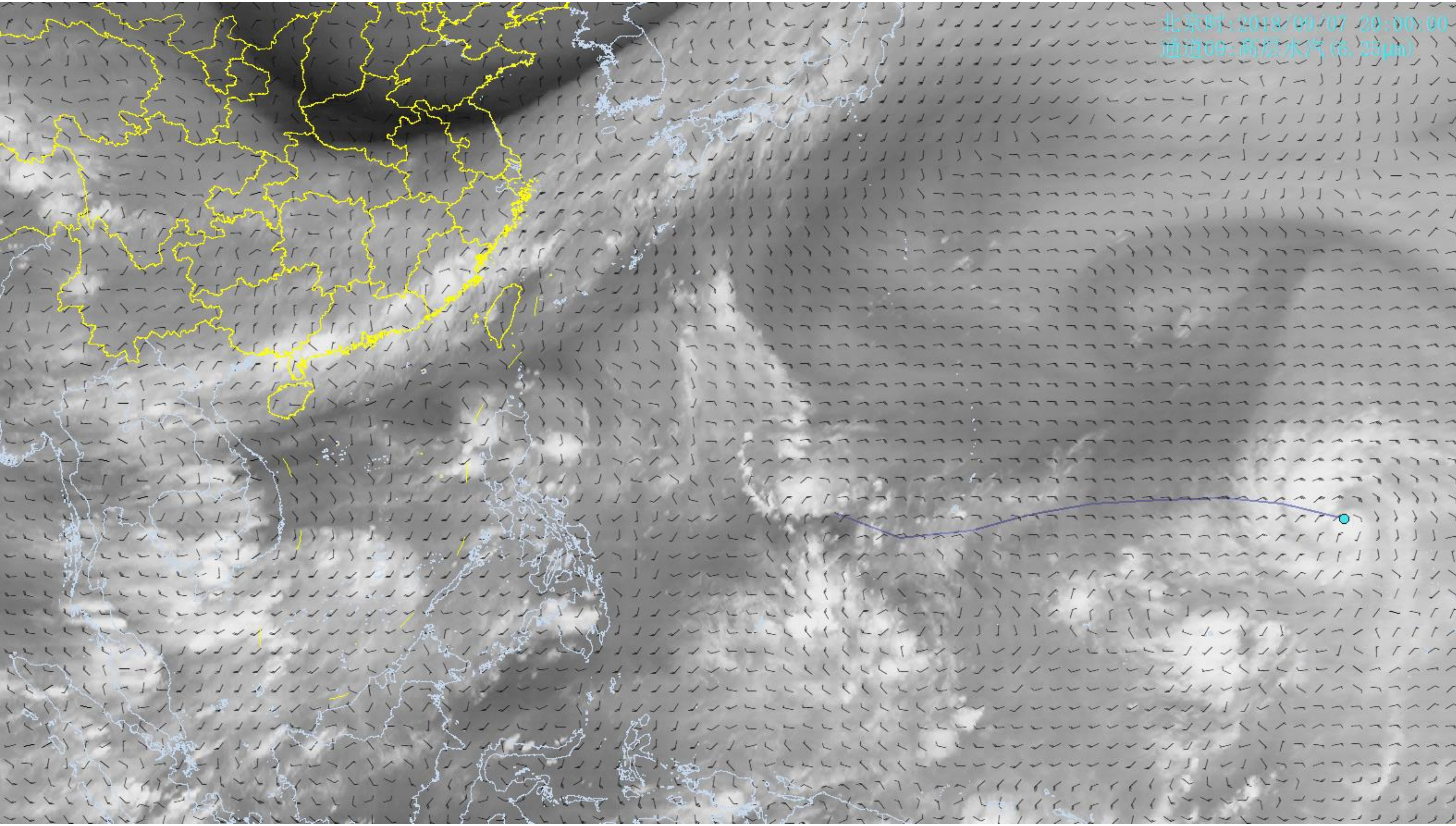
The first image from TIROS-1



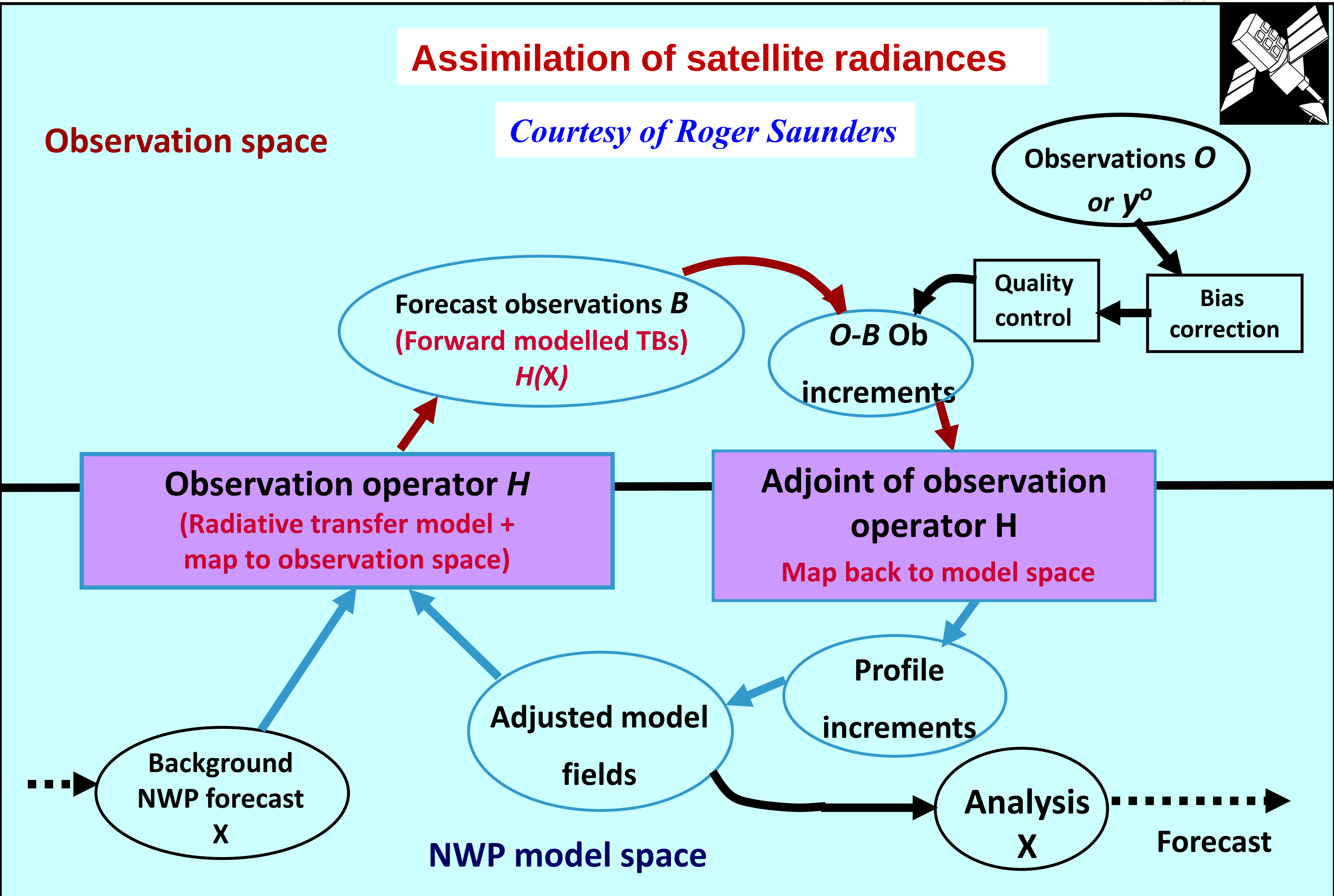
Courtesy of E. Källén



201822 Super Typhoon Mangkhut



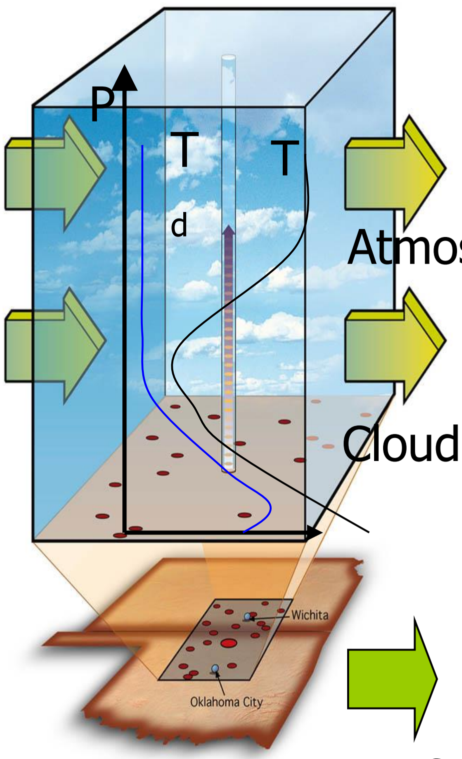
2. RTM for Satellite Data Assimilation

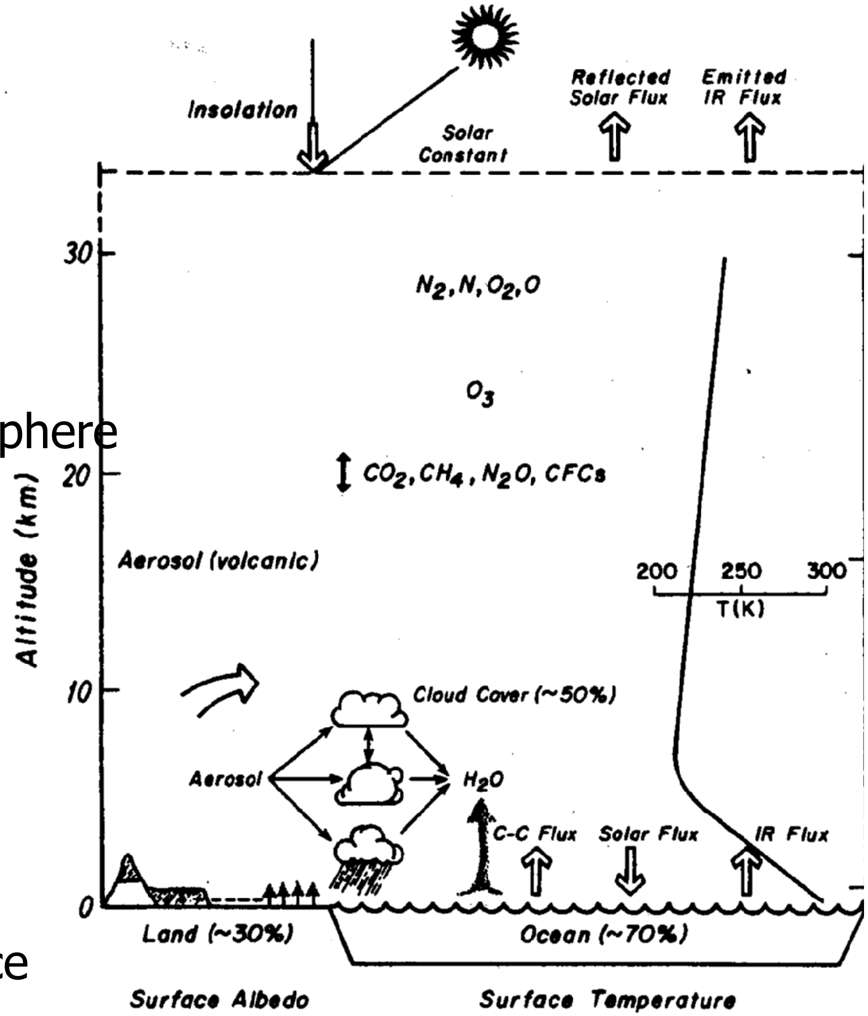


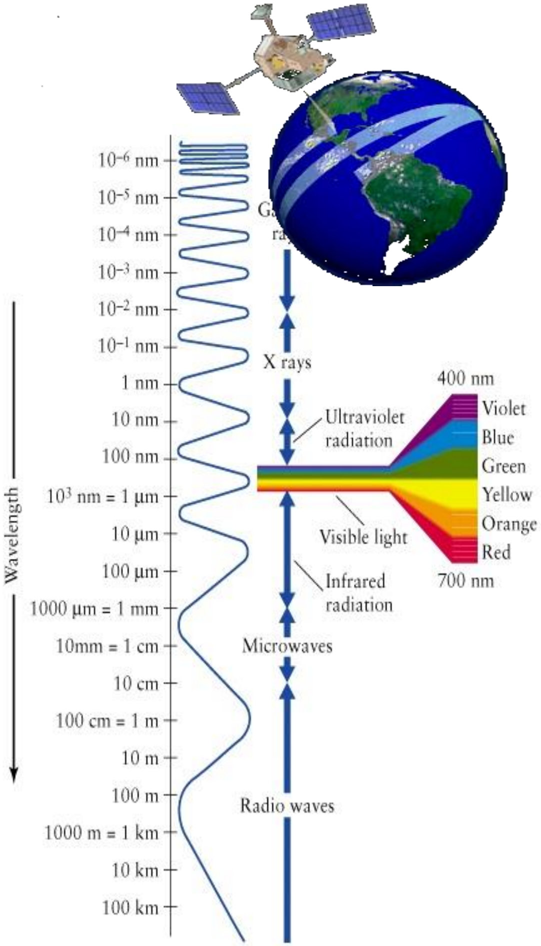
RTM in General

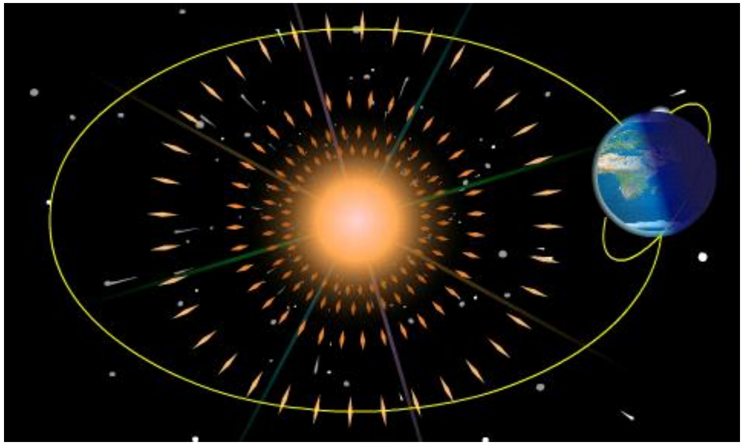
Meteorological Parameters

Radiance







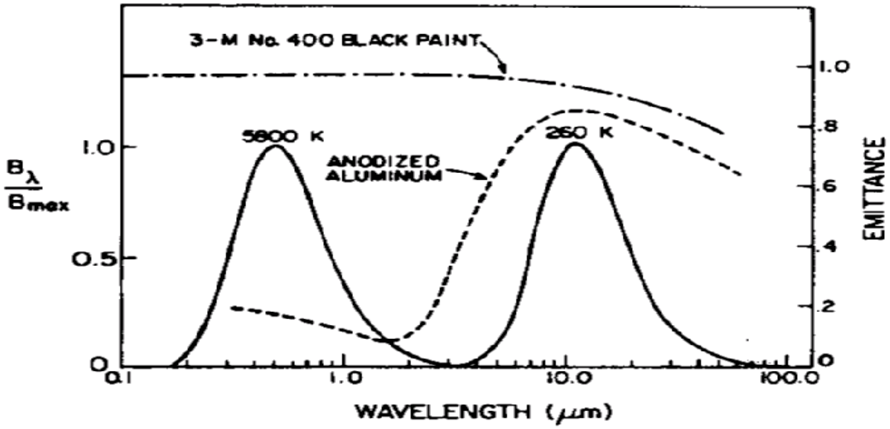


$$R_\nu \cong \varepsilon_\nu B_\nu(\Theta_s) T_{s,\nu} + \int_{p_s}^{0} B_\nu(\Theta(p)) \frac{\partial T_\nu(p, \theta_u)}{\partial p} dp$$
$$+(1-\varepsilon_\nu) T_{s,\nu} \int_{0}^{p_s} B_\nu(\Theta(p)) \frac{\partial T_\nu^*(p, \theta_d)}{\partial p} dp$$
$$+\rho_\nu T_{s,\nu} T_\nu(p_s, \theta_{sun}) F_{0,\nu} \cos\theta_{sun}$$

Energy balance on the Earth:

The Solar heats the Earth
The Earth emits the energy

$$B_i(T) = \frac{c_{1,i}}{\exp(\frac{c_{2,i}}{a_i + b_i \cdot T} - 1)}$$



RTM Solver

- **Mathematical methods in which the atmospheric radiation transfer differential equation is solved directly**

  discrete coordinate algorithm DISORT, SCIATRAN, LIDORT, VLIDORT

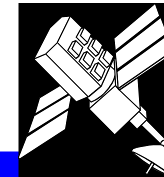
- **Physical methods based on the physical process of atmospheric radiation transferred in the atmosphere**

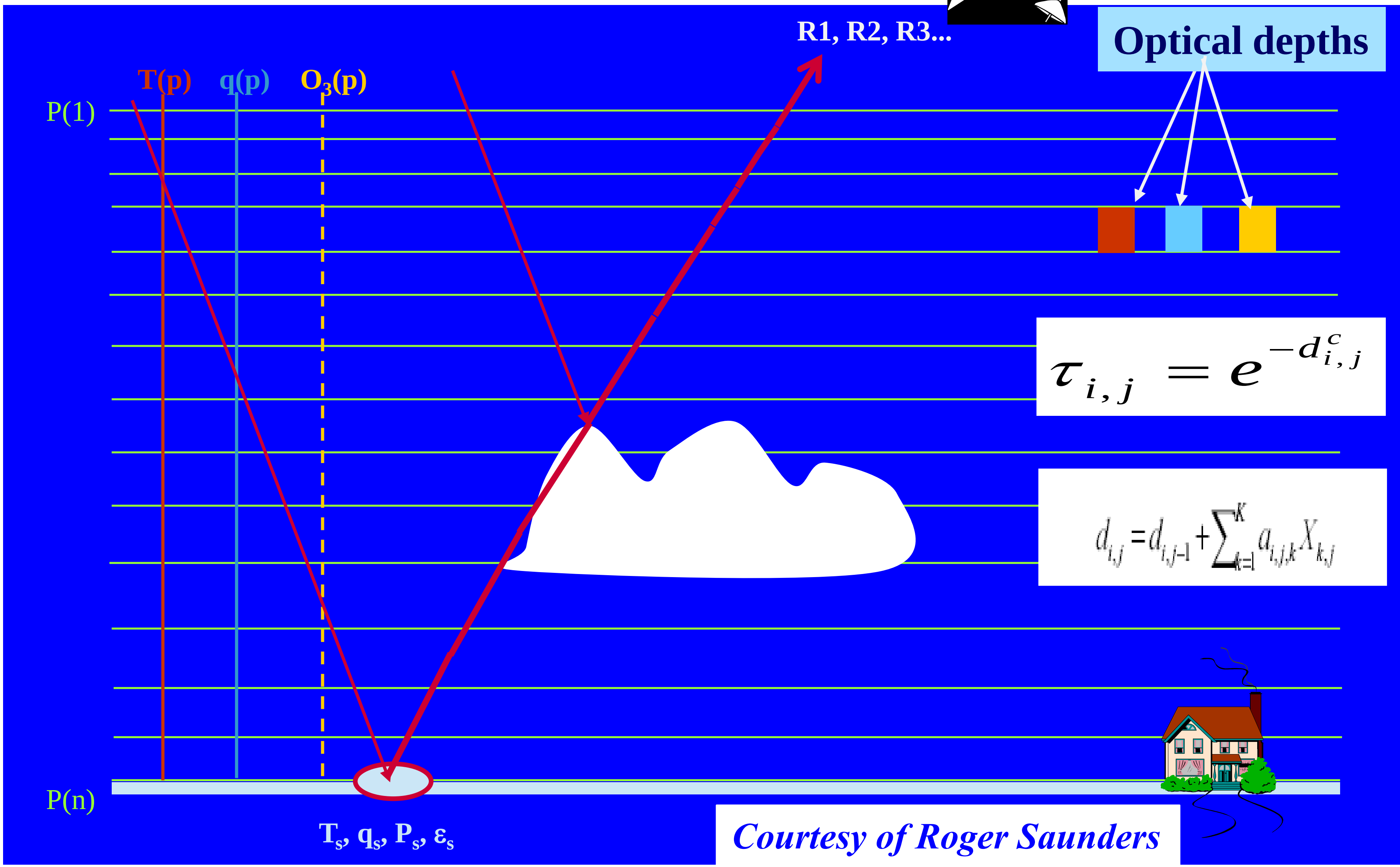
  successive scattering method 6S

  Double adding method CRTM

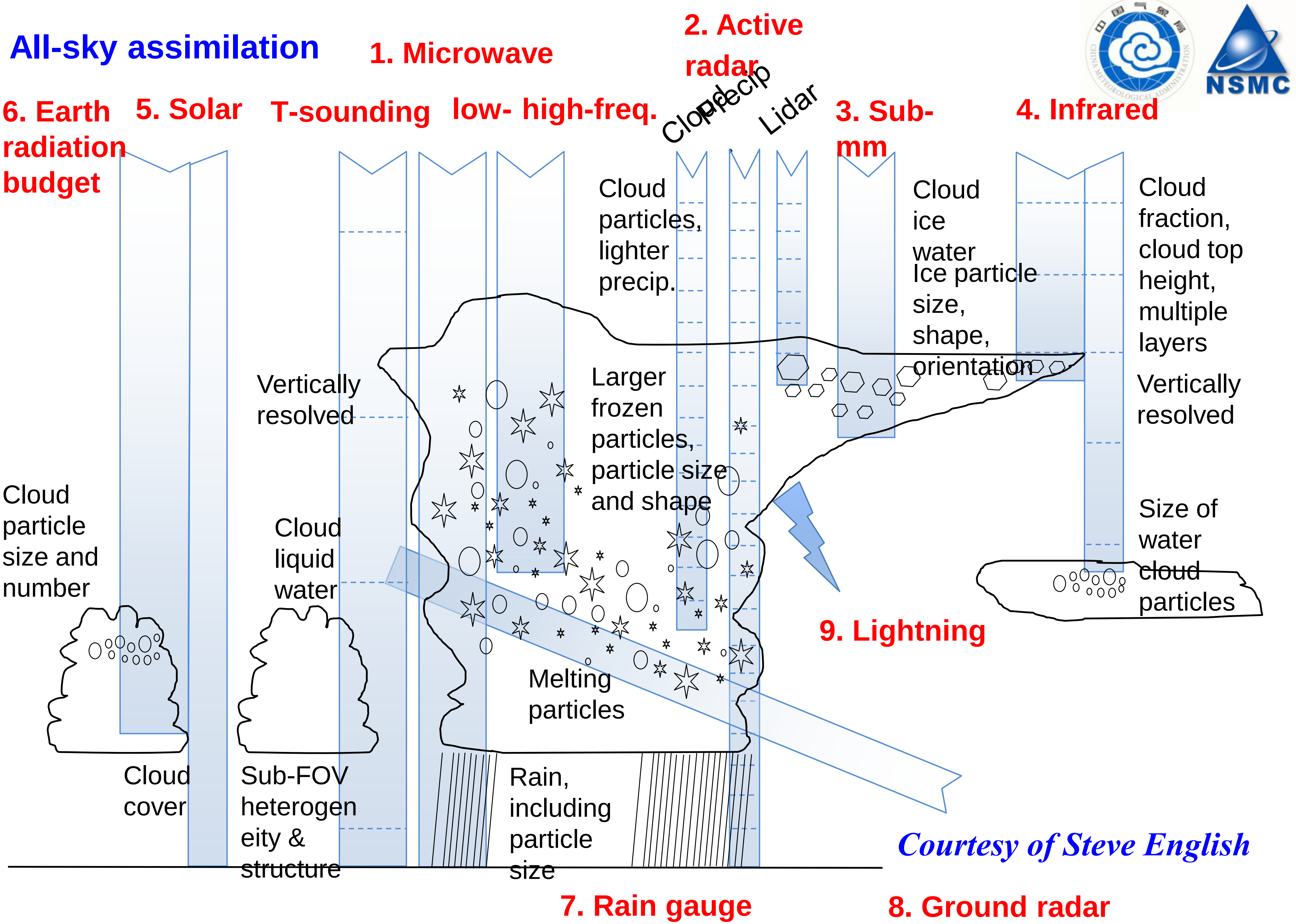
- **Monte Carlo method which is based on the physical statistics of photo scattering**

Transmittance Matrix





All-sky assimilation



Courtesy of Steve English

RTTOV & CRTM

- Assimilation of TOVS top-of-atmosphere radiance began operational in the ECMWF NWP model in early 1990's, and accurate radiative transfer model started to be important.

- **CRTM** has a long scientific heritage beginning in mid 1970's with the work of Larry M. McMilling and Henry E. Fleming, and it is started to be sustainable in 2005 by NOAA. Latest version is V2.3.

- **RTTOV** first coded in the beginning of the 1990's by John Eyre and now is supported by NWP Satellite Application Facilities. Latest version is V12.3

- **RTTOV** is operational at ECMWF, UK Met-Office, Meteo-France, JMA, DWD, CMA and many other national weather services center; **CRTM** is operational at NCEP.

Model provide

- Satellite radiance simulation model:

$$R = F(X)$$

- Tangent-linear model:

$$\delta R = (\partial F/\partial X)\partial X$$

- Adjoint model:

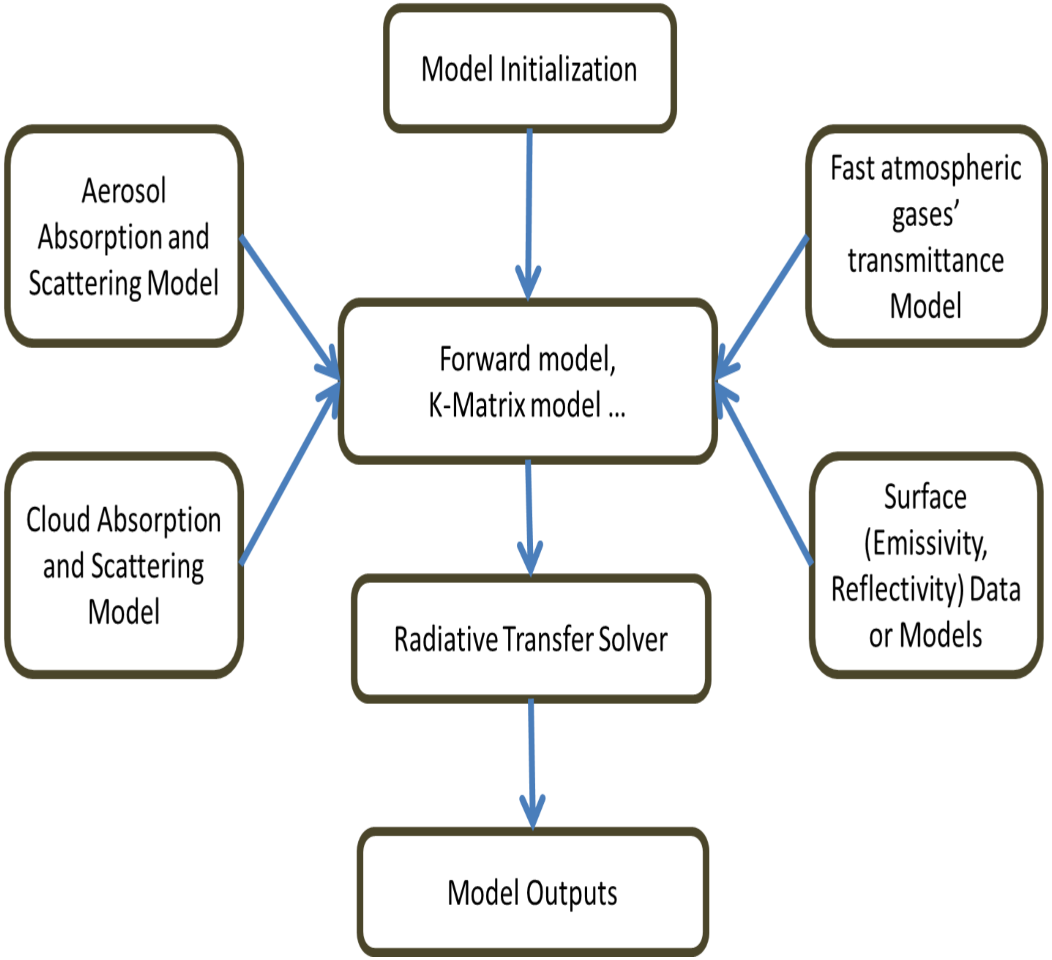
$$\delta^* X = (\partial F/\partial X)^T \delta^* R$$

- K-Matrix (Jacobian) model:

$$\partial F/\partial X$$

- Covering Microwave and infrared sensors

Model structure



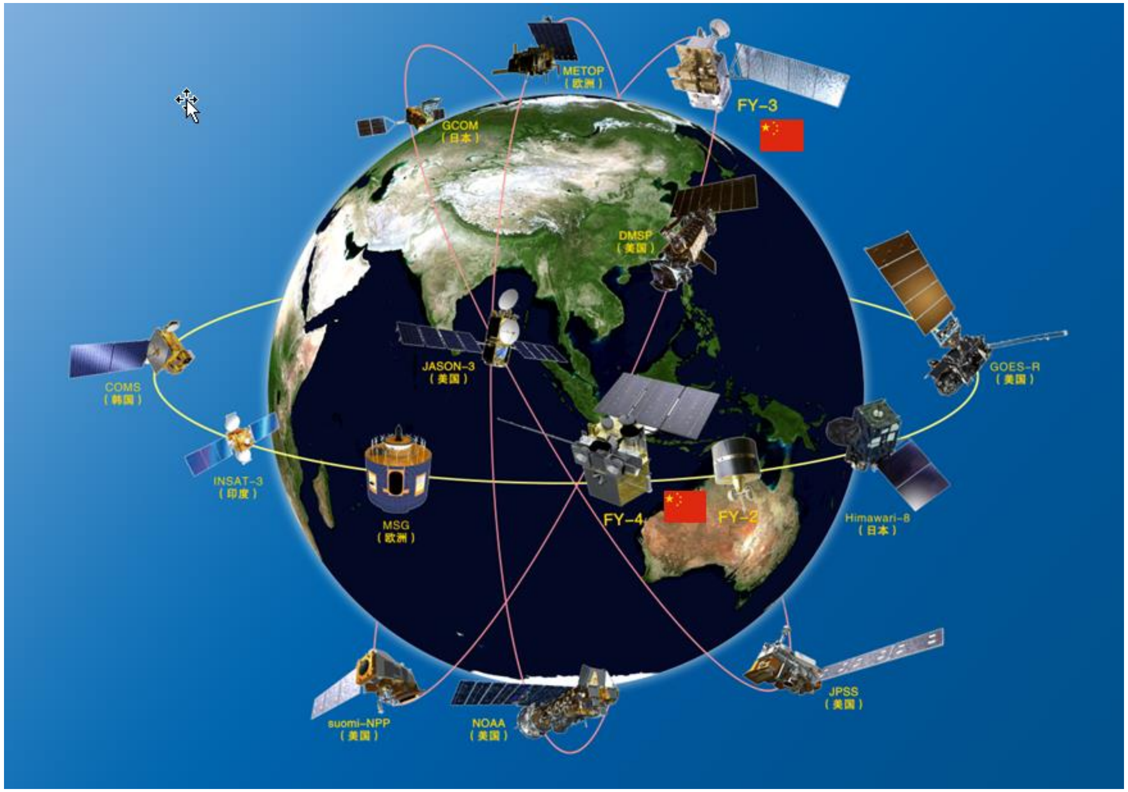
Fast RT model applications

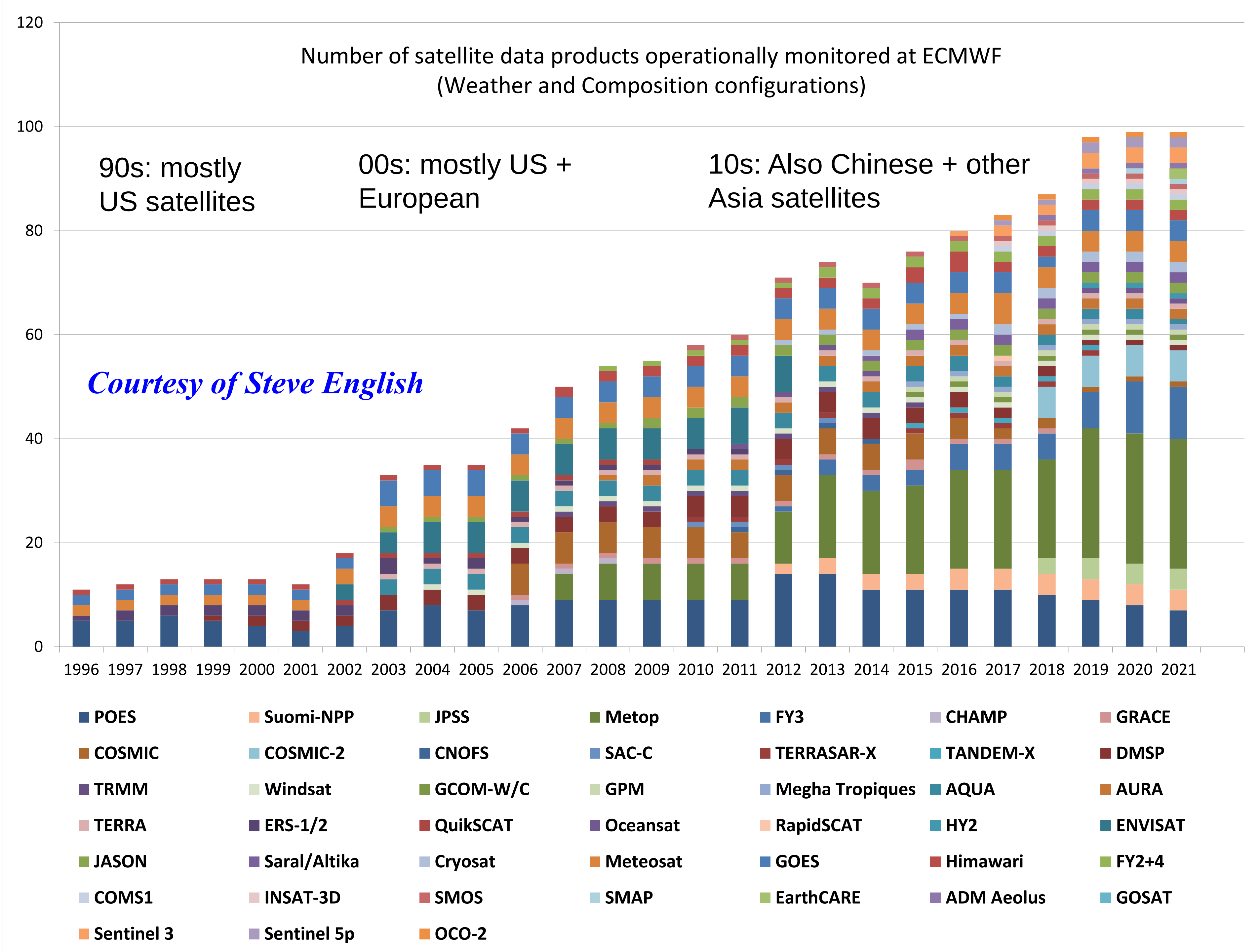
- Assimilation of satellite radiance for NWP and reanalysis;
- Physical retrieval of temperature, water vapor, ozone profiles etc from satellite measurements;
- Satellite radiance observation monitoring;
- Simulate satellite imagery from NWP model fields;
- Studies of new satellite sensors …

3. Global Satellite Program

Important Component of WMO Space Program

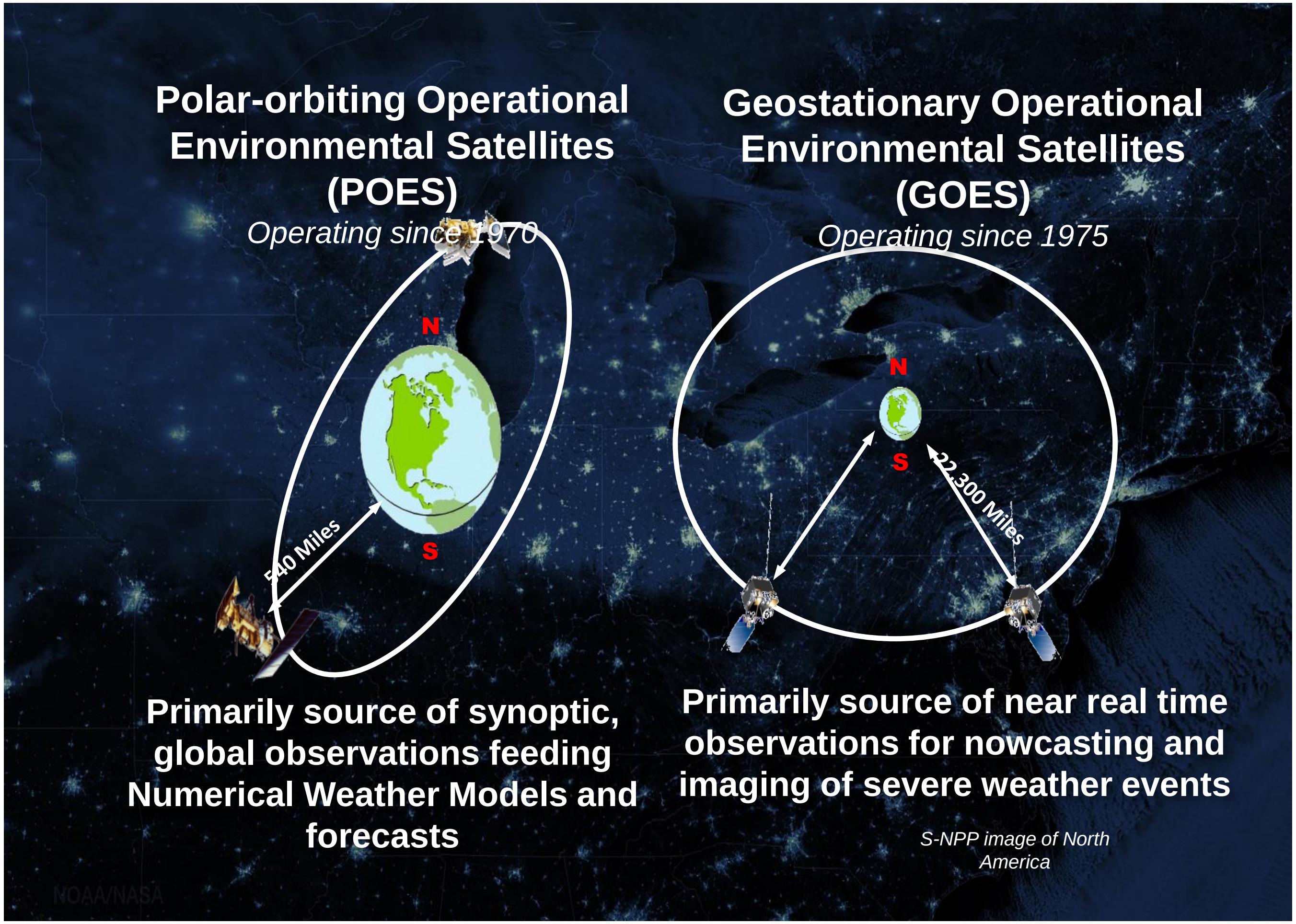
- reliable and sustained observation in operation
- open data policy to free access





Number of satellite data products operationally monitored at ECMWF
(Weather and Composition configurations)
90s: mostly US satellites
00s: mostly US + European
10s: Also Chinese + other Asia satellites
Courtesy of Steve English
0
20
40
60
80
100
120
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
POES
Suomi-NPP
JPSS
Metop
FY3
CHAMP
GRACE
COSMIC
COSMIC-2
CNOFS
SAC-C
TERRASAR-X
TANDEM-X
DMSP
TRMM
Windsat
GCOM-W/C
GPM
Megha Tropiques
AQUA
AURA
TERRA
ERS-1/2
QuikSCAT
Oceansat
RapidSCAT
HY2
ENVISAT
JASON
Saral/Altika
Cryosat
Meteosat
GOES
Himawari
FY2+4
COMS1
INSAT-3D
SMOS
SMAP
EarthCARE
ADM Aeolus
GOSAT
Sentinel 3
Sentinel 5p
OCO-2

NOAA's Observational Paradigm Has Been: Two Orbits, One Mission

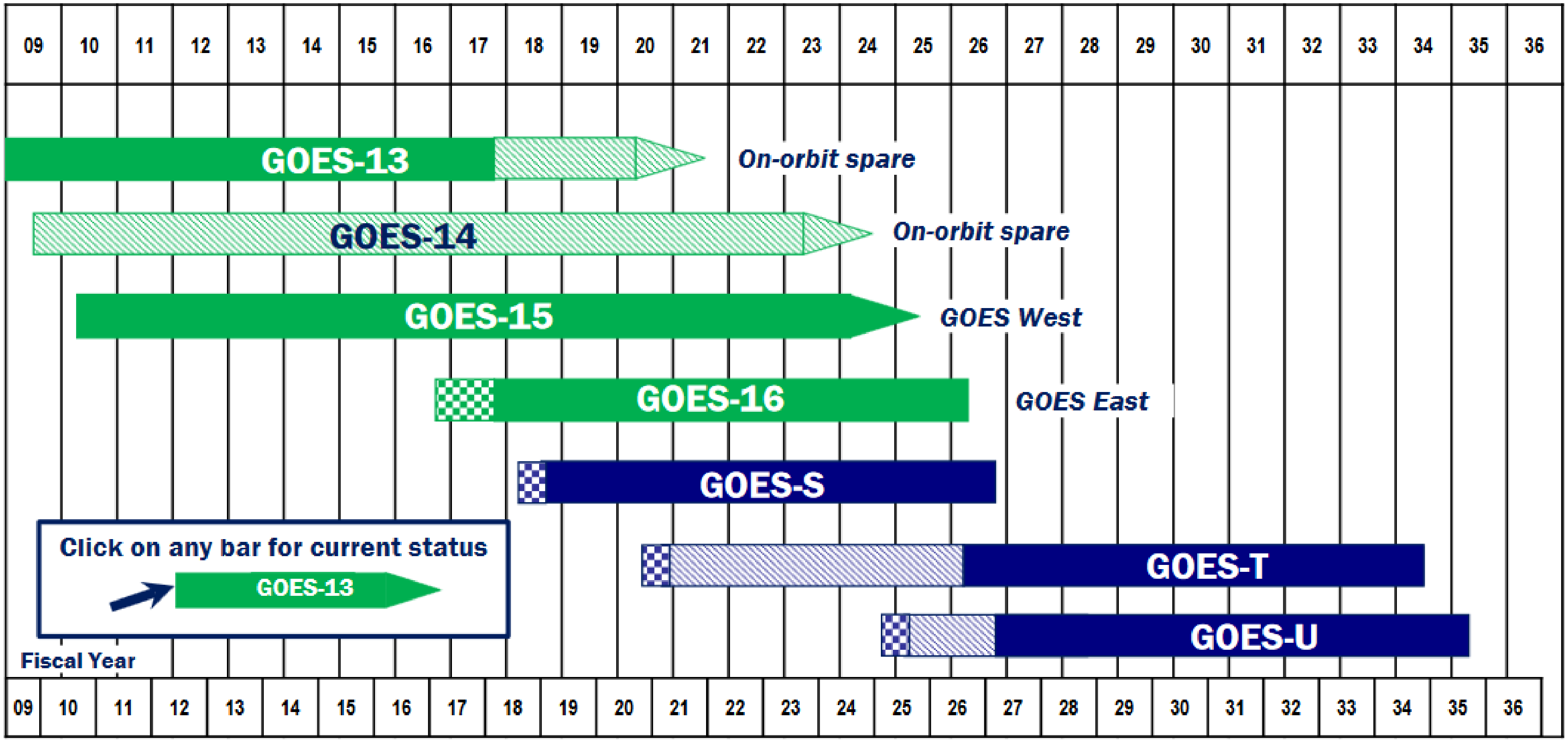


Courtesy of Mitch Goldberg

GOES-R Series Payload Capability

	GOES-R Series Instruments		*Measurements & Products*	*Vendor*
Earth-Observing		**ABI** – Advanced Baseline Imager	Provides Earth weather, climate, ocean, and environment imagery, 4x spatial resolution, 5x faster	Harris
		**GLM** – Geostationary Lightning Mapper	Maps in-cloud and cloud-to-ground lightning activity	Lockheed Martin
Solar-Observing		**SEISS** – Space Environment In-Situ Suite	Monitors proton, electron, and heavy ion fluxes	ATC
		**Magnetometer**	Measures space environment magnetic field	Lockheed Martin
		**EXIS** – Extreme Ultraviolet and X-Ray Irradiance Sensors	Monitors solar flares and solar variations	LASP
		**SUVI** – Solar Ultraviolet Imager	Observes coronal holes, solar flares, and coronal mass ejections	Lockheed Martin

GOES Flyout Chart



Approved:
Assistant Administrator for Satellite and Information Services

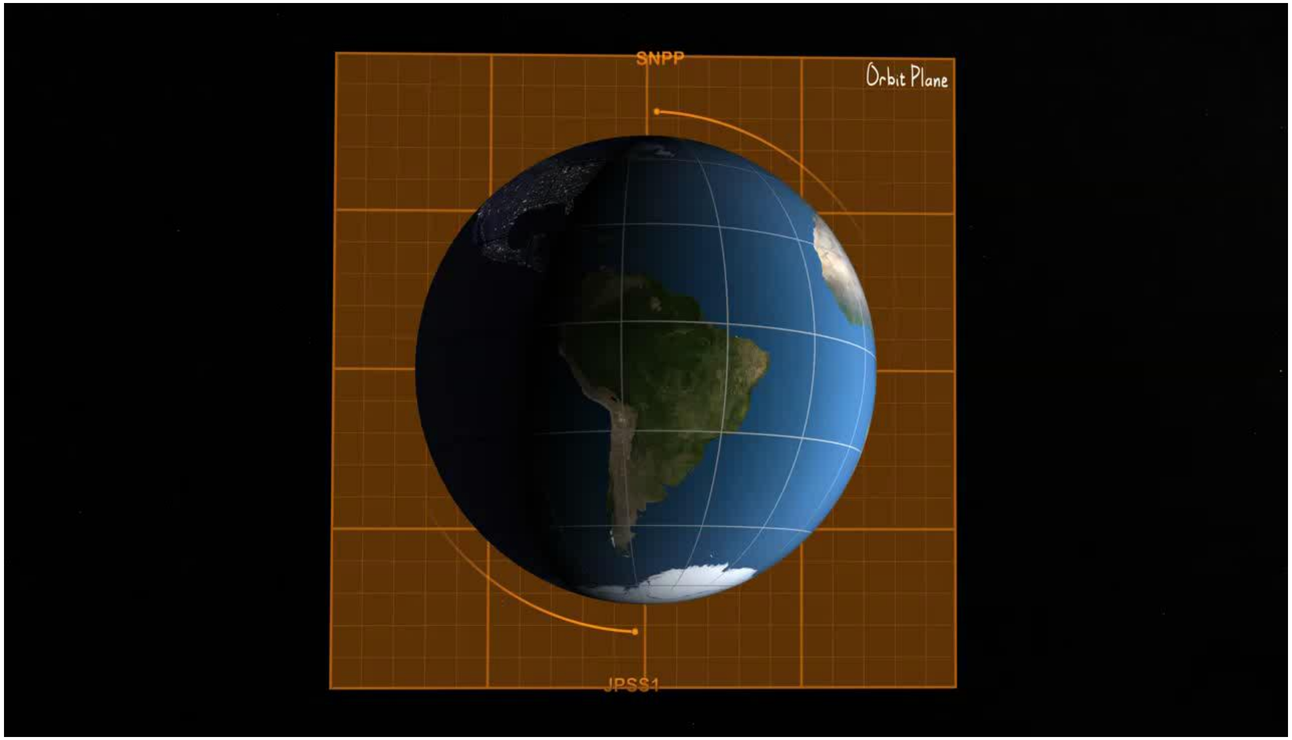
- In orbit, operational
- In orbit, storage
- Planned in-orbit Storage
- Planned in-orbit Checkout
- Planned Mission Life
- Reliability analysis-based extended weather observation life estimate (60% confidence) for satellites on orbit for a minimum of one year -- Most recent analysis: March 2017

https://www.nesdis.noaa.gov/content/our-satellites

Improving Forecast Accuracy & Timeliness

JPSS satellites:

- **Circle the Earth from pole-to-pole and cross the equator 14 times daily in the afternoon orbit—providing full global coverage twice a day.**
- **Provide critical data to the numerical forecast models that produce 3- to 7-day mid-range forecasts.**

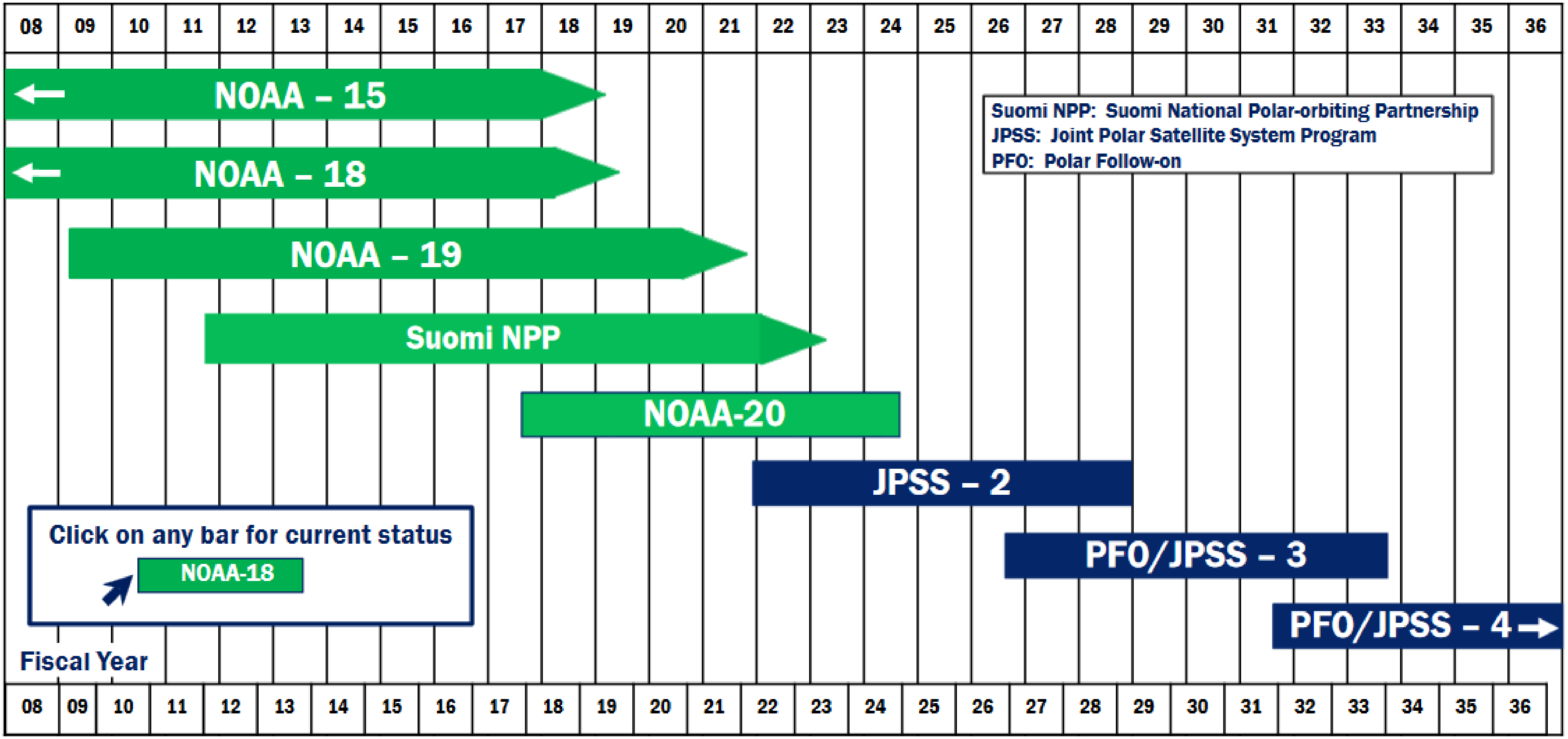


- **Provide support for zero to 3-day operational forecasting in Polar Regions**

JPSS Payload Capability

JPSS Instruments		*Measurements & Products*	*Vendor*
	**ATMS** – Advanced Technology Microwave Sounder	High vertical resolution temperature and water vapor information critical for forecasting extreme weather events, 5 to 7 days in advance	NGES
	**CrIS** – Cross-track Infrared Sounder		Harris
	**VIIRS** – Visible Infrared Imaging Radiometer Suite	Critical Imagery products, including snow/ice cover, clouds, fog, aerosols, fire smoke plume, vegetation health, phytoplankton abundance/chlorophyll	Raytheon
	**OMPS** – Ozone Mapping Profiler Suite (Nadir Mapper, Nadir Profiler, Limb - S-NPP, JPSS-2+)	Ozone spectrometers for monitoring ozone hole health, recovery of stratospheric ozone, and for UV index forecast	Ball Aerospac e
	**CERES** – Clouds and the Earth's Radiant Energy System (S-NPP & JPSS-1) **New procurement** (JPSS-3, 4)	Scanning radiometer that supports studies of Earth Radiation	CERES – NGAS

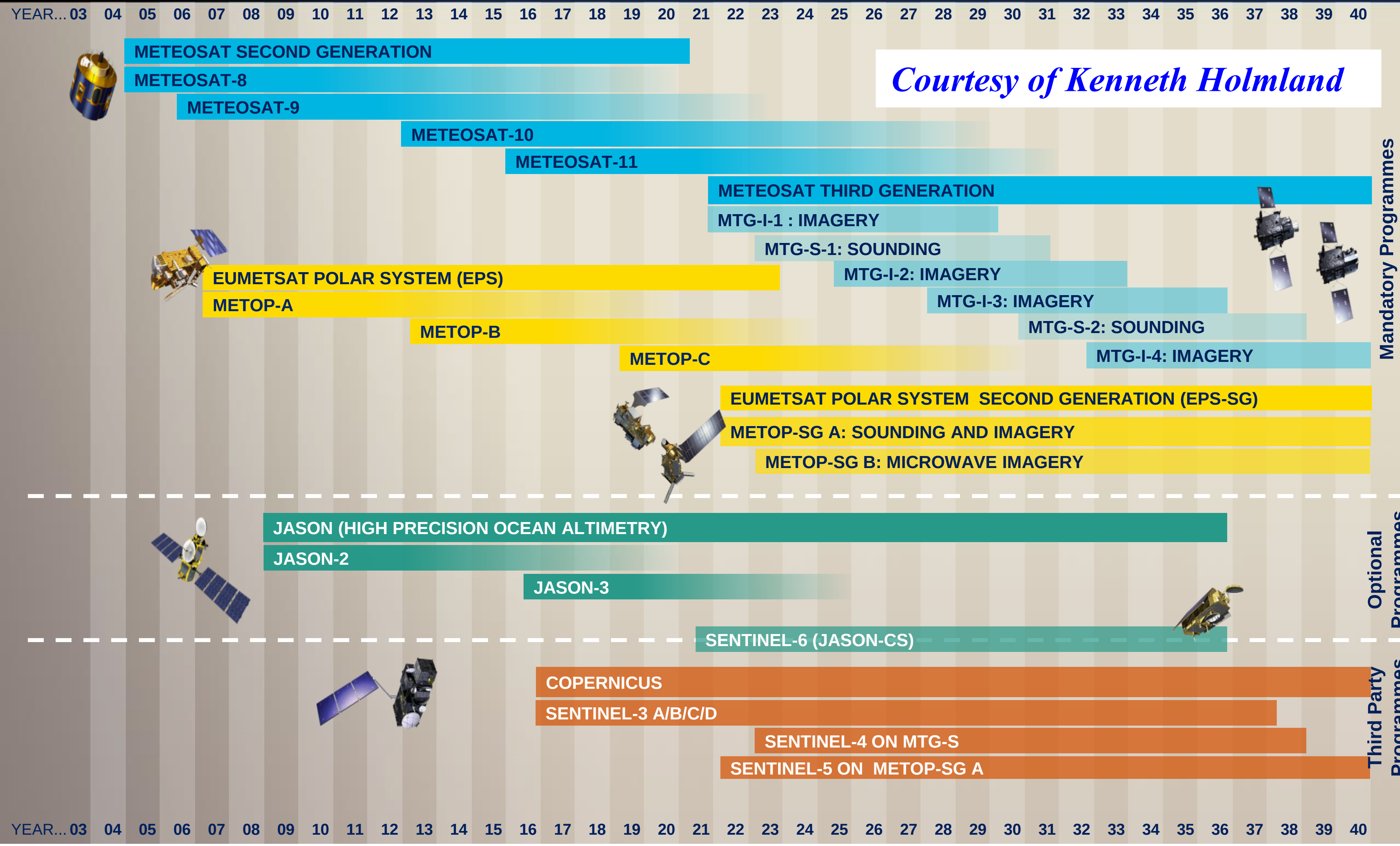
Polar Flyout Chart



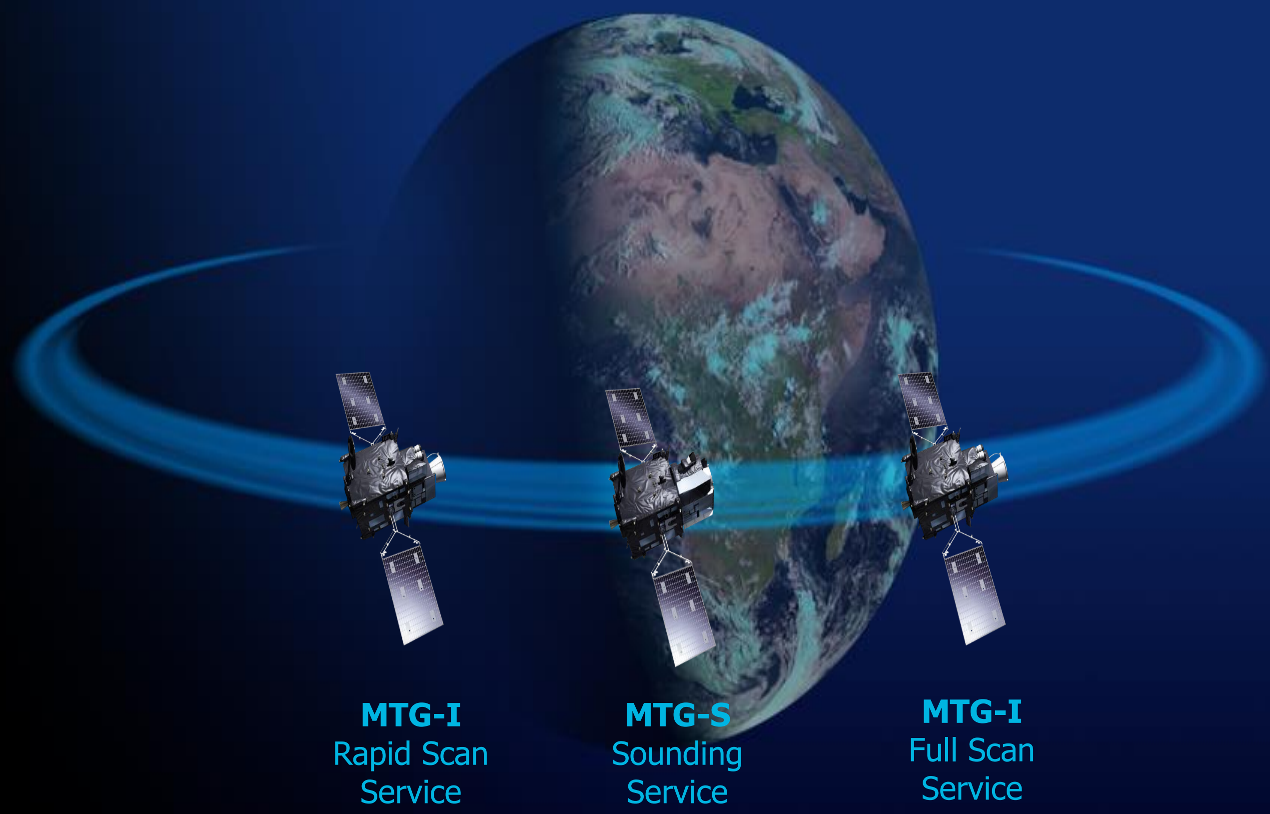
Approved: [signature]

Assistant Administrator for Satellite and Information Services

EUMETSAT Mission Planning

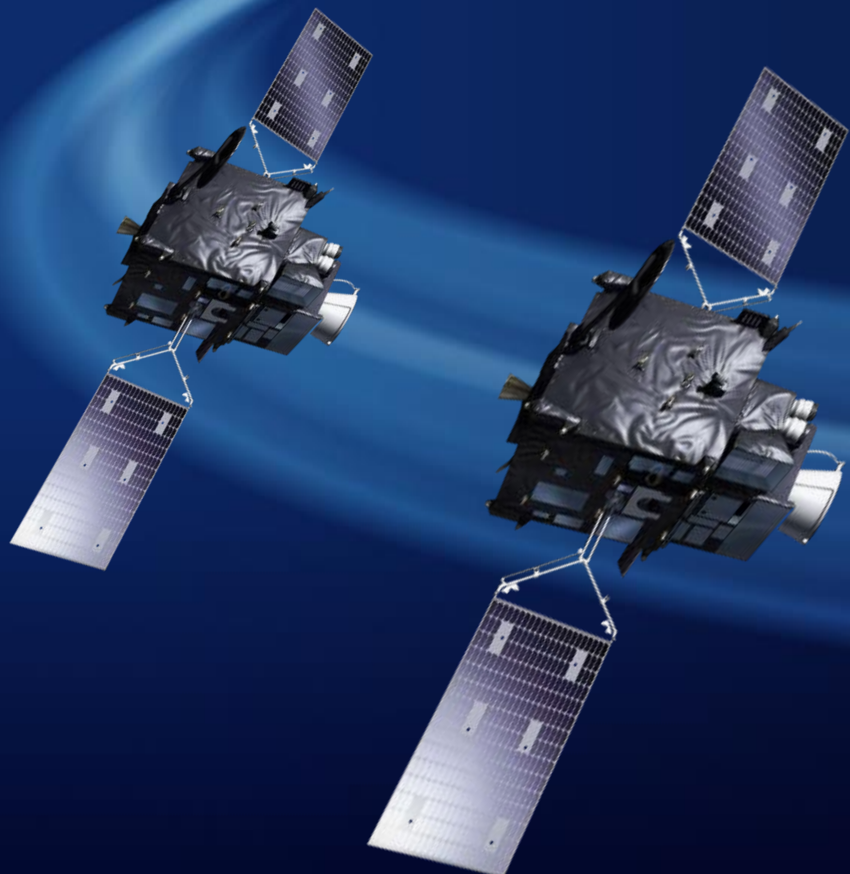


MTG full operational configuration



EUMETSAT

MTG-I imaging mission

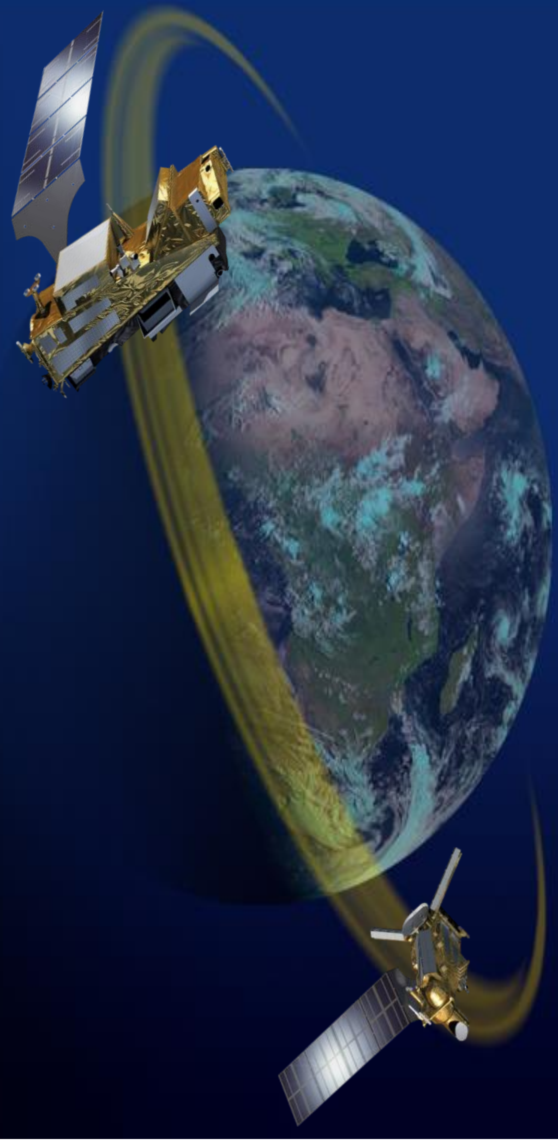


- Imagery mission implemented by two MTG-I satellites
- Full disc imagery every 10 minutes in 16 bands
- Fast imagery of Europe every 2.5 minutes
- New Lightning Imager (LI)
- Start of operations in 2021
- Operational exploitation: 2021-2042

MTG-S sounding mission

- Hyperspectral infrared sounding mission
- 3D weather cube: temperature, water vapour, O3, every 30 minutes over Europe
- Air quality monitoring and atmospheric chemistry in synergy with Copernicus Sentinel-4 instrument
- Start of operations in 2023
- Operational exploitation: 2023-2042

EPS-SG full operational configuration



EUMETSAT

EPS-SG A sounding and imagery mission

1. **IASI-NG**
   Infrared Atmospheric Sounding
2. **MWS**
   Microwave Sounding
3. **METImage**
   Visible-Infrared Imaging
4. **RO**
   Radio Occultation
5. **3MI**
   Multi-viewing, -channel, -polarisation Imaging
6. **Copernicus Sentinel-5**
   UN/VIS/NIR/SWIR Sounding

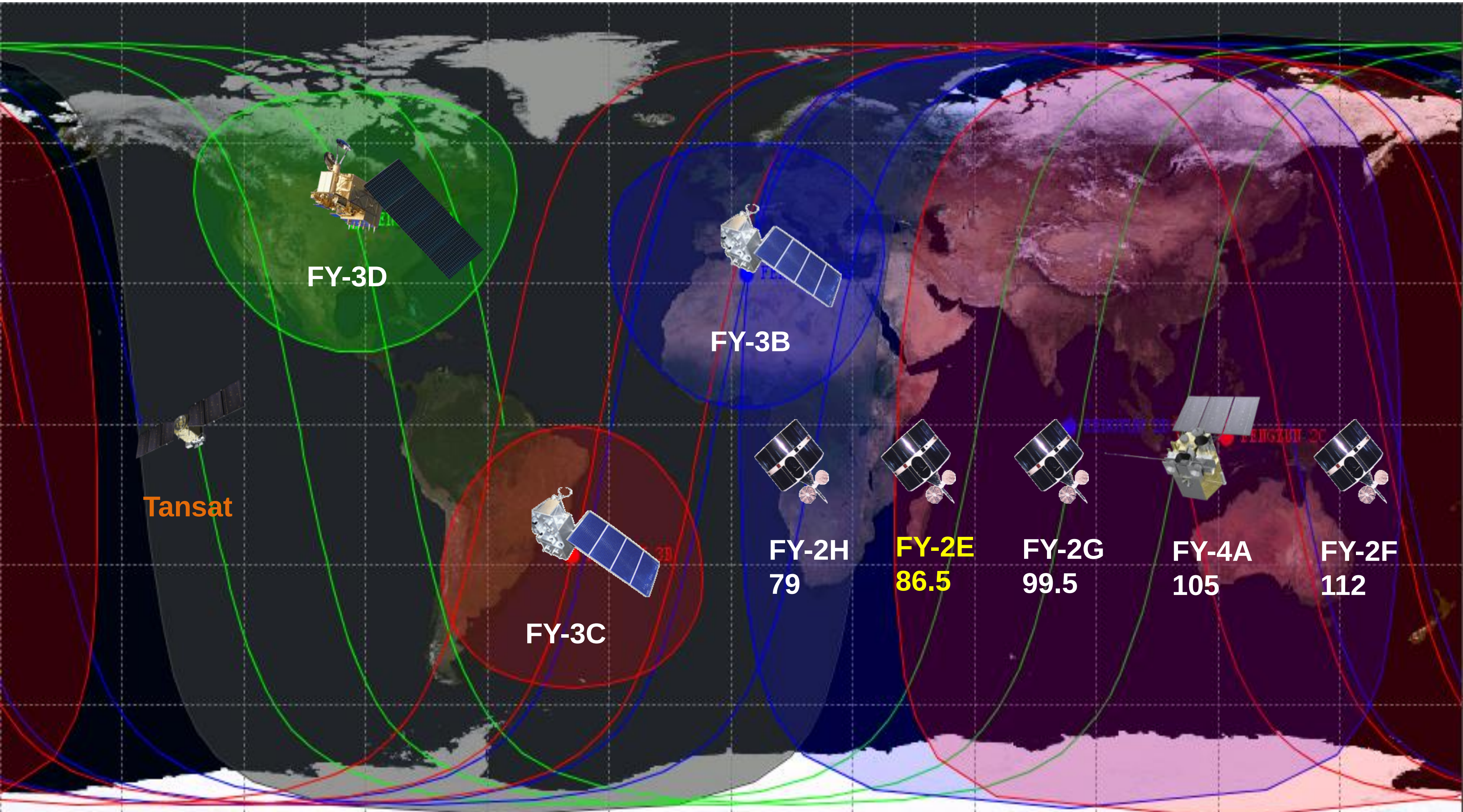
EPS-SG B microwave imagery mission

1. **SCA**
   Scatterometer
2. **RO**
   Radio Occultation
3. **MWI**
   Microwave Imaging for Precipitation
4. **ICI**
   Ice Cloud Imager
5. **ARGOS-4**
   Advanced Data Collection System

Current FengYun Constellation

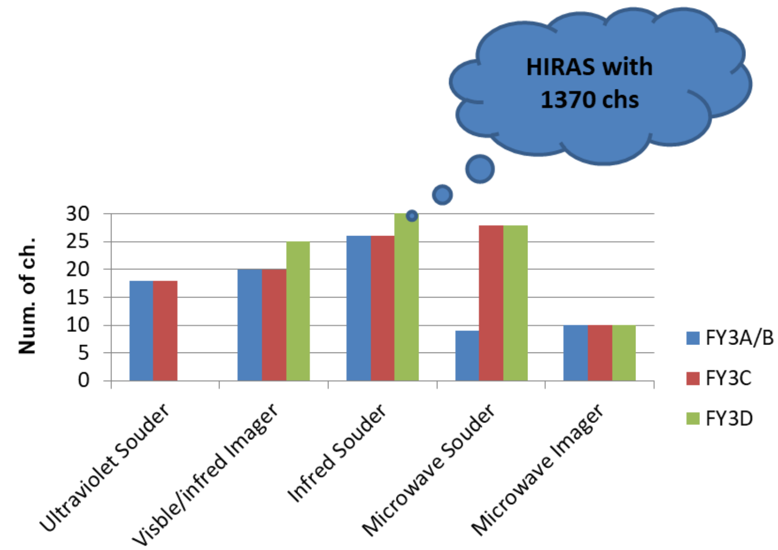
FengYun Programs: 8 in orbit, 7 in operation, 1 in orbital testing (FY-2H)

Joint programs: Tansat, GF-4



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

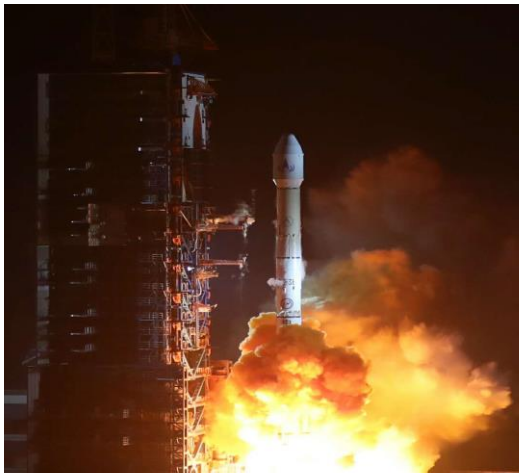
Atmospheric Sounder

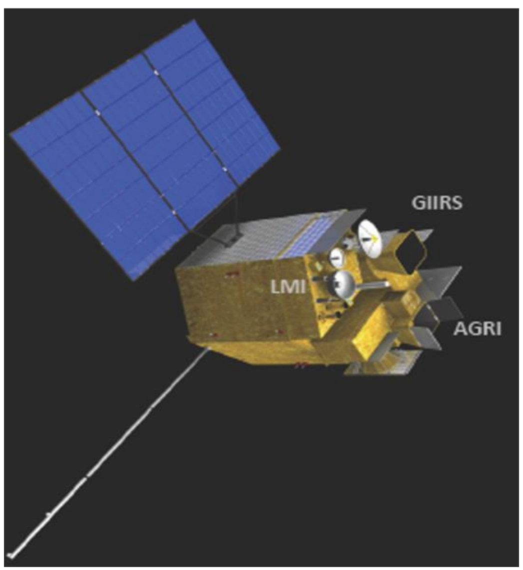
Microwave Imager

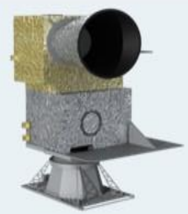
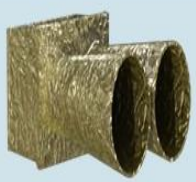
Atmospheric Composition Detector

Radiation Budget Monitor

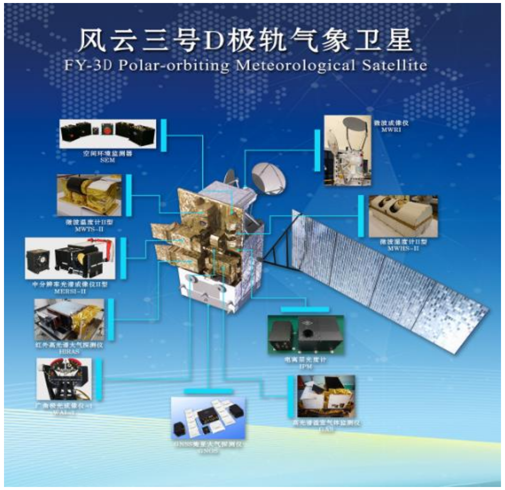
FY-4A: Launched on 11 Dec, 2016





Instrument		Purposes
	**AGRI**: *Advanced Geosynchronous Radiation Imager*	14 -channel Earth images
	**GIIRS :** *Geostationary Interferometric InfraRed Sounder*	Clear-sky atmospheric temperature and humidity profiles
	**LMI :** *Lightning Mapping Imager*	Lightning distribution map in China area
	**SEP:** *Space Environment Package*	Space electric and magnetic environment information

FY-3D: Launched on 15 Nov, 2017

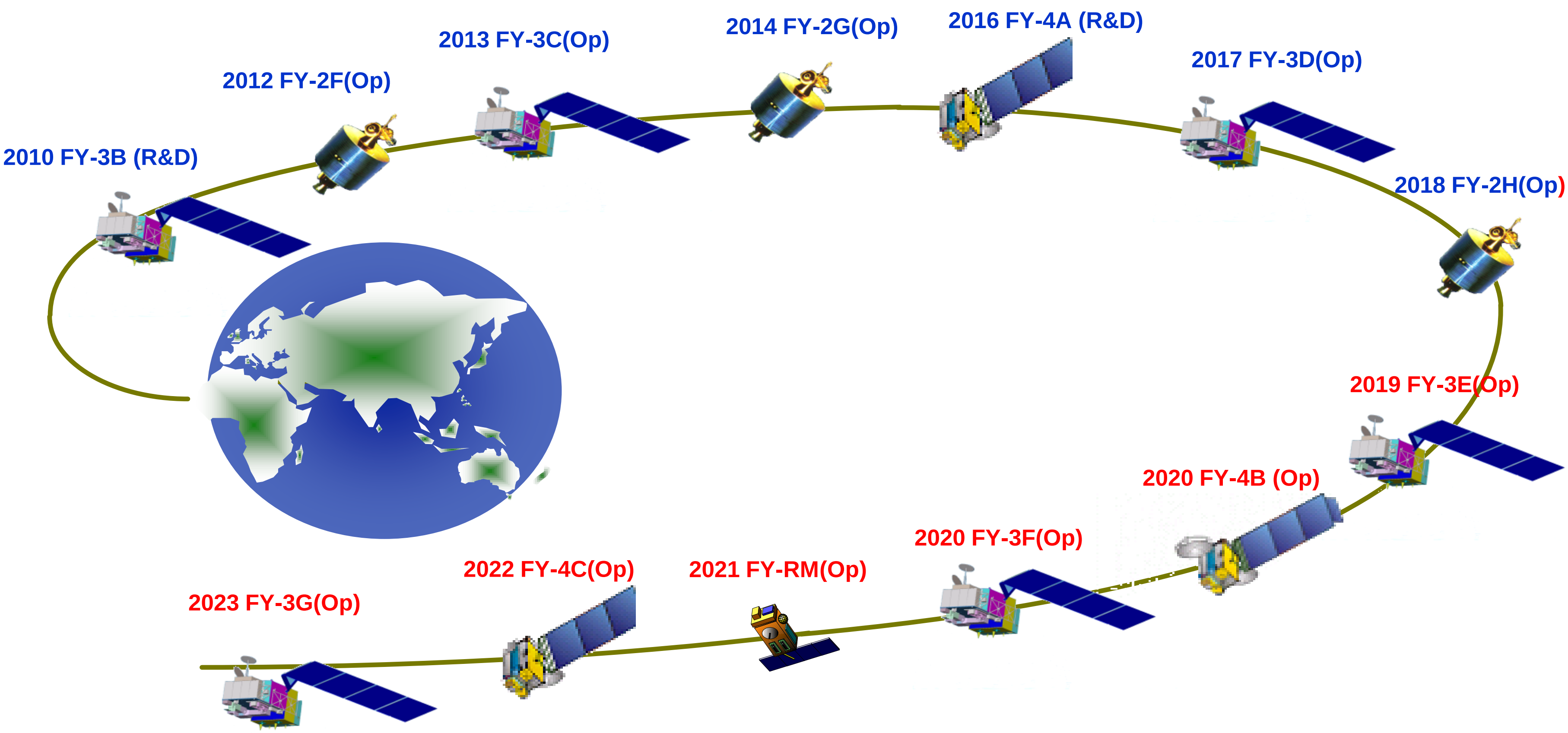


Payload Name	Channel Numbers with Spectral Coverage
MEdium Resolution Spectral Imager (MERSI-2)	25 (0.413 – 12 μm)
Hyperspectral InfraRed Atmospheric Sounder (HIRAS)	1370 (3.92 – 15.38 μm)
MicroWave Radiation Imager (MWRI)	10 (10.65 – 89 GHz)
MicroWave Temperature Sounder (MWTS-2)	13 (50.3 – 57.29 GHz)
MicroWave Humidity Sounder (MWHS-2)	15 (89.0 – 183.31 GHz)
GNSS Occultation Sounder (GNOS)	29 (--)
Greenhouse-gases Absorption Spectrometer (GAS)	5540 (0.75 – 2.38 μm)
Wide angle Aurora Imager (WAI)	1 (140 – 180 nm)
Ionospheric PhotoMeter (IPM)	3 (130 – 180 nm)
Space Environment Monitor (SEM)	25 (--)

- **Performance are improved significantly for the key characteristics, such as S/N, calibration accuracy, etc.**

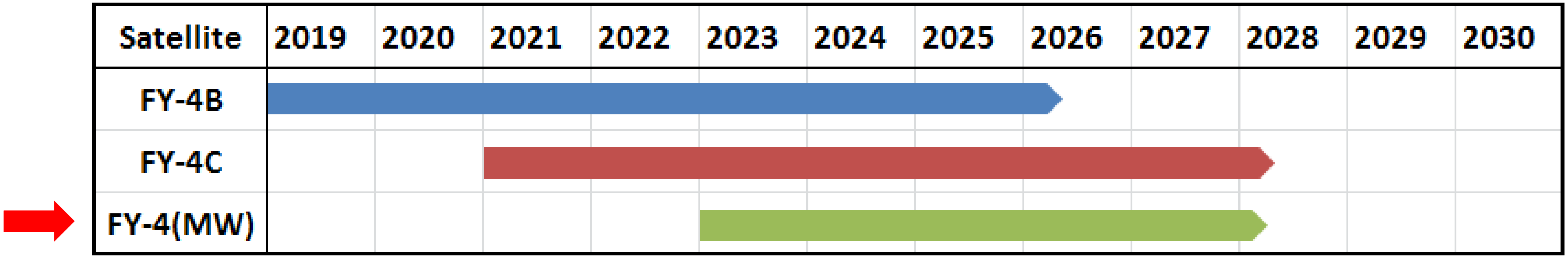
Future Fengyun Programs

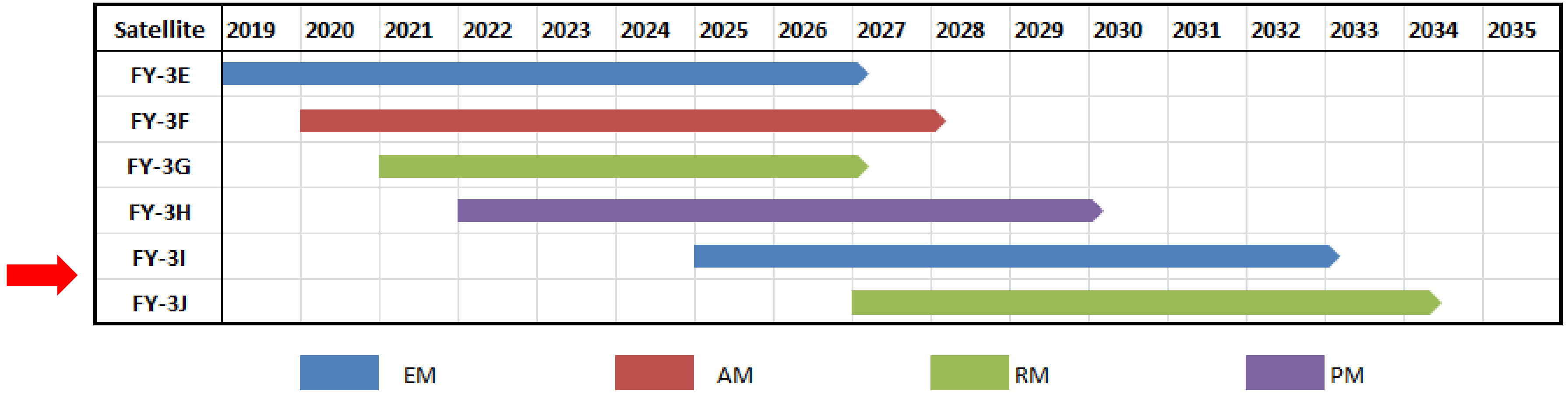
National Program for Fengyun Meteorological Satellite from 2011-2020



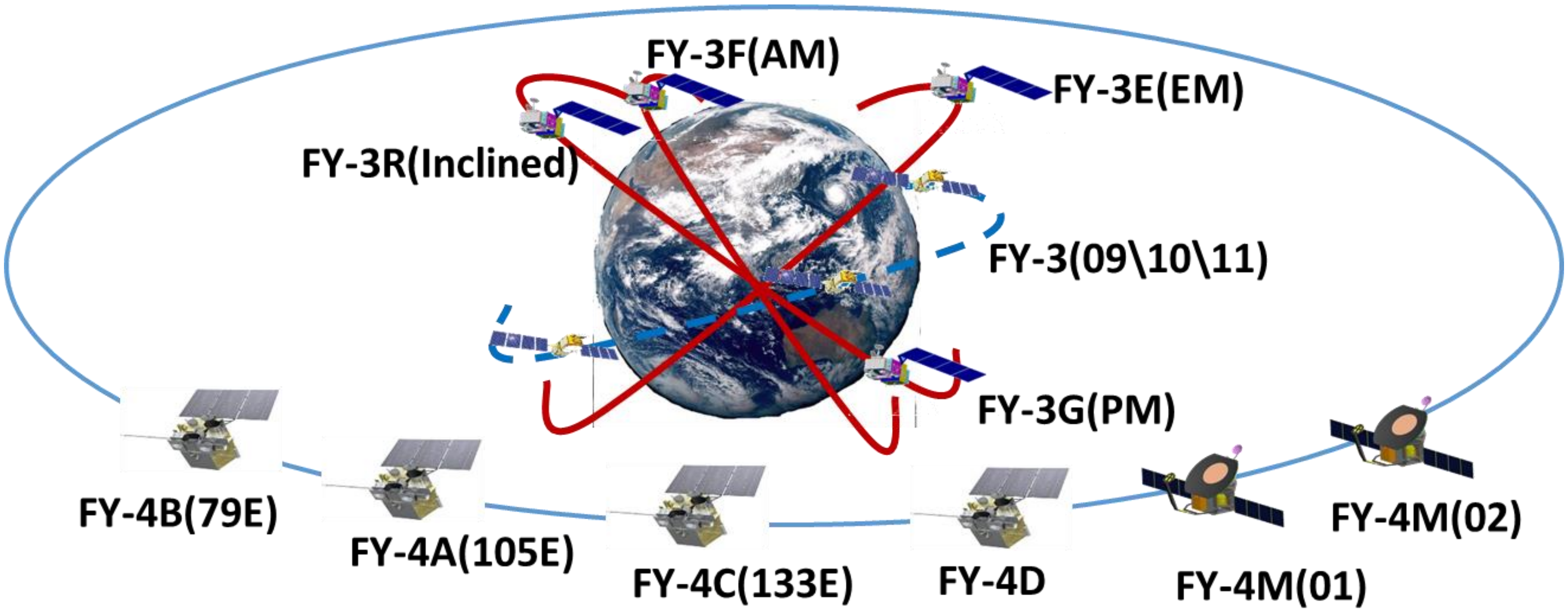
- **6 satellites will be launched within this decade**

National Space Infrastructure Program for Meteorological Satellites (from 2020 to 2025) approved by the State Council





In the next 10 years, CMA will have 6 GEO and 7 LEO main operational satellites, which means the updates for the satellite observation network will be completed.

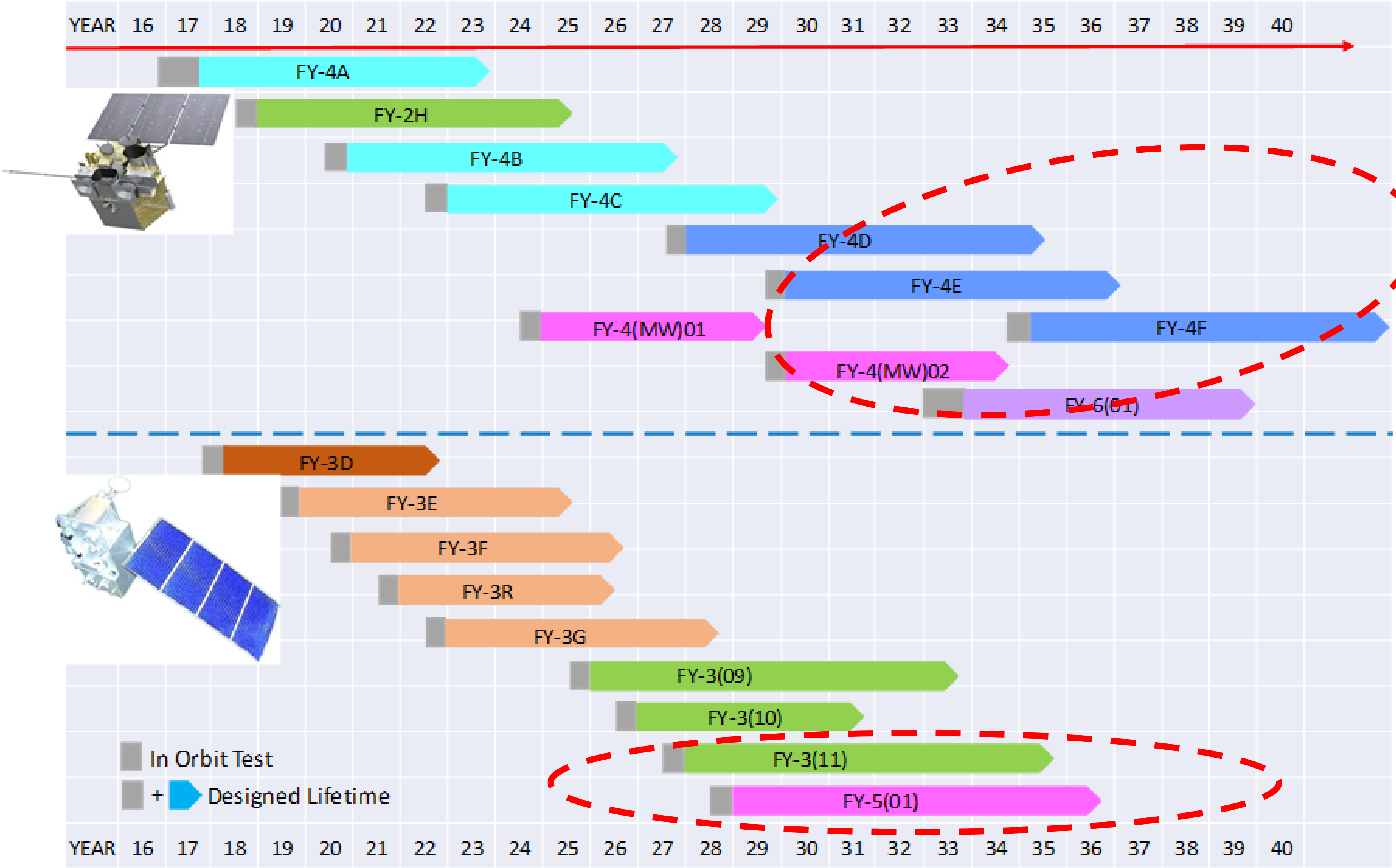


The LEO realizes the network of covering the EM, AM and PM satellite observation, and the time limit of global data updating has been raised from 6 hours to 3 hours. Fine detection of elements such as precipitation and greenhouse gas.

The new pattern of GEO observation: imaging, hyper-spectral and microwave sounding.

FY-4B: rapid scan(min), FY-4C: five minutes disk image, sounding abilities, whole disk lightening mapper.

FengYun Vision for Meteorological Satellites Program in 2035



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

Tier 2. Backbone system – Open measurement approaches (flexibility to optimize the implementation)

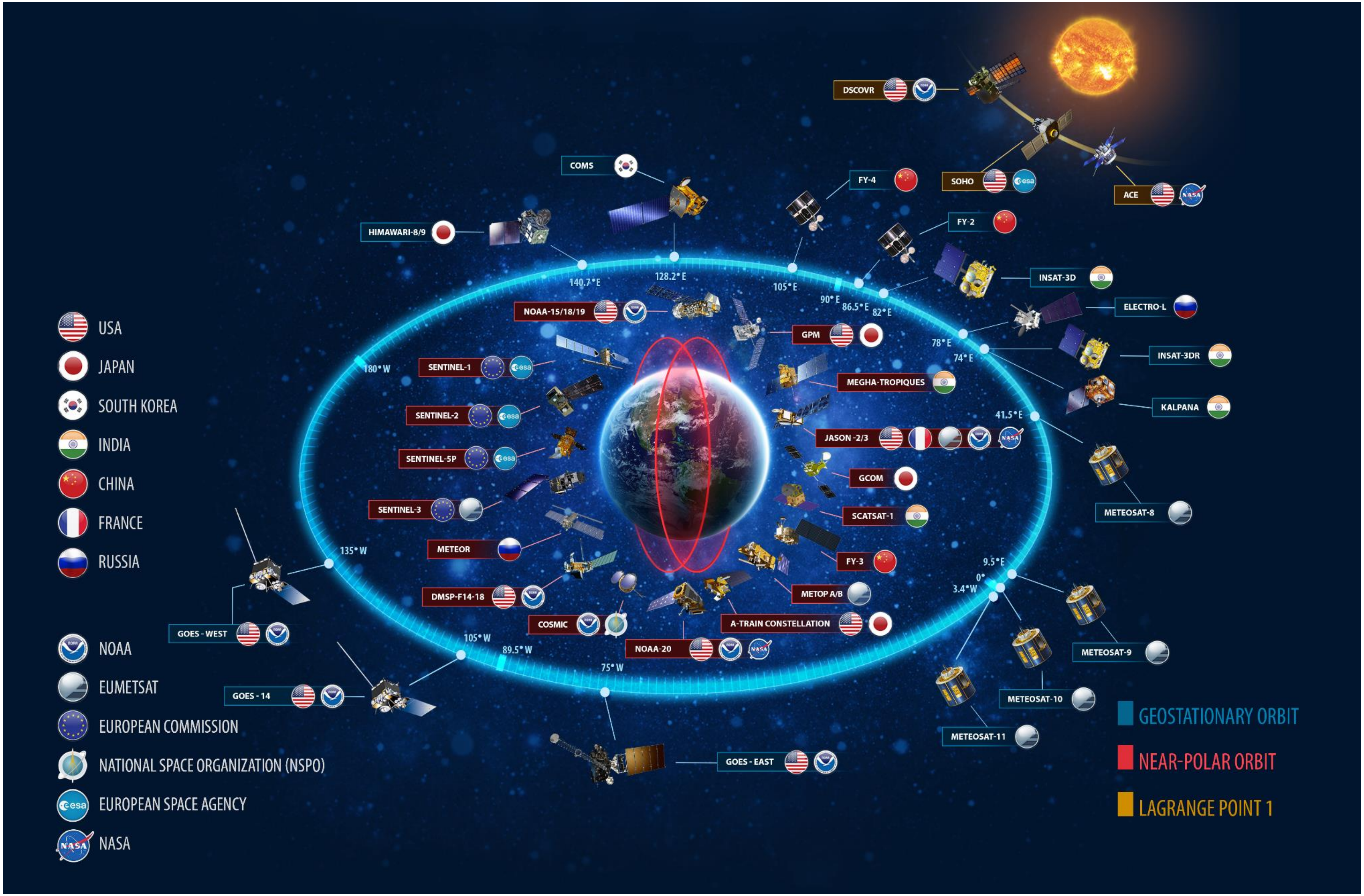
- Surface pressure by NIR spectrometry
- HEO VIS/IR mission for continuous polar coverage (Arctic & Antarctica)
- Solar magnetograph , solar EUV/X-ray imager, and X-ray irradiance, both on the Earth-Sun line (e.g. L1, GEO) and off the Earth-Sun line (e.g. L5, L4)
- Solar wind in situ plasma and energetic particles and magnetic field off the Earth-Sun line (e.g. L5)
- Solar coronagraph and heliospheric imager off the Earth-Sun line (e.g. L4, L5)
- Magnetospheric energetic particles (e.g. GEO, HEO, MEO, LEO)

Tier 3. Operational pathfinders and technology and science demonstrators

- RO constellation for enhanced atmospheric/ionospheric soundings
  - Including additional frequencies optimized for atmospheric sounding
- Radar and Lidar for vegetation
- Hyperspectral MW sensors
- Solar coronal magnetic field imager, solar wind beyond L1
- Ionosphere/thermosphere spectral imager (e.g. GEO, HEO, MEO, LEO)
- Ionospheric electron and major ion density,
- Thermospheric neutral density and constituents
- Process study missions (content and duration TBD depending on process cycles)
- Use of nanosatellites for demonstration or science missions, and for contigency planning as gap fillers (notwithstanding possible use in Tier 2.)
- Use of orbiting platforms (like the International Space Station) for demonstration or science missions

NOAA Satellites

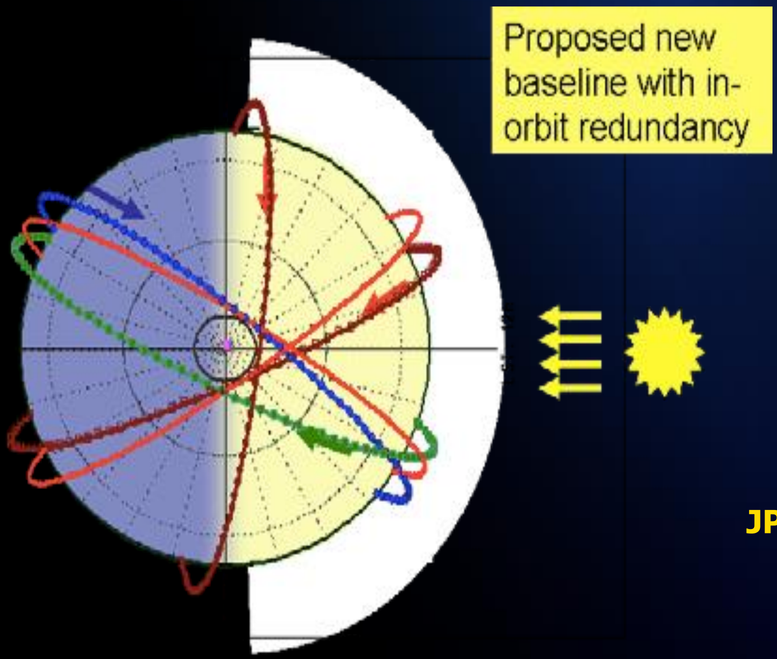
NOAA and International Partners

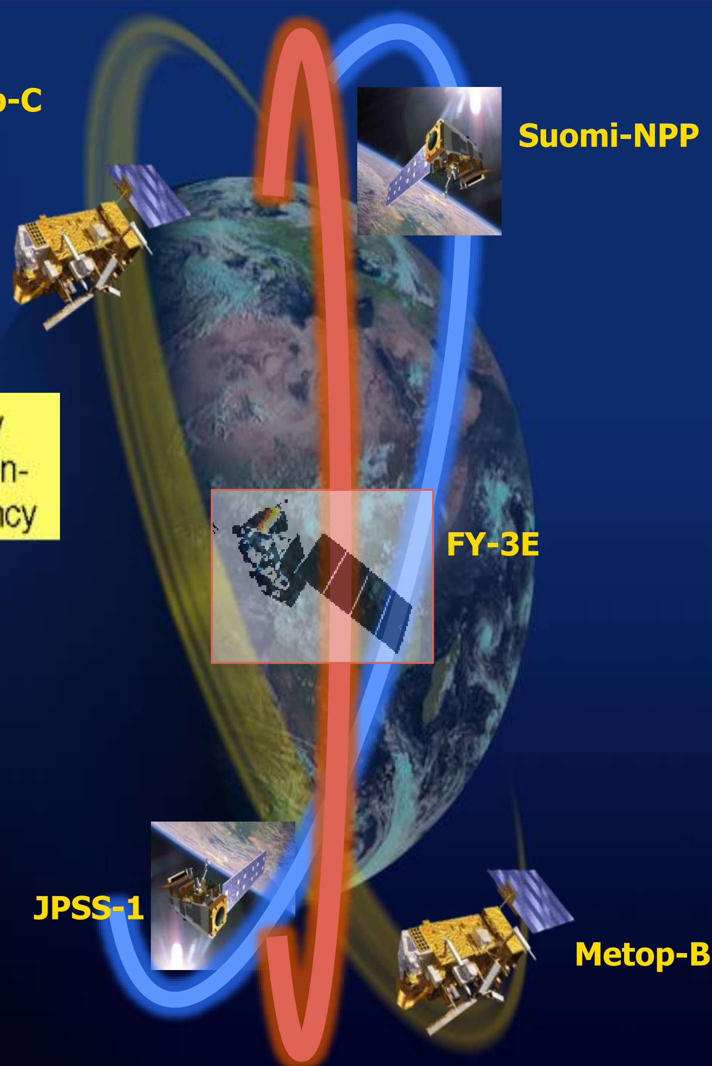


Benefits of international cooperation meeting WIGOS Vision 2040 Three primary orbits covered by EUMETSAT, NOAA and in the near-future CMA

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

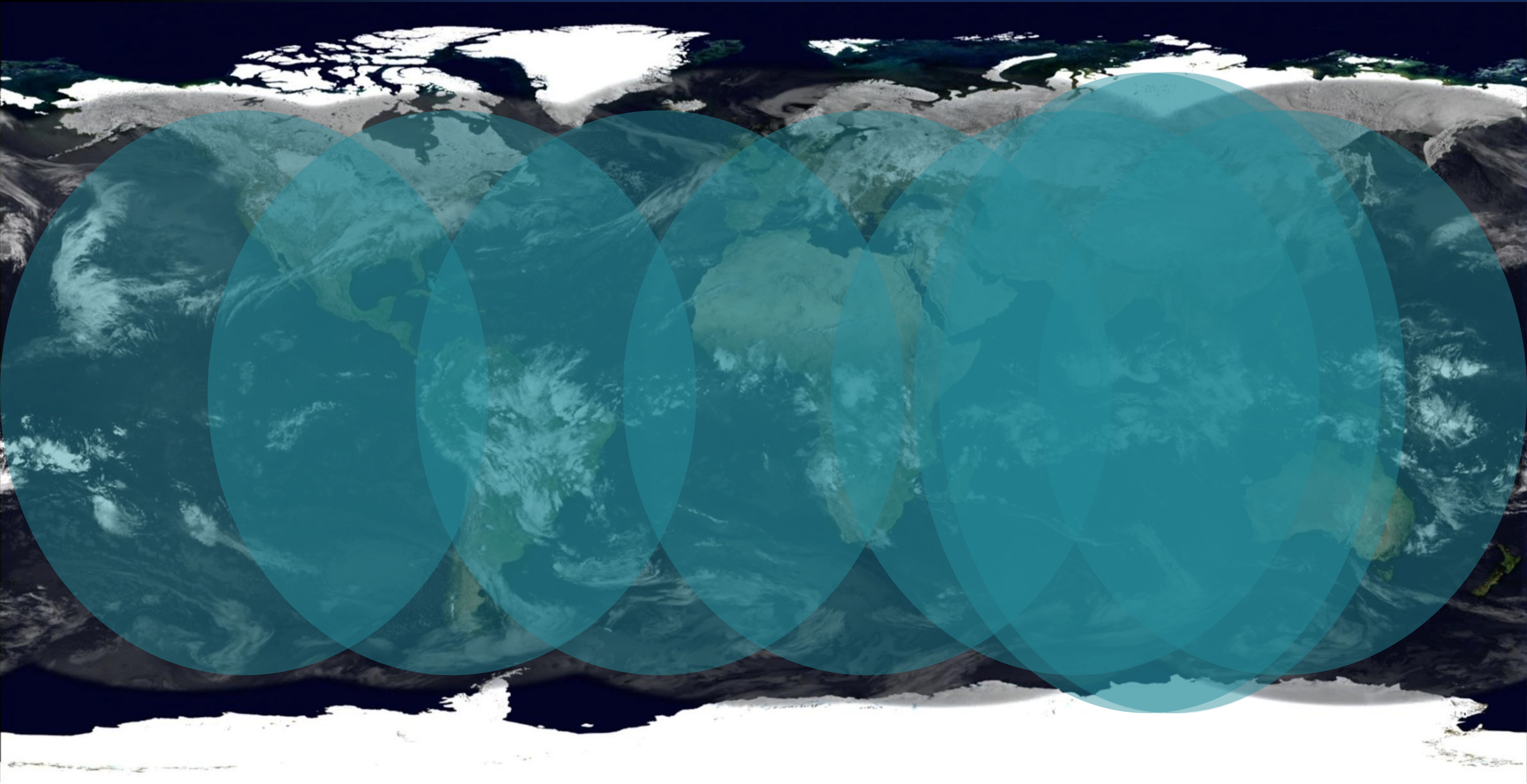
Not to forget
CMA: 14:00 asc





EUMETSAT

The value of international cooperation: "the GEO ring"



4. Issues to be Discussed

(1) the trade-off between speed and accuracy in scattering radiative transfer modeling for data assimilation;

(2) the impact of highly variable gaseous absorption coefficients within a given instrument's band and its implications on scattering RT;

(3) accuracy surface properties description ;

(4) lack of knowledge of scattering optical properties and large bias between simulation and observation under cloudy conditions;

(5) nonlocal thermodynamic equilibrium (NLTE) contribution in short infrared bands;

(6) large errors caused by plane-parallel RT assumption …….


Together
For Better
谢
谢

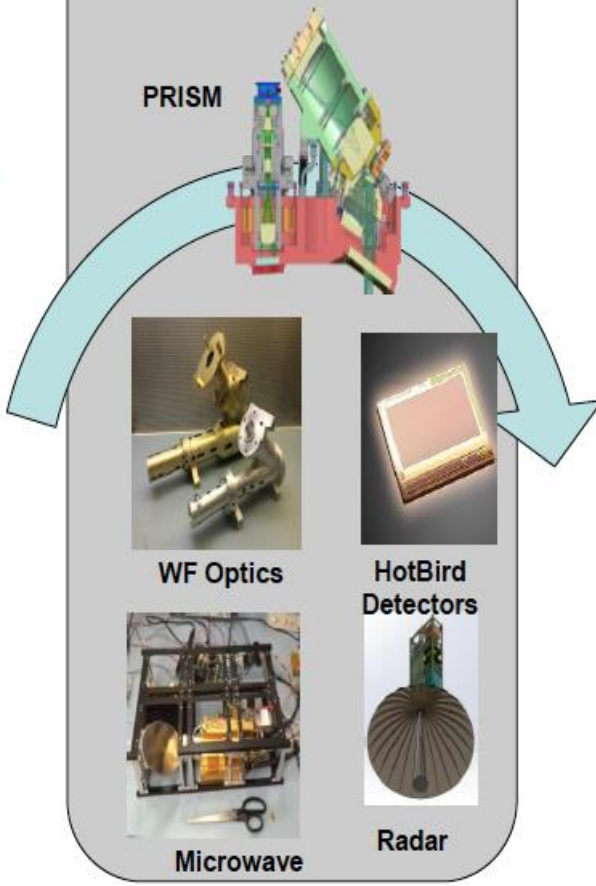
Current Approach

VIIRS

CrIS

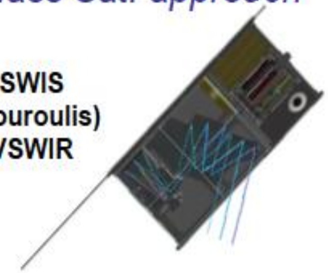
ATMS

Technology Investments

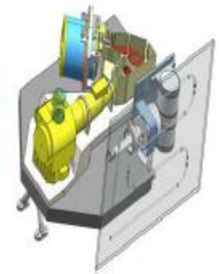


UClass Sat. approach

SWIS (Mouroulis) VSWIR

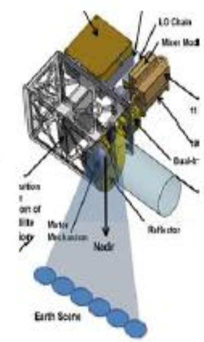


CIRAS (Pagano) Infrared sounder



March 2018

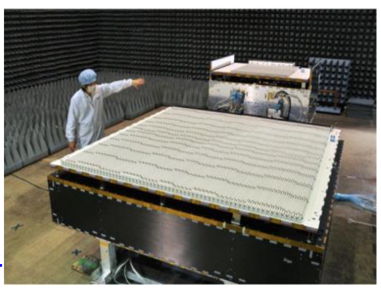
TEMPEST-D (Reising) MW Sounder



March 2018

GPM DPR

May 1



Raincube Ka band radar

March 2018

And many other examples, e.g GPS, water vapor winds,