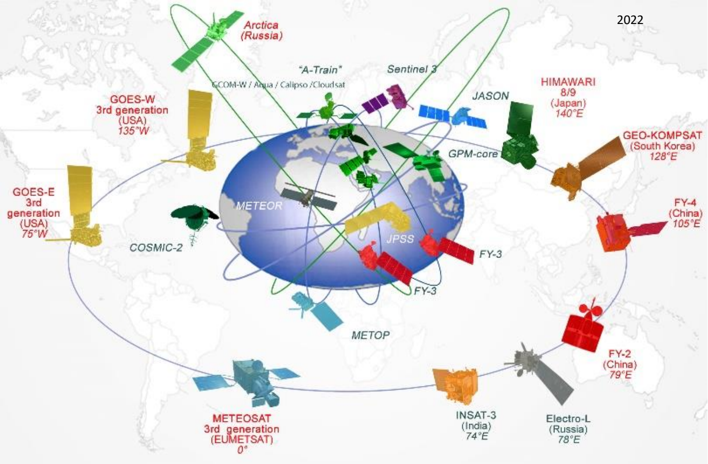

The Earth-Observing Satellite Constellation (EOSC)

A Complex, Inter-Connected Global System with Extensive Applications

(A review from a meteorological perspective)

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Coordination Group for Meteorological Satellites

Presented to CGMS-49 Plenary session

Executive summary of the WP

The global Earth-observing satellite constellation (EOSC) is a major international asset that has developed over the past six decades with a dramatic growth in size and complexity in the recent past. This paper takes stock and summarizes, from a meteorological perspective, the current constellation's capabilities, highlight the complex value chain of satellite data from measurements to decision making, and illustrate the interconnected and evolving nature of those processes. When assessed in terms of application areas (atmosphere, oceans, land/hydrology, space weather), the constellation is highly interdependent, robust and the observations it provides complement each other. EOSC is deemed a remarkable international success story that depended on effective collaboration and coordination of international partners and on free and open exchange of critical environmental data.

EOSC is rapidly evolving with many factors driving it including technology, emerging data providers, commercial sector, new capabilities, etc. In this context, EOSC Optimization to meet Applications needs (current & future) would need a concerted effort to optimize its evolution, possibly including Ground and Space components. This paper offers suggestions on ways to achieve this and on how CGMS could help in the essential coordination and in highlighting both the technical and socio-economic benefits of EOSC.

Agenda

1 **EOSC: Earth-Observing Satellite Constellation**

Capabilities, Complementarity, Diversity and Resilience, EOSC Performance, Value Network

2 **EOSC Trends and Factors Driving Its Evolution**

Technology, Smallsats/Cubesats, Emerging new capabilities. Earth System Model and expected Increased Resolutions

3 **Conclusions**

Goal is to review the status of the global EOSC and highlight its complex nature, the complementarity of its components, its vast applicability and offer a few suggestions as to what are the driving forces shaping its evolution.

Goal is NOT to be comprehensive nor very detailed in the descriptions.

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EOSC Geophysical capabilities assessment

*source: WMO OSCAR (2021)

Earth System Components: *atmosphere, ocean, Land, Hydrosphere, Cryosphere*

Sensor types	Atmospheric temperature profile	Specific humidity	Wind (horizontal)	Atmospheric discontinuities	Ozone and other trace gases	Aerosol and volcanic ashes	Cloud cover, top height, type	Cloud interior and microphysics	Precipitation	Lightning	Solar irradiance	Earth radiation	Sea surface temperature	Sea surface wind	Ocean dynamic topography	Ocean colour	Ocean waves	Sea ice cover and properties	Land surface temperature	Soil moisture	Biomass, vegetation parameters	Fire cover, temperature, radiative power	Snow cover, status, water equivalent	Land cover, use, topography	Glacier & ice sheet cover & topography	Geoid, crustal plates, gravity
Moderate resolution optical imager		High relevance	Very high relevance: GEO, Polar			High relevance	Primary mission objective		Significant relevance: GEO			Significant relevance	Primary mission objective			Primary mission objective		Significant relevance	Very high relevance		High relevance	High relevance	Significant relevance			
High resolution optical imager																					Very high relevance	Significant relevance		Primary mission objective	High relevance	
Cross-nadir UV/VIS/ NIR/SWIR sounder		Significant relevance			Primary mission objective	Very high relevance	Significant relevance																			
Cross-nadir MWIR/TIR sounder	Primary mission objective	Primary mission objective	High relevance	Significant relevance	Primary mission objective	High relevance	High relevance					Significant relevance	Very high relevance						Significant relevance							
Limb sounder	Very high relevance	Very high relevance: UTLS			Primary mission objective: UTLS	High relevance: UTLS																				
Conical scanning MW imager		Very high relevance						High relevance	Primary mission objective				Very high relevance	High relevance				Primary mission objective	Significant relevance	High relevance			High relevance			
Cross-track or conical MW sounder	Primary mission objective	Primary mission objective						High relevance	Very high relevance									Significant relevance					Significant relevance			
Radio-occultation sounder	Primary mission objective	Very high relevance		High relevance																						
Broadband SW/LW radiometer												Primary mission objective														
Solar irradiance monitor											Primary mission objective															
Cloud and precipitation radar								Primary mission objective	Primary mission objective																	
Lightning imager										Primary mission objective																
Lidar (Doppler, DIAL, altimeter, backscatter)			Primary mission objective: Dop.	Very high relevance: Back	Very high relevance: DIAL	Primary mission objective: Back									Significant relevance: Alt.			Very high relevance: Alt.			High relevance: Alt.				High relevance: Alt.	
Radar scatterometer														Primary mission objective				High relevance		Very high relevance			Significant relevance			
Radar altimeter														Significant relevance	Primary mission objective		High relevance								Significant relevance	Very high relevance
Imaging radar (SAR)																	High relevance	Very high relevance		Significant relevance	Very high relevance		High relevance	Primary mission objective	High relevance	
Positioning systems (GNSS, laser ranging)														Significant relevance												Primary mission objective

Relevance code: Primary mission objective | Very high relevance | High relevance | Significant relevance | No relevance

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It takes a variety of technologies, sensors, constellations to be able to sense the Earth System environment. But with varying degrees of accuracy, coverage, resolutions, etc

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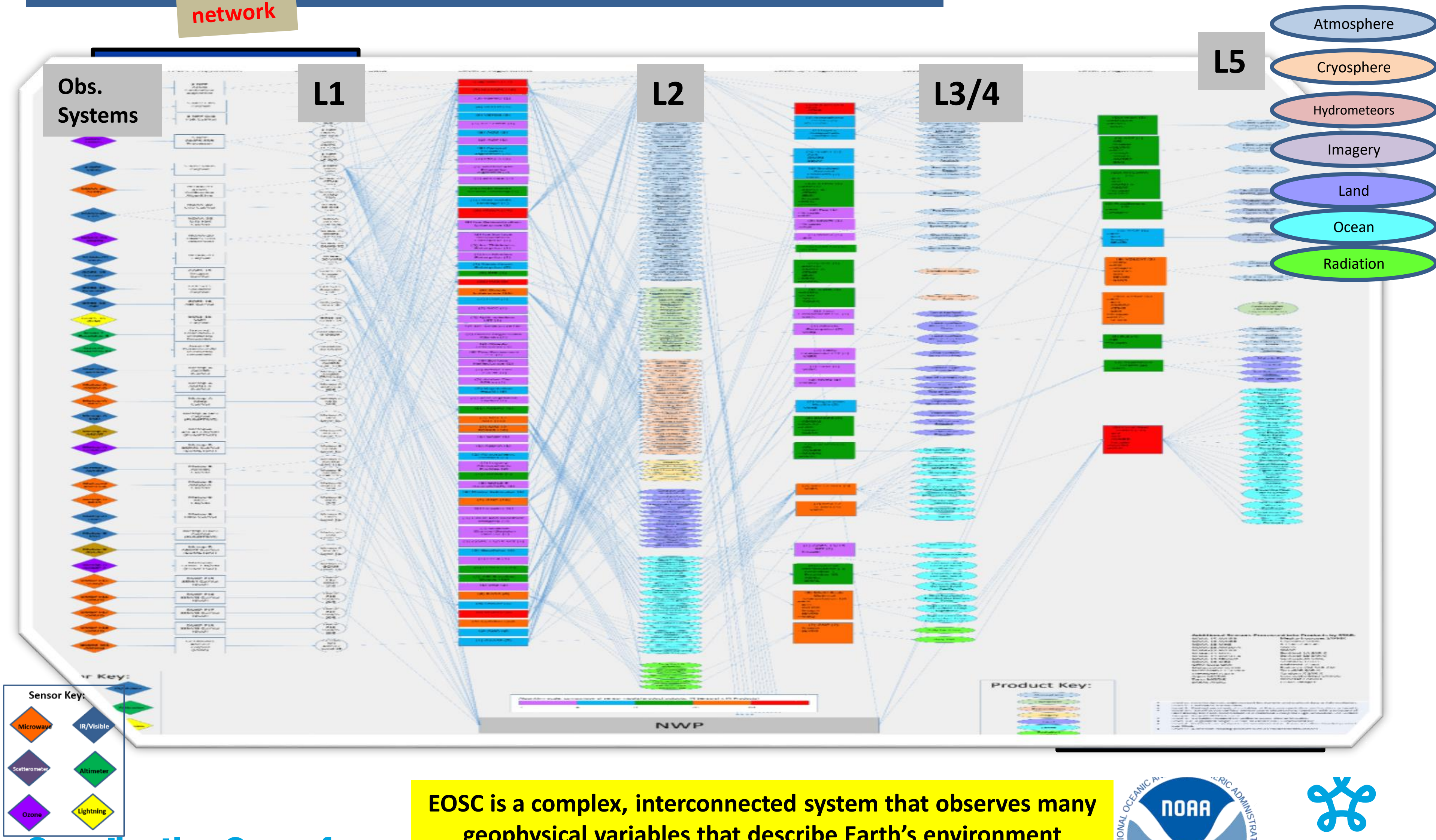
CGMS

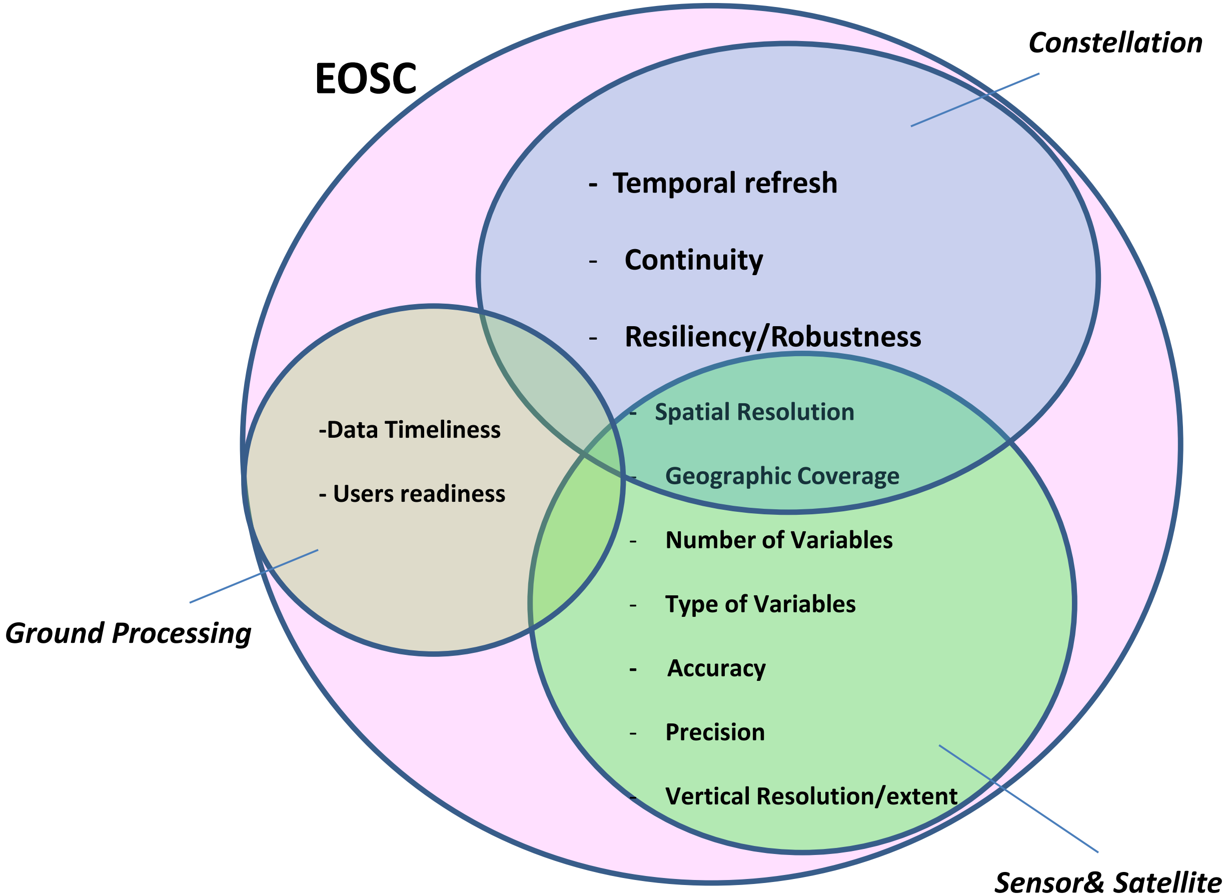
NOAA, version 1, Date May 20th 2021

The value ~~chain~~ network of the measurements



EOSC is a complex, interconnected system that observes many geophysical variables that describe Earth's environment (atmosphere, oceans, land and ice surfaces).

EOSC Attributes & Performance

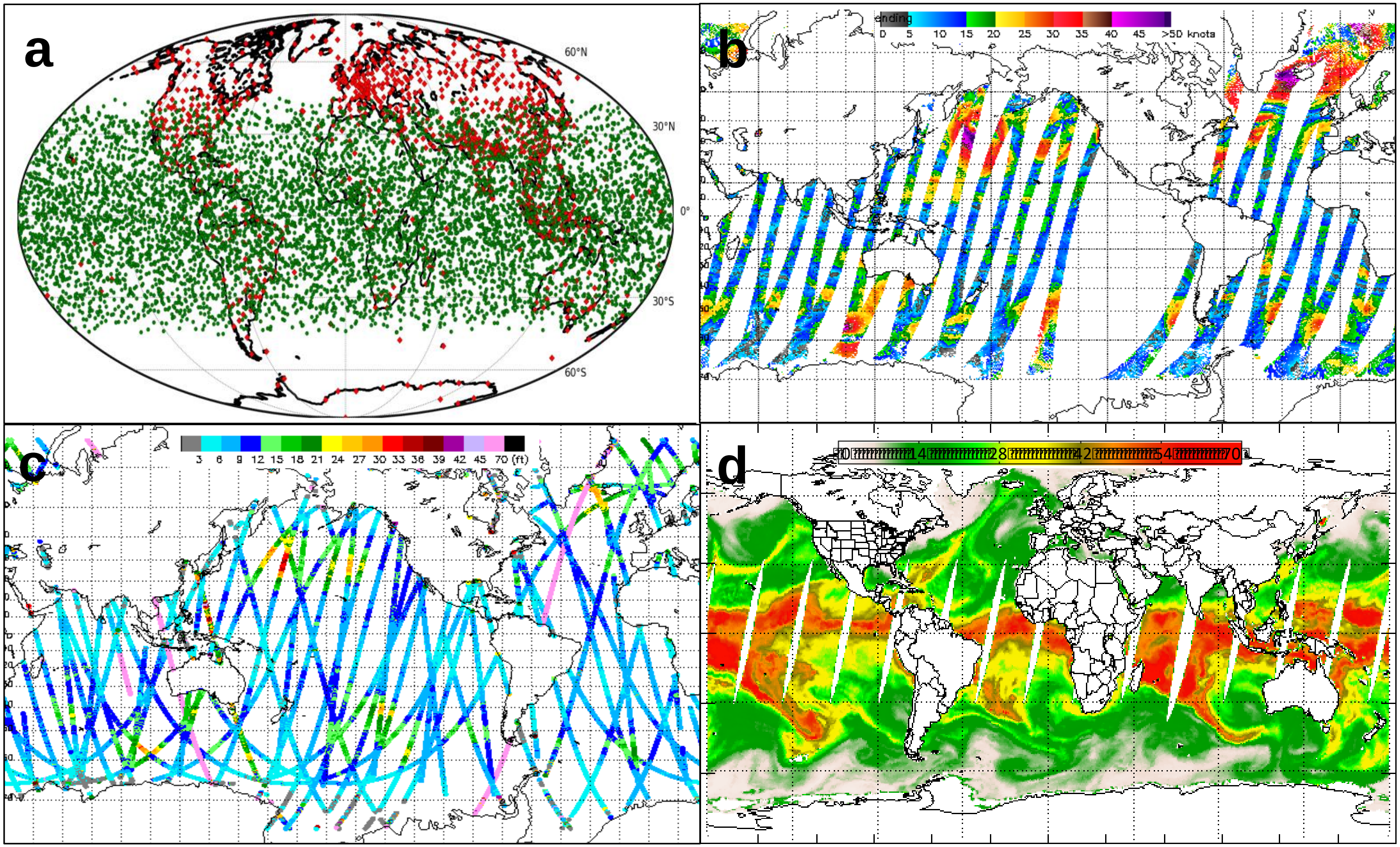


Performance of EOSC is dependent on the individual performances of sensors, satellites and how they are optimally deployed in tandem, in constellations, consisting of components from all partners.

Performance is more than accuracy or precision of individual sensors

EOSC aims to meet the needs of a diverse set of applications with varying requirements on the EOSC attributes

Example of Data coverage and diversity of EOSC Measurements



a: Radiosondes and COSMIC-2 RO, **b:** Scatterometer wind, **c:** Altimeter wave height, **d:** Microwave TPW

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Complementarity of EOSC Components

- Applications at different temporal and spatial scales impose different requirements on EOSC for various geophysical variables and their attributes
- Sensors with seemingly similar observing characteristics in fact add temporal, horizontal coverage, complement other attributes, and enhance the overall system's robustness and resiliency
- *Example:* Atmospheric Temperature from Microwave, Infrared sounders, as well as from Radio Occultation, Radiosondes: Some provide high vert. resolution, some high spatial coverage, etc.
- ***An evolving Capability:***
  - Today's contaminating noise is Tomorrow's critical signal: The use of observations evolves as knowledge and processing techniques improve.
  - *Example:* Assimilation of Cloudy/Rainy MW signal, RO data in the lower troposphere, upcoming: lightning data, salinity, etc.

EOSC diverse components provide complementary capabilities and add robustness and resiliency to the global system, especially important for operational systems

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3 **Conclusions**

Diversity of Earth-Observing Systems

	1960s	1970s	1980s	1990s	2000s	2010s
U.S.	16	26	14	14	20	35
ESA and/or EUMETSAT	0	1	3	7	11	14
Japan	0	1	4	4	6	8
Korea	0	0	0	1	2	6
India	0	0	4	13	10	13
China	0	0	1	3	11	46
France	0	0	1	3	4	7
Russia*	0	2	4	3	3	15
Germany	0	0	0	0	2	1
Algeria	0	0	0	0	1	3
Turkey	0	0	0	0	1	3
Brazil	0	0	0	1	2	0
Total	16	30	31	49	73	151+

* Russia launched a large number of short-lived satellites in the 1960s that are not included in this table.
+ In the 2010s an additional 18 countries launched 33 satellites not included in the table.

NUMBERS OF MAJOR ENVIRONMENTAL SATELLITES (RESEARCH AND OPERATIONAL) AND THEIR COUNTRIES/AGENCIES OF ORIGIN, LAUNCHED DURING EACH DECADE. SATELLITES WITH GEO SYNCHRONOUS, SUN SYNCHRONOUS, AND IN GEOSTATIONARY AND L1 ORBITS WERE SELECTED. SOURCE AND CREDIT: WORLD METEOROLOGICAL ORGANIZATION (WMO) OBSERVING SYSTEMS CAPABILITY ANALYSIS AND REVIEW (WMO, 2019) WEBSITE (HTTPS://WWW.WMO-SAT.INFO/OSCAR/SATELLITES). MAINLY PUBLIC-SECTOR OWNED SATELLITES WERE INCLUDED IN THESE STATISTICS.

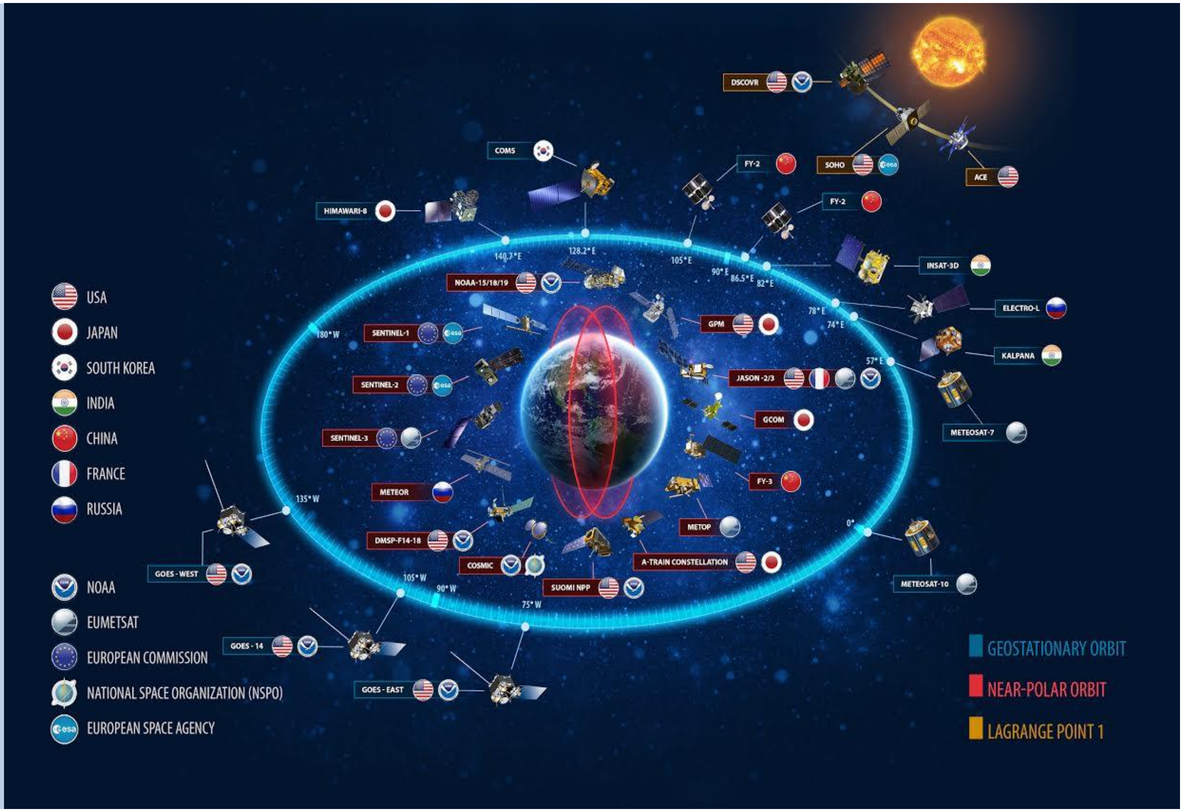
A clear increase in diversity and number of public-sector Earth-observing satellites in last 2 decades

Trends in Global Earth Observation Systems

(Toward the Ability to Comprehensively sense the environment all the time, everywhere)

GOS Trends and Driving Factors:

- New and Emerging Actors in Global Observing System
- New & enhanced Sensors (higher resolutions, higher SNR, etc.)
- New technology (smallsats, cubesats..)
- Emergence of potential new Payload hosting platforms (commercial, Near-Space platforms, rideshare, etc.)
- New sensing Technology : Hyperspectral MW, Wind Lidar, Polarimetric RO, Reflectometry, etc
- Emergence of New GOS (IoT, etc)
- Increase in volume and diversity of data
- Commercialization of satellite data and new business models
- Spectrum challenges in the MW
- Risk due to Space Debris



Space agencies are making long-term plans. Similar to the Earth System model (ESM) approach (on the modeling and requirements side), the EOSC design and evolution is approached in a similar comprehensive, coordinated fashion (on the Observation side).

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Looking Forward: Design, Evolution and Assessment

- **Evolution of EOSC ideally should maximize the overall value of the global constellation in satisfying the applications needs, current & future.**

- **How to optimal evolve/design EOSC given the diversity of the applications?**
  - Global Coordination of EOSC evolution, to cost-effectively meet users needs evolution
  - Effective User engagement at both technical and strategic levels to define priorities
  - Optimization in terms of observables, coverage, refresh rate, robustness, etc.
  - Defining what Metric(s) to optimize (?)
  - Needs to account for all relevant applications but also the expected evolution toward ESM
  - Optimization with other non-Space components (ground, airborne, emerging near-space platforms): WIGOS is an ideal mechanism for this multi-components optimization.

- **EOSC is the Satellite-Observations equivalent of the Earth System Model**

CGMS is Key for an Optimized EOSC

- Potential Areas Worth Pursuing at International Level:
  - Perform multi-applications Space-Based Observations Gap Analysis in Coordination with WIGOS (esp. surface component)
  - Develop a mechanism to optimize the design and evolution of global EOSC to ensure best (and cost effective) value to users
  - Engage with users incl. Earth System Modelers, to keep space observations and applications needs in synch (for the future)
  - Quantitatively Assess the value of individual sensors, constellations, or the overall EOSC (to the applications)
  - Assessment of socio-economic values of EOSC: Similar to the effort performed recently regarding surface-based observations (*The Value of Surface-based Meteorological Observation Data, Kull et al. 2021, World Bank and WMO*)

Conclusions

- **EOSC is a global asset providing widespread benefits across many applications and with various societal benefits, including the protection of life & property.**
- EOSC is a remarkable international success story that depended on effective collaboration and coordination of international partners and free and open exchange of critical environmental data.
- **EOSC is a complementary, robust, complex and evolving system that observes the Earth's system components: atmosphere, oceans, land, space weather.**
- EOSC is rapidly evolving with many factors driving it (technology, emerging data providers, commercial sector, new capabilities, etc.)
- **EOSC Optimization to meet Applications needs (current & future): would need a concerted effort to optimize EOSC evolution. Possibly including Ground and Space components.**

BACKUP

Geophysical observation attributes

Attribute	Definition	Why is it important? Typical examples
Number of variables observed	How many geophysical variables can be derived from the observing system measurements.	The capability of an observing system to measure or retrieve a wide range of variables makes it relevant to a wider number of applications.
Types of variables observed	The types of geophysical information provided by an observing system; its geophysical capability.	The geophysical capability of a system defines its ability to satisfy the applications needs. A scatterometer provides both ocean surface wind and land surface information.
Geographic coverage	The horizontal domain of the observations.	Polar satellites provide global coverage of the Earth's surface. A geostationary satellite on the other hand covers a specific area of the globe.
Horizontal resolution	The average horizontal distance or spacing between individual observations. For imagers, this is often equivalent to the footprint size.	It is the combination of horizontal resolution and footprint size that determines resolving power.
Footprint size	Horizontal scale represented by a single observation	Small footprints represent fine scales (*e.g.*, nearly point measurements) and permit high resolving power if the resolution is high.
Resolving power	Ability of a sensing system to separate or distinguish small, closely adjacent features.	High resolving power permits detecting fine-scale spatial features, *e.g.*, fronts, thunderstorms, and individual convective cells. It is also necessary to support precision agriculture, which requires highly resolved soil and vegetative state variables.
Temporal refresh	How many times a given spot on the globe is observed in a given time period. Alternatively, the time required to observe the horizontal domain.	For some slow-moving environmental features (such as vegetative phenology or sea ice motion), this might not be a critical attribute, but for hurricanes, storms, or other phenomena with rapid evolution or a diurnal variation, short temporal refresh is critical.
Vertical extent	The bottom and top levels of the derived observations.	The full vertical extent of phenomena of interest should be observed. The vertical extent for global NWP and space weather are quite different.

Geophysical observation attributes, part 2

Attribute	Definition	Why is it important? Typical examples
Vertical resolution	The number of independent pieces of information (degrees of freedom) derived at an observation location (GIFOV in most cases). This may be expressed in km as the vertical extent divided by the degrees of freedom.	The vertical resolution is critical for capturing fine-scale vertical features of the profile. Whether for determining the height of the tropopause, detecting temperature inversions, or resolving the cloud layers heights and assigning AMV heights. The RO sensors provide excellent vertical resolution for temperature.
Accuracy and Precision	Often lumped together as size of errors, which consist of bias and random errors. Accuracy refers to bias errors while precision refers to random errors. There are various metrics of these errors such as root-mean-square-error (RMSE).	This is a core characteristic of an observing system. An observation with large errors might be of limited value even if it has great vertical and horizontal resolutions and is provided with a global, dense coverage.
Validity range	Only values between the low and high limits of the validity range are reliably determined.	It is possible that the most important values are not measured or retrieved. For example, current scatterometer designs are not sensitive to wind speeds $>$ 30 m/s, but for marine warnings the maximum wind speed in a storm is critical.
Continuity	The time period of overlapping intercalibrated sensors that can be used to monitor the geophysical variable.	Continuity is particularly important for climate trend detection.
Robustness	How robust is the availability of this observation. We define this as the number of sensors that can be used to retrieve a given geophysical variable.	The robustness of the observing system (for each variable) is important for all operational applications. A gap in some key variables might lead to a significant degradation of the performance of various applications.
Resiliency	How quickly can a sensor be replaced.	Replacement could be by repositioning an on-orbit asset or by a launching a new satellite.
Data timeliness	The time between the observation time and when the observation is available for use in applications.	Real-time operational applications require timely data.