The WMO Vision for global observing systems in 2025: to what extent will it be met by space agencies' plans

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ABSTRACT
The WMO Vision for global observing systems in 2025 presents a high-level summary of a system of observing systems to address the need for observations for all WMO programmes and co-sponsored programmes. The Vision is intended to be challenging but achievable on the 2025 timescale. In this paper, the plans of the world's space agencies to implement observing systems that will contribute to meeting these goals are assessed. It is concluded that, for those observing systems of most importance for supporting operational numerical weather prediction, space agencies' plans represent, in general, a good response to the Vision. However some gaps and some vulnerabilities to early failures of satellites and instrument are identified. Also the importance of improving systems for timely international dissemination of data is stressed.

1 Introduction

The Rolling Review of Requirements (RRR) process of the World Meteorological Organization (WMO) assesses: user requirements for observations, the capabilities of present and planned observing systems to meet these requirements, and the gaps between requirements and capabilities. The WMO "Vision for global observing systems" is then a high-level plan for a system of complementary observing systems to meet user requirements for observations in support of many different applications, taking note of the gaps that need to be filled.

Within the RRR process, gap analyses ("Statements of Guidance") have been developed for 12 Application Areas. These include global numerical weather prediction (NWP) and high-resolution NWP. In this paper, we discuss the extent to which the current WMO "Vision" responds to the requirements of these two applications. Similar analyses could be made for the others. Also, since this Seminar concerns only the use of satellite observations in NWP, we focus here on space-based observations.

Section 2 presents more details on the RRR process and summarises the space-based component of the "Vision". In Section 3, for each element of the space-based component, an assessment is provided of the current plans of space agencies and the extent to which they are likely to meet the aspirations of the "Vision" in 2025. Section 4 presents the key issues arising from this assessment and provides some concluding remarks.

2 The WMO "Vision for the GOS in 2025"

2.1 The role of the "Vision" within the RRR process

The RRR process contains the following elements:

- user requirements for observations are compiled, periodically reviewed and updated, for many Applications Areas (AAs) covering the whole range of the needs of WMO programmes and co-sponsored programmes;
- the capabilities of present and planned observing systems, both surface-based and space-based, are compiled, reviewed and updated;
- user requirements are compared with observing system capabilities, in order to assess the gaps between the two;
- key gaps and suggestions for filling them are documented in a gap analysis (which is referred to within the RRR process as a "Statement of Guidance") for each AA.

Based on knowledge of present/planned capabilities and the analysis of gaps provided by the RRR process, a long-term "Vision for global observing systems" is prepared. Then, as a response to the Vision, the Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP) is developed.

The documentation associated with all these activities is made available to WMO Members and to cooperating agencies (e.g. space agencies) to guide the development of their programmes. As applications develop − in response to improved observations and to other scientific and technological advances − user requirements also evolve, and so the whole "rolling" process has to be repeated.

Documentation is available on the WMO web site:

- the RRR process: http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html ,
- OSCAR (Observing System Capabilities Analysis and Review Tool)
  - User requirements, "OSCAR/Requirements": http://www.wmo-sat.info/oscar/requirements ,
  - Space-based observing capabilities, "OSCAR/Space": http://www.wmo-sat.info/oscar/spacecapabilities ,
  - Surface-based observing capabilities "OSCAR/Surface" – under development,
- Gap Analyses – "Statements of Guidance": http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html#SOG ,
- Vision for the GOS in 2025: http://www.wmo.int/pages/prog/www/OSY/gos-vision.html ,
- EGOS-IP: http://www.wmo.int/pages/prog/www/OSY/gos-vision.html#egos-ip .

The "Vision" was prepared for and endorsed by the WMO Commission for Basic Systems (CBS) in 2009. It is intended to be a realistic target and aspiration for 2025. EGOS-IP is a response to the Vision and provides guidance for WMO Members and partner consortia. It proposes the roles of various agents in fulfilling the Vision and sets out a "road-map" for achieving it, including 115 "Actions". EGOS-IP was endorsed by WMO/CBS in 2012.

2.2 The "Vision": a summary of the space-based component

The Vision calls for the implementation of the following space-based observing systems. Those expected to be of most importance for NWP, and discussed in Section 3, are highlighted in bold.

Operational geostationary satellites
– at least 6 – each with:

- **Infra-red/visible multi-spectral imager**
- **Infra-red hyper-spectral sounder**
- Lightning imager

Operational polar-orbiting sun-synchronous satellites
- in 3 orbital planes – each with:

- **Infra-red/visible multi-spectral imager**
- **Microwave sounder**
- **Infra-red hyper-spectral sounder**

Additional operational missions in appropriate orbits:

- **Microwave imagers**
- **Scatterometers**
- **Radio occultation constellation**
- Altimeter constellation
- Infra-red dual-view imager (for sea surface temperature)
- Advanced visible/NIR imagers (for ocean colour and vegetation)
- Visible/infra-red imager constellation (for land-surface monitoring)
- **Precipitation radars**
- Broad-band visible/IR radiometers (for radiation budget monitoring)
- Atmospheric composition monitoring instruments
- Synthetic aperture radar

Operational pathfinders and technology demonstrators:

- **Doppler wind lidar**
- **Low-frequency microwave radiometer** (for soil moisture and sea-surface salinity)
- Microwave imager/sounder on geostationary satellites (for precipitation)
- Advanced imagers on geostationary satellites
- **Imagers on satellites in high-inclination, elliptical orbits**
- Gravimetric sensors (for water in lakes, rivers and the ground)

Polar-orbiting and geostationary platforms/instruments for space weather

- for solar imagery, particle detection, electron density

3 Comparison of the Vision with space agencies' plans

The following analysis was derived mainly from:

- information in OSCAR/Space, on the programmes of all the space agencies, their satellites and instruments, and the capabilities of each instrument in terms of the geophysical variables on which they provide information;
- the WMO satellite status list: http://www.wmo.int/pages/prog/sat/satellitestatus.php

3.1 Operational geostationary satellites

Table 1 lists the operational geostationary satellites in orbit in 2014 and planned for 2025, organised roughly according to their longitudes and hence coverage regions. Those in green are currently delivering atmospheric motion vectors (AMVs) judged to be of sufficient quality to be used operationally in NWP at the Met Office (UK). Those in amber have not yet reached this quality or are not distributed.

	2014	→ 2025
E. Pacific Ocean	GOES-13,-14,-15	GOES-R,-S,-T,-U
W. Atlantic Ocean		Electro-M
E. Atlantic Ocean	MSG: M-8,-9,-10	MTG/I+S
Indian Ocean	Meteosat-7 INSAT-3C Kalpana-1 Electro-L N1 INSAT-3D FY-2D INSAT-3A FY-2E FY-2F COMS-1	MSG? INSAT-3 Electro-M FY-4 GEO-KOMSAT-2
W. Pacific Ocean	Himawari-6,-7 (MTSAT-1R,-2)	Himawari-8,-9 Electro-M

Table 1: Operational geostationary satellites, in 2014 and planned for 2025.

Table 2 lists the instruments to be carried by each of the satellites planned to be operational in 2025. For further information on the instruments in this and subsequent tables, see OSCAR/Space. Green indicates that the specification of the instrument meets the aspiration described in the Vision and EGOS-IP. Amber indicates a basic capability and red no planned capability.

Satellite series	Vis/IR imager	Hyper-spectral IR sounder	Lightning imager
MSG	SEVIRI (12 channels)	no	no
MTG	FCI (16 channels)	IRS	LI
GOES-R	ABI (16 channels)	no	GLM
Himawari	AHI (16 channels)	no	no
FY-4	AGRI (14 channels)	GIIRS	LMI
INSAT-3DS	IMAGER (6 channels)	no (low-res SOUNDER)	no
GEO-KOMSAT-2	AMI (16 channels)	no	no
Electro-M	MSU-GSM (20 channels)	IRFS-GS	LM

Table 2: Instruments on geostationary satellites planned to be operational in 2025.

Table 3 summarises the operational geostationary capability currently planned for 2025 in terms of whether it meets the aspiration in the Vision and EGOS-IP or not.

	Vis/IR imager	Hyper-spectral IR sounder	Lightning imager
E. Pacific Ocean	**YES**	**no**	**YES**
W. Atlantic Ocean	**YES**	**no**	**YES**
E. Atlantic Ocean	**YES**	**YES**	**YES**
Indian Ocean	**YES**	**YES**	**YES**
W. Pacific Ocean	**YES**	**no**	**no**

Table 3: Summary of operational geostationary capability in 2025 in relation to the Vision.

The most important contribution currently made by operational geostationary satellites to global NWP is via the AMVs generated from their imagery. As indicated in Table 1, some AMVs are currently of sufficient quality to be used operationally but others need improvement. Continued efforts will be needed in this area to ensure that, by 2025, the AMVs from all satellites are of sufficient quality.

Visible/infra-red imagers for these satellites have an established heritage which gives confidence that their quality and longevity will be high in 2025. However, the planned hyper-spectral infra-red sounders and lightning imagers represent new technologies for geostationary satellites, and so there can be less confidence at this stage in their maturity and longevity. For these instruments, there is also likely to be less back-up in the overall system in case of instrument failure.

3.2 Operational polar-orbiting sun-synchronous satellites

Table 4 lists the operational polar-orbiting sun-synchronous satellites in orbit in 2014 and planned for 2025, organised according to their orbital plane and hence local equator crossing time. Those in green are currently delivering near-real time data which are distributed internationally. Those in amber should soon reach this status. For those in red, there are currently no established plans for international data distribution.

	2014	→ 2025
Early morning (LECT ~1730)	**DMSP F-16,-17,-19**	**DMSP F20** **FY-3E,-3G**
Morning (LECT ~0930)	**Metop-A,-B** **DMSP-18 FY-3C** **Meteor-M N1,-N2**	**Metop-C Metop-SG** **Meteor-M N2**
Afternoon (LECT ~1330)	**NOAA-15,-18,-19** **Suomi-NPP** **FY-3B**	**JPSS-1,-2** **FY-3F**
(LECT ~1530)		**Meteor-M N2, -MP**

Table 4: Operational polar-orbiting sun-synchronous satellites, in 2014 and planned for 2025.

Table 5 lists the instruments to be carried by each of the satellites planned to be operational in 2025 for the core meteorological observing capability of: hyper-spectral infra-red sounding, microwave sounding and visible/infra-red imagery. Green indicates that the specification of the instrument meets the aspiration described in the Vision and EGOS-IP. Red indicates no planned capability and grey that data are not available for international distribution.

satellite series	Hyper-spectral IR sounder	MW sounder	Vis/IR imager
Metop-SG	**IASI-NG**	**MWS**	**METimage**
JPSS	**CrIS**	**ATMS**	**VIIRS**
FY-3, FY-3M	**HIRAS**	**MWTS-2, MWHS-2**	**MERSI-2**
Meteor-3M	**IKFS-2**	**MTVZA-GY**	**MSU-MR**
Metop	**IASI**	**AMSU-A, MHS**	**AVHRR**
DMSP	**no**	**SSMIS**	**OLS**

Table 5: Instruments on polar-orbiting sun-synchronous satellites planned to be operational in 2025, providing infra-red and microwave soundings and visible/infra-red imagery.

Table 6 summarises the operational polar-orbiting sun-synchronous capability planned for 2025 in terms of whether it meets the aspiration in the Vision and EGOS-IP or not.

	Vis/IR imager	Hyper-spectral IR sounder	MW sounder
Early morning	**YES**	**YES**	**YES**
Morning	**YES**	**YES**	**YES**
Afternoon	**YES**	**YES**	**YES**

Table 6: Summary of operational polar-orbiting sun-synchronous capability in 2025 in relation to the Vision.

Table 6 indicates that expectations for 2025 are good, with all three of these core capabilities planned for all 3 orbital planes. However, in the period leading up to 2025, there are concerns about the likelihood of operational continuity, with some vulnerability to early failure, particularly in the afternoon orbit. Also, full capability in the early morning orbit will only be established when satellites of the FY-3 series have been successfully placed there.

Another concern, particularly for NWP, is the performance of the microwave sounders. The NWP community has been very well served in recent years by AMSU-A instruments on several satellites. Despite their low noise and high stability, their performance is starting to become marginal for NWP because of the very high levels of accuracy of NWP background fields (short-range forecasts) when expressed in brightness temperature space (currently ~50-100 mK for critical tropospheric sounding channels). It will be important to maintain and, if possible, improve this performance for future microwave sounders.

3.3 Additional operational missions in appropriate orbits

3.3.1 Microwave imagers

Microwave imagery data are assimilated in NWP for the information that they provide on total column water vapour, sea surface wind, cloud and precipitation. They also provide important information for surface analyses, particularly for sea-ice coverage and sea surface temperature. Table 7 lists the microwave imagers in space in 2014, together with the satellites on which they fly and the frequency ranges of their channels. Those in green are currently delivering near-real time data which are distributed internationally. Those in amber should soon reach this status. For those in red, there are currently no established plans for international data distribution.

satellites	Instrument	channels (GHz)
DMSP F15	**SSM/I**	19-85
DMSP F16, F18, F19	**SSMIS**	19-183, incl.50-60
TRMM	**TMI**	10-85
Coriolis	**Windsat**	6.8-37
GCOM-W1	**AMSR-2**	6.9-89
FY-3B,-3C	**MWRI**	10-89
Megha-Tropiques	**MADRAS**	18-157
GPM Core	**GMI**	10-183
Meteor-M N1, N2	**MTVZA-GY**	10-183, incl.50-60
HY-2A	**MWI**	6.6-37

Table 7: Microwave imagers in 2014.

Table 8 lists the microwave imagers planned for the period up to 2025.

satellite series	instrument	channels (GHz)	
DMSP	**SSMIS**	19-183, incl.50-60	→ 2025
GCOM-W	**AMSR-2**	6.9-89	→ 2025
GPM-Core, -Braz	**GMI**	10-183	→2021+
HY-2	**MWI**	6.6-37	→ 2025
FY-3, FY-3M	**MWRI**	10-89	→ 2028
Metop-SG	**MWI**	18-183, incl.50-54,118	2022→
Metop-SG	**ICI**	183-664	2022→
DWSS	**MIS**	6.3-183, incl.50-60	??
Meteor-M	**MTVZA-GY**	10-183, incl.50-60	→ 2025
Meteor-MP	**MTVZA-GY-MP**	6.9-183, incl.50-60	2024-2031

Table 8: Microwave imagers planned up to 2025.

3.3.2 Scatterometers

Scatterometer data are assimilated in NWP for the information that they provide on sea surface wind speed and direction. They also provide important information on soil moisture. Table 9 lists the scatterometers in space in 2014, together with the satellites on which they fly and their frequency bands. Those in green are currently delivering near-real time data which are distributed internationally. Those in amber should soon reach this status. Grey indicates that the satellite provided important operational data but has recently failed.

satellites	Instrument	
Metop-A,-B	**ASCAT**	C-band
Oceansat-2	**OSCAT**	Ku-band
ISS	**RapidScat**	Ku-band
HY-2A	**SCAT**	Ku-band

Table 9: Scatterometers in 2014.

Table 10 lists the scatterometers planned for the period up to 2025. Those in green should be available in 2025. Those in grey will provide important data between 2014 and 2025 but are unlikely still to be available in 2025.

satellite series	instrument		
Metop	**ASCAT**	C-band	→2024+?
Metop-SG	**SCA**	C-band	2022→
FY-3	**WindRad**	C+Ku-band	2018-27
HY-2	**SCAT**	Ku-band	→ 2025
Meteor-M, -MP	**SCAT**	Ku-band	2020-30
ScatSat-1	**OSCAT**	Ku-band	2016-19
CFOSAT	**SCAT**	Ku-band	2016-21
OceanSat-3	**OSCAT**	Ku-band	2017-22

Table 10: Scatterometers planned up to 2025.

3.3.3 Radio occultation constellation

Radio occultation (RO) sensors provide information on the delay/bending of GNSS signals caused by the atmosphere. This is related to the vertical profile of atmospheric refractivity, which in turn is related to the profiles of temperature and humidity. RO data provide all-weather capabilities of high vertical resolution and absolute accuracy. Table 11 lists the radio occultation receivers in space in 2014, together with the satellites on which they fly. Those in green are currently delivering near-real time data which are distributed internationally. Those in amber should soon reach this status. Those in red are not currently available for international distribution. In July 2014, the available constellation provided about 2600 occultations per day to NWP centres.

Satellites	Instrument	
COSMIC	**IGOR**	5 satellites
Metop-A, -B	**GRAS**	
GRACE-A, -B	**Blackjack**	
TerraSAR-X	**IGOR**	
Tandem-X	**IGOR**	
FY-3C	**GNOS**	
SAC-D	**ROSA**	
Oceansat-2	**ROSA**	
Megha-tropiques	**ROSA**	
KOMPSAT-5	**AOPOD**	

Table 11: Radio occultation receivers in 2014.

Table 12 lists the radio occultation receivers planned for the period up to 2025. Those in green should be available in 2025. Those in grey will provide important data between 2014 and 2025 but are unlikely still to be available in 2025. The WMO EGOS-IP calls for "at least 10,000 occultations per day" by 2025, and this should be met by the planned constellation.

satellite series	instrument		
COSMIC-2	**Tri-G**	12 satellites	2016-25
Metop-C	**GRAS**		→ 2024+?
Metop-SG	**RO**	2 satellites	2021→
FY-3	**GNOS**		→ 2027
Meteor-M N3, -MP	**Radiomet**		2020-30
JASON-CS	**Tri-G**		2018-31
SEOSAR/Paz	**ROHPP**		2014-19
GRACE-FO	**Tri-G**	2 satellites	2017-22

Table 12: Radio occultation receivers planned up to 2025.

3.3.4 Precipitation radars

Table 13 lists the precipitation radars planned for the period from 2014 to 2025. Those in green (only Hu/Ka-PR on FY-3RM satellites) should be available in 2025. Those in grey will provide important data between 2014 and 2025 but are unlikely still to be available in 2025.

satellites	Instrument	frequency (GHz)	
TRMM	PR	13.8	1997-2014+
Cloudsat	CPR	94	2006-14+
GPM-Core	DR	13.6 + 35.6	2014-17
EarthCARE	CPR	94	2017-20
FY-3RM-1, -2	Ku/Ka-PR	12-18 + 26-40	2019-28

Table 13: Precipitation radars from 2014 to 2025.

3.4 Operational pathfinders and technology demonstrators

3.4.1 Doppler wind lidars

Doppler wind lidars (DWL) will provide information on profiles of the component of atmospheric wind along the line-of-sight of the measurement. They will also yield information on profiles of cloud and aerosol. At present, as shown in Table 14, only one DWL mission is planned. This is unlikely still to be providing data in 2025, and no further missions are currently funded.

satellites	instrument	
ADM-Aeolus	ALADIN	2016-19

Table 14: Doppler wind lidars from 2014 to 2025.

3.4.2 Low-frequency microwave radiometers

This class of microwave radiometer measures radiation around 1.4 GHz and provides information on soil moisture and ocean surface salinity. It also has potential to provide information on sea-surface wind/wave conditions, particularly in areas of high wind speed and in all-weather conditions, and on sea-ice thickness. As shown in Table 15, three missions are current or imminent, but it is unlikely that they will still be providing data in 2025, and no further missions are currently planned.

satellites	Instrument	
SMOS	MIRAS	2009-14+
SAC-D	Aquarius	2011-16
SMAP	SMAP	2015-18

Table 15: Low-frequency microwave missions from 2014 to 2025.

3.4.3 Imagers on satellites in high-inclination, elliptical orbits

This class of instrument will offer visible/infra-red imagery and derived products, e.g. AMVs, comparable with those currently available from geostationary satellites. As shown in Table 16, two missions are currently planned, of which one is expected to be providing data in 2025.

Satellites	Instrument		
Arctica-M N1, N2	**MSU-GS/A**	10 channels	2015-21
PCW-1, -2	**ISR**	21 channels	2022-29

Table 16: Imagers on satellites in high-inclination, elliptical orbits from 2014 to 2025.

4 Summary and conclusions

For those space-based observations of most importance for NWP, the current plans of world's space agencies, when considered together, represent a good response to the WMO Vision for 2025. If these plans come to fruition, they will contribute substantially to the stated observational requirements of NWP. A key gap will continue to be the requirement for observations of the global 3D wind field. Doppler wind lidar observations can potentially contribute to filling this gap, but only the ESA ADM/Aeolus mission is planned (2016–19) and no mission is currently planned to provide observations in 2025. Another key technology without planned continuity is low-frequency microwave imagery, which is currently demonstrating important potential contributions to NWP and other applications.

The gap analysis discussed in this paper has focussed on the key requirements of NWP. The space-based observing system serves many important applications other than NWP and, for some of these, the gaps between requirements and planned capabilities are both different and more extensive. This is particularly true for observations to ensure continued monitoring of important climate variables.

Although the plans for the space-based observing capability in 2025 are generally good in relation to the needs of NWP, there are several vulnerabilities to early failure of satellites and instruments within the next decade, with risks of gaps in or degradation of the observing system. These will need to be monitored carefully and contingency plans developed.

A recurring issue in this review has been that of data availability. For most of the operational systems planned for the next 10 years, the plans for international distribution of data are either in place or under discussion. However, the tables in this paper show there are exceptions where no plans exist for near-real time international distribution of potentially valuable data sets. It should be stressed that, from the perspective of WMO, a satellite or instrument is not a contribution to global observing systems unless data are communicated internationally in a timely manner.

It is also highly desirable that data from new satellite missions are made widely available to the global NWP community as soon after launch as possible, including during the calibration/validation phase of the mission. This not only gives the NWP community early access to the data, which accelerates its ability to make the earliest possible operational use of the data, but also results in effective feedback from NWP centres to space agencies, which can often be crucial for characterising new instruments and for effective calibration and pre-processing of their data. It has been demonstrated many times that the data assimilation systems of operational NWP systems are very powerful tools in this respect.

Section 2.2 of this paper outlines the WMO Vision for global observing systems in 2025. Within WMO/CBS activities, work is now beginning on the development of a WMO Vision for 2040. Two key questions to be addressed in developing this new Vision are:

- Which key user requirements for observations would remain unfulfilled, even if the Vision for 2025 were to be implemented in full?
- Which observing technologies are likely to become mature and cost-effective during the period 2025 to 2040?

Input to the new Vision will be sought from many communities, representing users of observations for many applications and experts in the technologies of observing systems. Advice from the NWP community will be an important part of this process.

Acknowledgements

The review provided by this paper would not have been possible without the excellent information provided by the OSCAR/Space database. The author thanks all those, in the WMO Space Programme and the space agencies, who have contributed to the content, facilities and maintenance of this database, and particularly to the leadership of this activity provided by Jerome Lafeuille. However, the interpretations (and any misinterpretations) of information extracted from the database are solely the responsibility of the author.