2022

Future GNSS radio occultation data needs

Sean Healy presenting on behalf of Rick Anthes

(to be presented at NOAA Science Assessment Team, 27 June 2022)

Presented to CGMS-50 plenary, item 4.8

Coordination Group for Meteorological Satellites

Executive summary of the WP

We summarise recent community discussions held in preparation for a presentation to the on NOAA Science Assessment Team, 27 June 2022. NOAA has asked for in input on future RO needs to help inform their planning. The key questions *include* how many RO are needed, what is the best coverage, required quality, and whether an agency led "backbone" RO constellation required.

The team emphasise the importance of free exchange of data, where there are no limitations on use in near-real-time applications. There remain good arguments for an agency-led backbone RO constellation. A new RO observation campaign, "ROMEX", assessing the impact of up to 30,000 observations per day, is suggested.

The main issues presented here will be discussed further at IROWG in September 2022.

NOAA has asked us for input on future RO needs to help in their planning

- How many RO profiles per day are needed? Is there an upper limit to the number that would be useful for NWP? Is there a knee in the cost-benefit curve?
- How should they be distributed, e.g.
  - Uniform globally or some latitudinal preference (e.g. more tropical or extratropical)?
  - Local time?
- Should NOAA provide a basic backbone and fill in with commercial data? Or would all-commercial be acceptable? What does “backbone” mean? How many backbone profiles are needed?
- Quality considerations?
- How much of space weather needs could be covered?
- What level data should NOAA obtain from vendors?
- Where should the data be processed and distributed?

Process

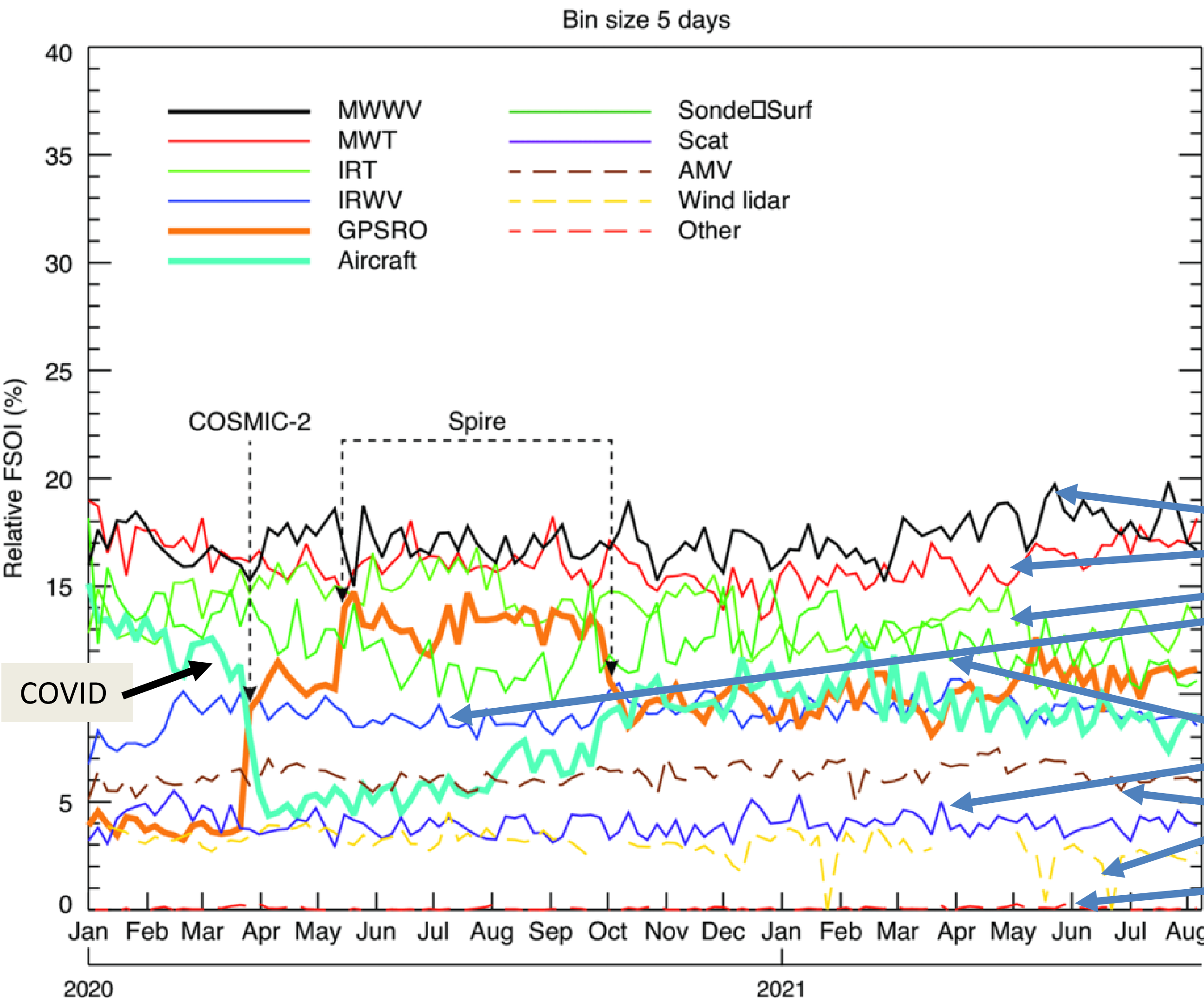
- Contacted leaders in RO community in weather, climate and space weather (the Team, see Appendix)
- Consulted IROWG and WMO documents and recommendations and scientific literature
- Prepared draft responses to questions
- Reviewed with Team in virtual meeting May 12, 2022
- Revised and shared with Team for further comments
- Appendix gives supporting material, details, and references

BACKGROUND and SUMMARY

- RO is one of the most impactful observations in NWP and science
  - Contributes to weather, climate, and space weather
  - Accurate and precise-can be assimilated without bias correction
  - All weather (cloudy and clear), land and sea (no emissivity issues)
  - Increases impact of infrared and microwave sounding systems- bias correction will be especially important with SmallSat IR and MW calibration requirements
- NWP impact increases steadily with number of observations up to at least 125,000 profiles per day
- RO data should be shared ***freely*** in real time under global license- this is to the advantage of all providers, users, and society.
  - ***"freely"*: data should be redistributed in NRT with no limitation on use and no limitations on products derived using that data**
- Cost/benefit: Costs go down, benefits go up with full data sharing

How many RO profiles per day are needed? Is there an upper limit to the number that would be useful for NWP? Is there a knee in the cost-benefit curve?

- Since IROWG-4 (April 2015 in Melbourne) IROWG has recommended at least 20,000 RO profiles per day.
- Independent peer-reviewed scientific studies support this number, but indicate that it may be conservative and should be revised upward. This will be considered at IROWG-9 in Graz, Austria in September 2022
- No evidence of saturation up to at least 125,000 profiles per day
- The most rapid increase of impact per observation is in the first 30,000 profiles; about half of the total impact of RO is achieved with the first 30,000 profiles
- This suggests that ~30K profiles per day may be close to a knee in the cost-benefit curve, but this depends on the pricing per observations. If it is cheaper per sounding for larger numbers, the optimum number of soundings will be larger.



Increase of RO has huge impact on ECMWF operational model.

FSOI is a global integrated energy metric of overall forecast skill that is useful for comparing the relative impact of different observational systems. Results are similar to data denial experiments.

This slide is a fair comparison of the relative impact of these observing systems by his metric over this period of time. FSOI has been shown to give similar results to data denial experiments.

Sean Healy, ECMWF

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How should RO observations be distributed?

- Combined constellation of all RO should provide
  - Uniformly globally---approximately equal horizontal separation (resolution) at all latitudes over a day
  - Uniformly in local times (especially important for climate and space weather)
- Will require a mix of orbits (polar and Equatorial)

Comment: Science is very clear on this answer.

Should NOAA provide a backbone and fill in with commercial data? Or would all-commercial be acceptable? What does “backbone” mean? How many backbone profiles are needed?

- NOAA and its partners (e.g. EUMETSAT) should provide an RO backbone of 10,000 RO profiles per day, roughly the current number of COSMIC-2 and Metop profiles
- Provide global data at all local times and shared to all without restrictions
- Should be
  - government (public) designed, owned, and managed
  - exceeds a minimum quality standards
  - long lasting and stable
  - well documented and independently processed and archived in at least two places, preferably more than two
- Similar to GRUAN radiosonde network—a high-quality reference radiosonde network that is useful for climate, calibration and validation of commercial RO missions and IR and MW sounders.

Why is a backbone needed?

- We get all data, metadata, processing details-valuable for understanding the errors, improving retrievals, reprocessing for research and reanalysis
- Uniformity of quality--long-lived instruments with overlapping periods to monitor quality and obtain long time series-important for climate, anchoring of NWP, and calibration of IR and MW sensors.
- Stability and reduction of risk (companies come and go, year to year budget and price fluctuations)
- Cost management-backbone with known costs helps control prices of commercial data.
- More than one processing center is needed—cross checks, verification of results by independent centers with independent scientists. True for commercial data as well.

Quality considerations? Are they different for commercial purchases and the background?

Current (April 2020) NOAA requirements: Latency<140 min, SNR>200, global coverage

Instead of SNR, it may be better to require RO profiles to pass certain quality metrics

- Latency-very important, especially for space weather. For <u>example</u>:
  - space weather: 50% < 30 min is threshold, <15 minutes is goal
  - NWP: 50% < 6 h is threshold. < 3 h is goal
- Uncertainties (random error standard deviations) in defined layers (e.g. 0-5, 8-15, 30-40 km)
- Maximum biases in certain layers (e.g. 0-2 km, 2-5 km, 8-15 km)
- “Stdv”(standard deviation of bending angle differences from climatology between 60-80 km)-a measure of quality of occultation
- Penetration depth-certain % (e.g. 80%) reaching at least 1 km from surface

For examples see Appendix. Need an expert team to develop the requirements.

What level data should NOAA obtain from vendors?

NOAA should get Level 0, 1A and 1B as defined by EUMETSAT's ROM SAF as well as all the metadata

Level 0: Raw sounding, tracking and ancillary data, and other GNSS data before clock correction

Level 1A: Full resolution excess phases, total phases, pseudo ranges, SNR's, orbit information, navigation bits, and quality information

Level 1B: Bending angles and impact parameters, tangent point location

How much of space weather needs could be covered?

- RO provides valuable information on the following space weather geophysical parameters:
  - Absolute TEC
  - Relative TEC
  - S4 amplitude scintillation index
  - Sigma-phi phase scintillation index
  - Electron number density profiles 100-600 km

- RO cannot provide other important space weather observations such as coronograph imagery,

heliospheric imagery, auroral imagery, solar X-ray irradiance. See SPRWG report (NOAA 2018; Anthes et al. BAMS 2019) for list of priority space weather observations.

- Latency very important, more stringent than NWP, < 15 min goal <30 still useful (threshold)
- TEC data should be phase connected above/below 0 degrees elevation angle-important to obtain absolute TEC for the occultation portion of the observation

Where should the data be processed and distributed?

- Data should be processed and continually monitored for quality by at least two reliable institutions with expertise in RO retrievals and uses in NWP, climate and space weather. More than two would be desirable. Cross comparison, comparison of results. Similar to why we need more than one climate model.
- All RO data that NOAA and its partners obtains should be processed in near-real-time and distributed free of charge to all users via the GTS.
- RO data should also be reprocessed and made available to the research community via a permanent archive within one year of acquisition.
- Complete documentation should be available, maintained and updated for all NRT and reprocessed data.

RO Modeling Experiment (ROMEX)

A Proposed Experiment of opportunity
Similar to an observational field experiment

- Partners obtain and share all possible RO data for a certain period (e.g. 6 months)-take whatever data are available
- May reach 30,000 profiles per day-or even more in the near future!
- Different centers can do forecast experiments, including data denial experiments, and obtain solid evidence of benefit vs number of profiles
- Quality of different missions and sources can be compared for the same time period
- Plausible numbers (just an example)

COSMIC-2	5,000	
Metop, FengYun-3, Sentinel 6	4,000	
SPIRE		10,000
PlanetiQ	10,000	
GeoOptics	?	
Total:		29,000 or more

ROMEX

- Do in next two years (before COSMIC-2 fades)
- Suggested time period (August-December)
  Tropical cyclone season and one NH winter month

– Role of partners
  - Processing centers process all the data
  - Modeling centers carry out modeling experiments
  - Commercial data companies provide all data in delayed time with no restrictions
  - Government sponsors help with incremental costs incurred by processing and modeling centers

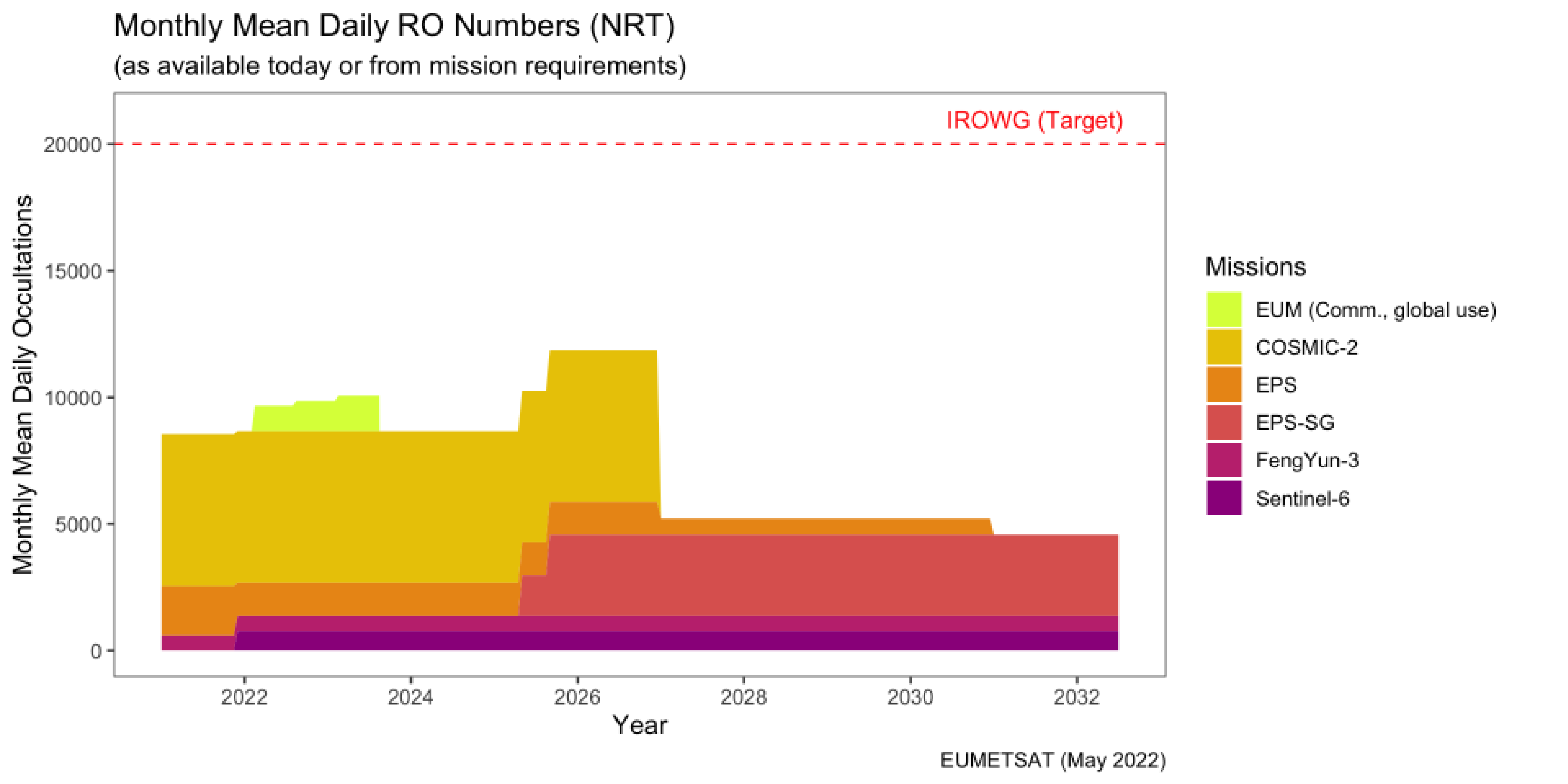
– All partners benefit
  - Science: unprecedented data set for research
  - Modeling centers: data impact studies, data denial experiments
  - Commercial providers-showcase their data and show value of large RO data sets to customers

Appendix: Details and references

Expected Radio Occultation Numbers for NRT Use

C. Marquardt, A. von Engeln, R. Notarpietro
EUMETSAT, Germany

6 May 2022



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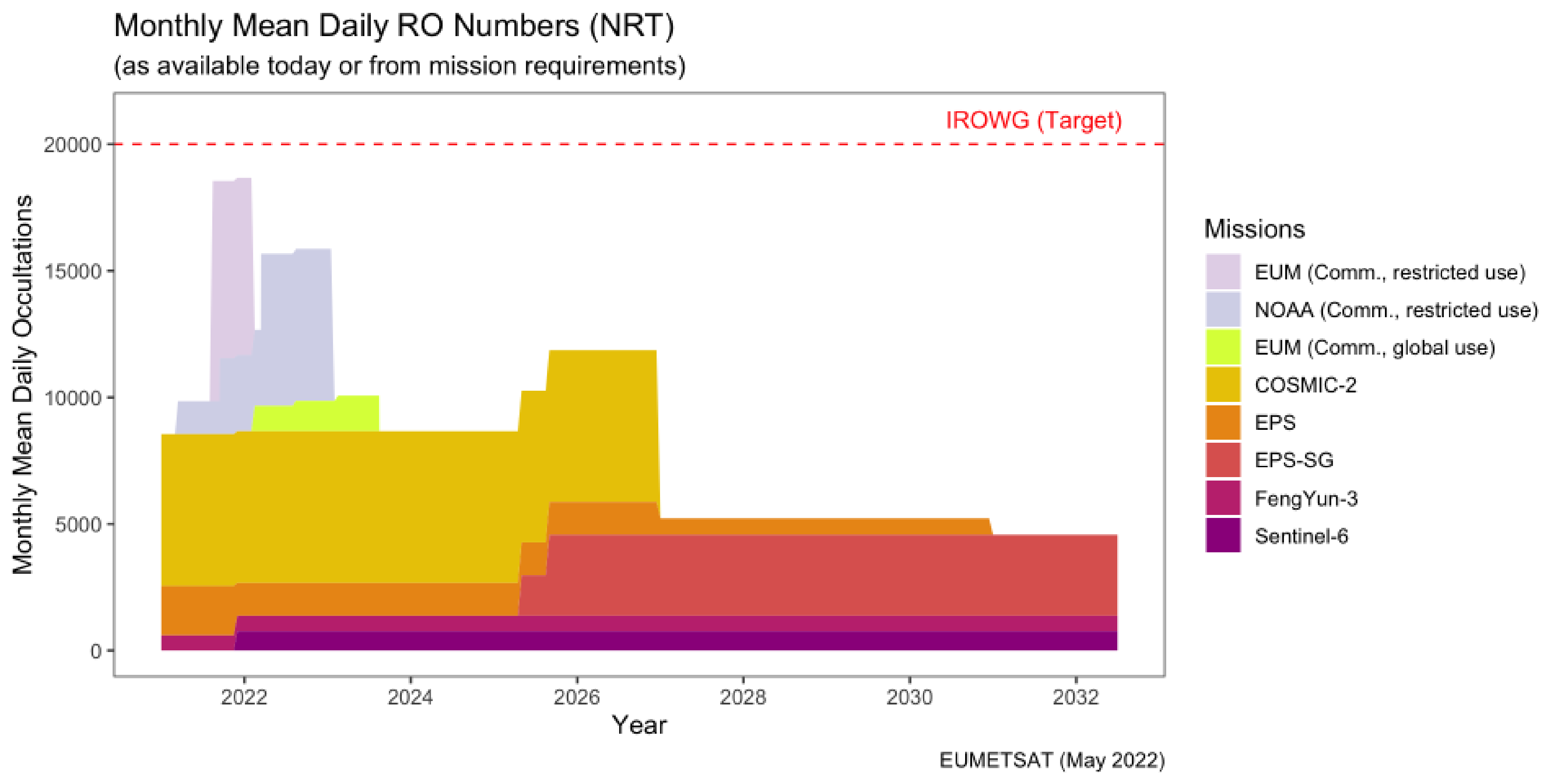

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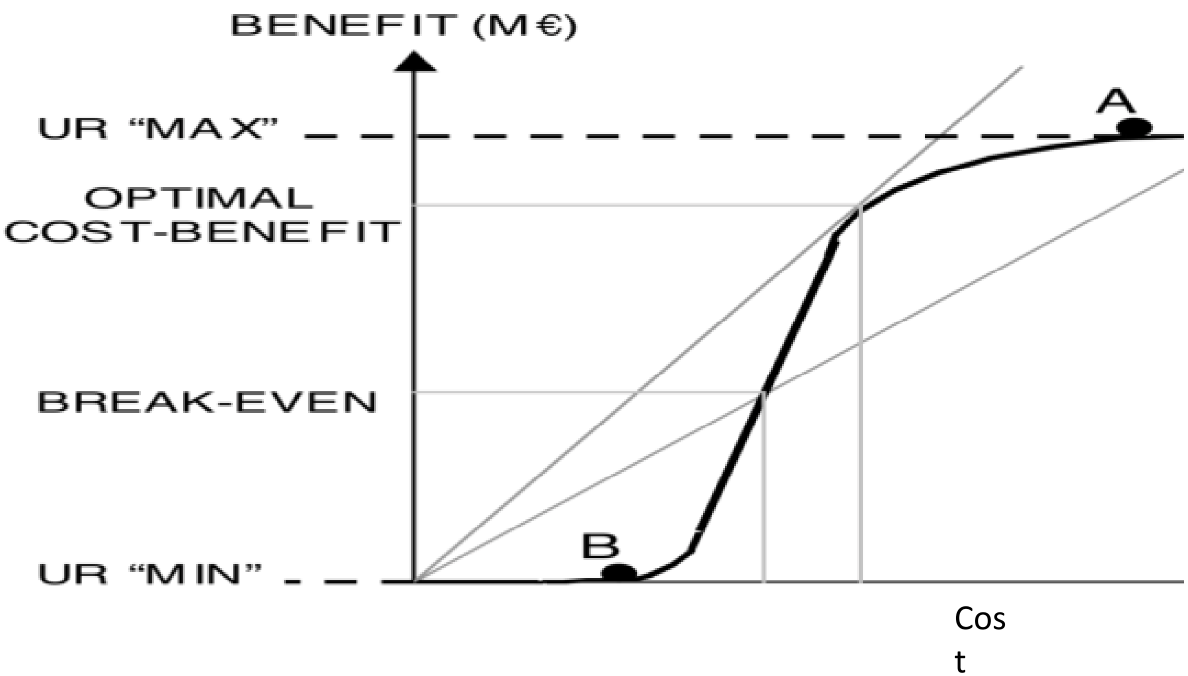

Is it better to spend Δ$ on ΔN RO observations rather than spend the same resources on something else? Should be asked of all observational systems.

WMO's guidance on the rolling-requirements review Fig. 2
https://wmoomm.sharepoint.com/:b:/s/wmocpdb/ETZhhknsfYJAlCBkkiMfftUBPsJpvtw64vNwiLUisgB-Ug?e=PEveDf)

Optimum Number of RO profiles per day

Harnisch et al. (2013) used ensemble of data assimilations (EDA) methods to evaluate the possible saturation of GNSS-RO observation impact on ensemble spread with up to 128,000 additional soundings per day. They found that saturation had not been reached at the maximum level of 128,000

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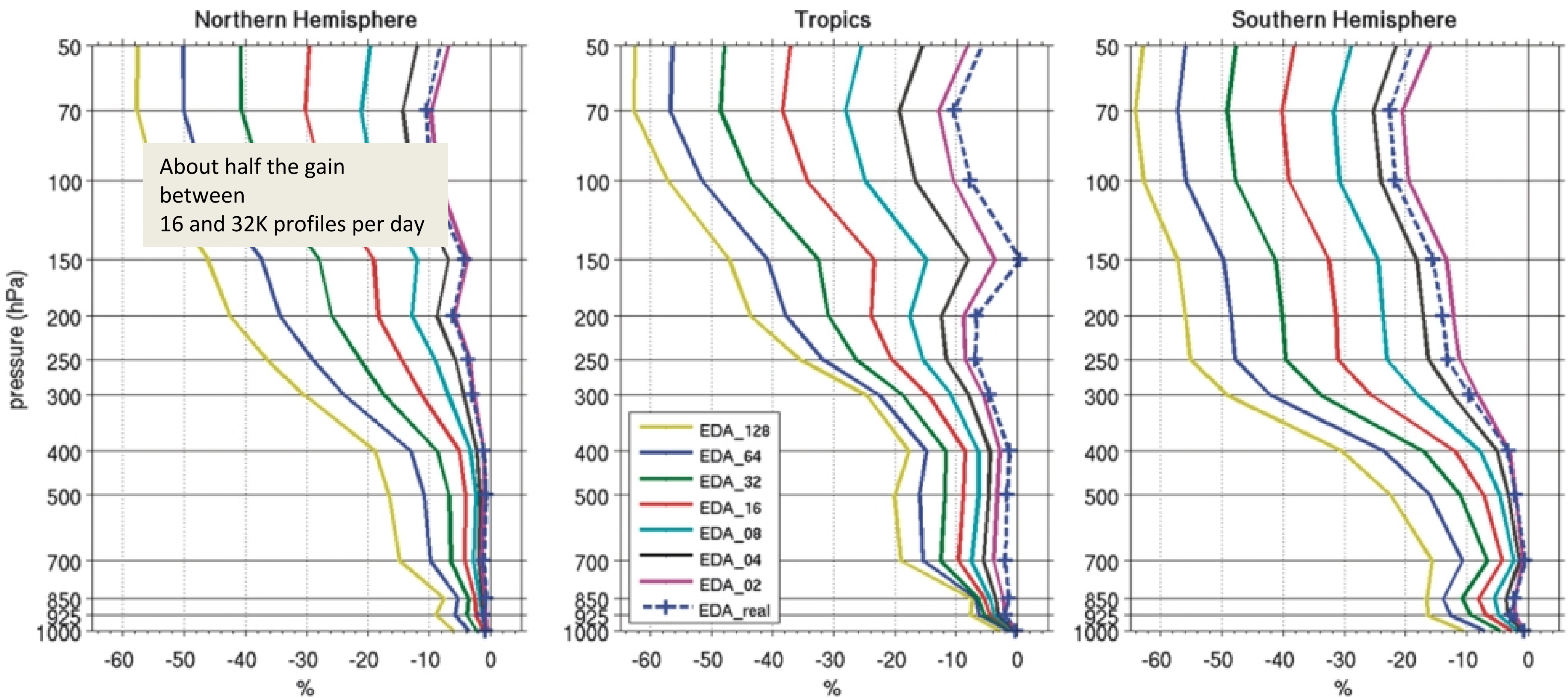
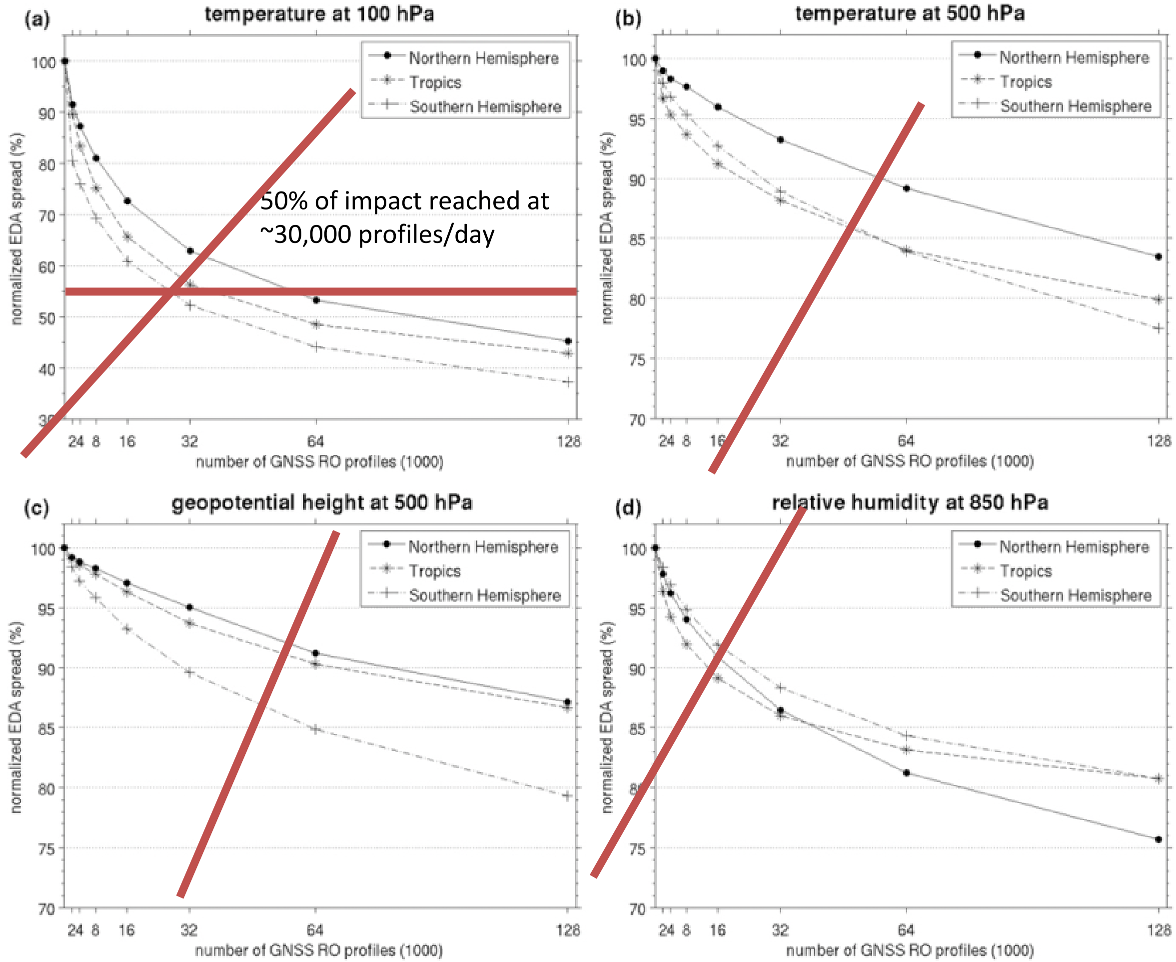


FIG. 4. Normalized difference of EDA spread (%) for temperature at analysis time averaged over the (left) Northern Hemisphere, (middle) tropics, and (right) Southern Hemisphere. Results are for the period 8 Jul–15 Aug 2008.

Harnisch et al.
2013

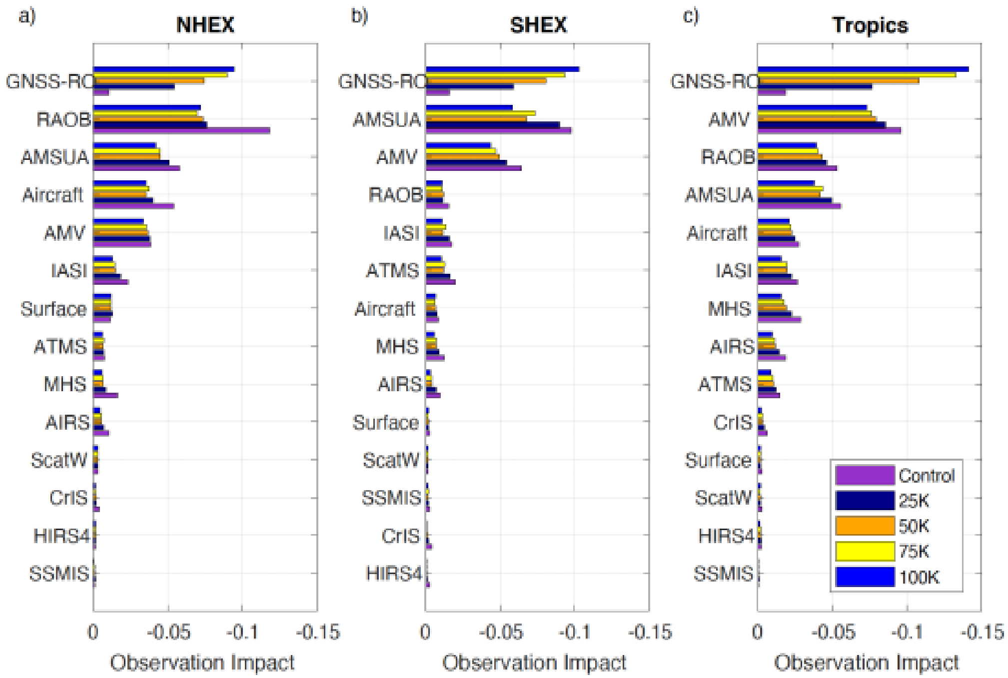
Evidence of inflection in benefit vs cost. Varies between ~15,000 and 50,000 per day depending on variable



Harnisch et al. 2013

FIG. 10. Normalized EDA spread (%) at analysis time as a function of the assimilated number of simulated GNSS RO profiles for (a) temperature at 100 hPa, (b) temperature at 500 hPa, (c) geopotential height at 500 hPa, and (d) relative humidity at 850 hPa. Results are for the period 8 Jul–15 Aug 2008.

Harnisch et al. (2013) results confirmed by Privé et al. 2022



Changes in impact of different observing systems as number of RO profiles increase from 2015 availability. Note rapid growth of RO impact for 1st 25,000 profiles. No saturation at + 100K.

Fig. 22 Privé et al. 2022

FSOI estimates of net observation impact, 24 hour global total wet energy norm, J/kg. a) NH; b) SH; c) Tropics. Control, purple; 25K case, black; 50K case, orange; 75K case, yellow; 100K case, blue

Results from recent studies

Lonitz, K., C. Marquardt, N. Bowler and S. Healy, 2021: Impact Assessment of Commercial GNSS-RO data, ESA Contract Report 15 Nov. 2021.
https://www.ecmwf.int/en/elibrary/20240-final-technical-note-impact-assessment-commercial-gnss-ro-data

Key points

- About 5,000 SPIRE and 4,000 COSMIC-2 profiles/day, plus Metop, KOMPSAT-5
- Large positive impact on nearly all forecast metrics, including winds, for both centers (as expected)
- SPIRE observations, with a lower SNR than COSMIC-2, had a similar positive impact on forecasts
- Different SPIRE satellites appear to have different BA uncertainties.
- SPIRE BA have significantly higher BA uncertainties than Metop above 30 km.
- Actual impact of increasing numbers of RO profiles on forecasts agrees with EDA results, supporting need for increasing RO observations above 10,000 per day at least.

Quality considerations
(Could be different for backbone and commercial data)

Signal to noise ratio (SNR)

- Random errors (uncertainties)---Little evidence of impact
- Bias errors---Higher SNR may produce slightly smaller biases, but this is uncertain
- Penetration depth---Higher SNR produces deeper penetration and more observations in challenging atmospheres (such as those with high water vapor, large horizontal gradients of temperature or water vapor). Confirmed by several independent studies.

The current NOAA requirement for commercial data is 200 V/V. This is probably more than adequate.
EUMETSAT's
Requirement is 100 V/V and this seems adequate)

Other Quality metrics (Examples)

Require a percentage of profiles purchased from vendors to meet certain metrics:

- Penetration depth: At least 80% reach 1 km MSL over tropical oceans
- Latency: At least 50% reach GTS within 15 minutes of observation time; at least 75% within 1 hour
- Uncertainties (relative error STD) in bending angles must meet following minimums between 30°S-30°N

40 km	5%
10-30 km	2%
0-5 km	15%

- Biases in bending angles must not exceed following between 30°S-30°N

5-50 km	1%
0-5 km	8%

(Biases should be with respect to some known and trusted data set, such as ERA5)

Exact metrics and their minimum values should be established by team of experts.

Latency

“Using dedicated satellite data denial experiments, it is shown that the lattermost 3 hr of observations are significantly more influential on the quality of the assimilation and forecasting system than the first 3 hr of data. Furthermore, it is found that the last 3 hr of data even outperforms the 6 hr of data (i.e. twice the number of observations) located in the first half of the window.” (McNally, 2019).

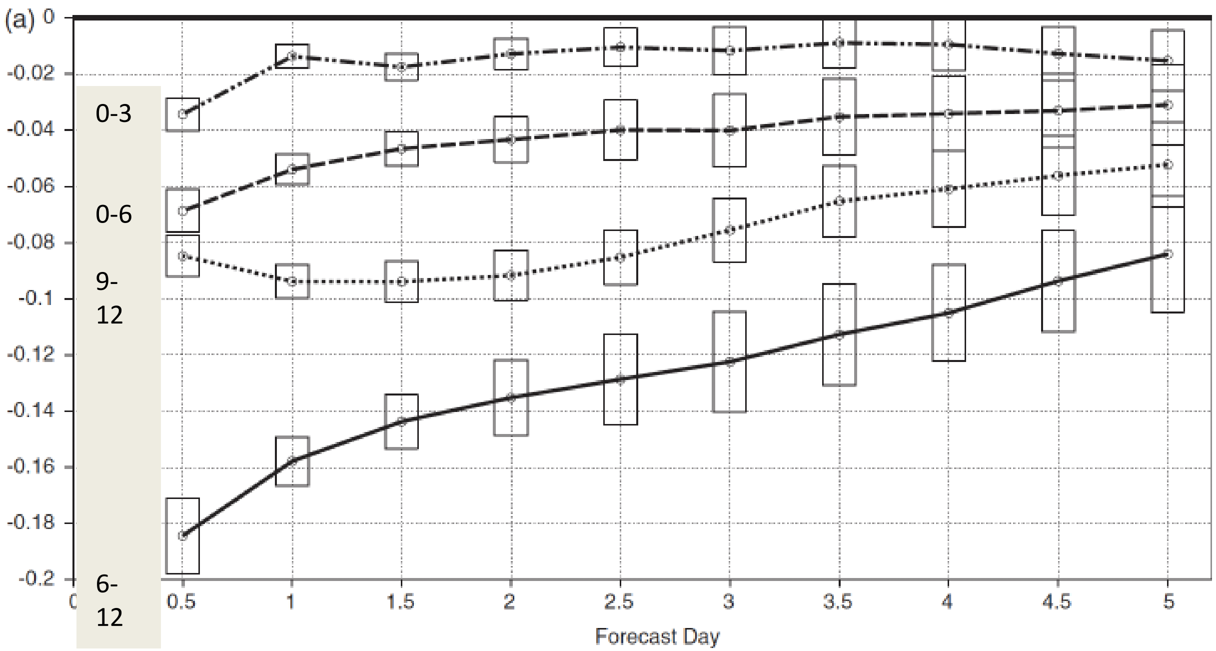


FIGURE 4 The fractional loss of forecast accuracy (in terms of r.m.s. errors for 500 hPa geopotential height, normalized with respect to errors of the control) when satellite data are denied from different times of the assimilation window. Forecast errors are evaluated against the ECMWF operational analyses and statistics are aggregated over the Northern Hemisphere Extratropics (20–70◦N) and (Remove last 6 hr (solid), remove last 3 hr (dotted), remove first 6 hr (dashed), remove first 3 hr (dot-dashed)

Brightness T misfit (STD K) increase with hour in assimilation window

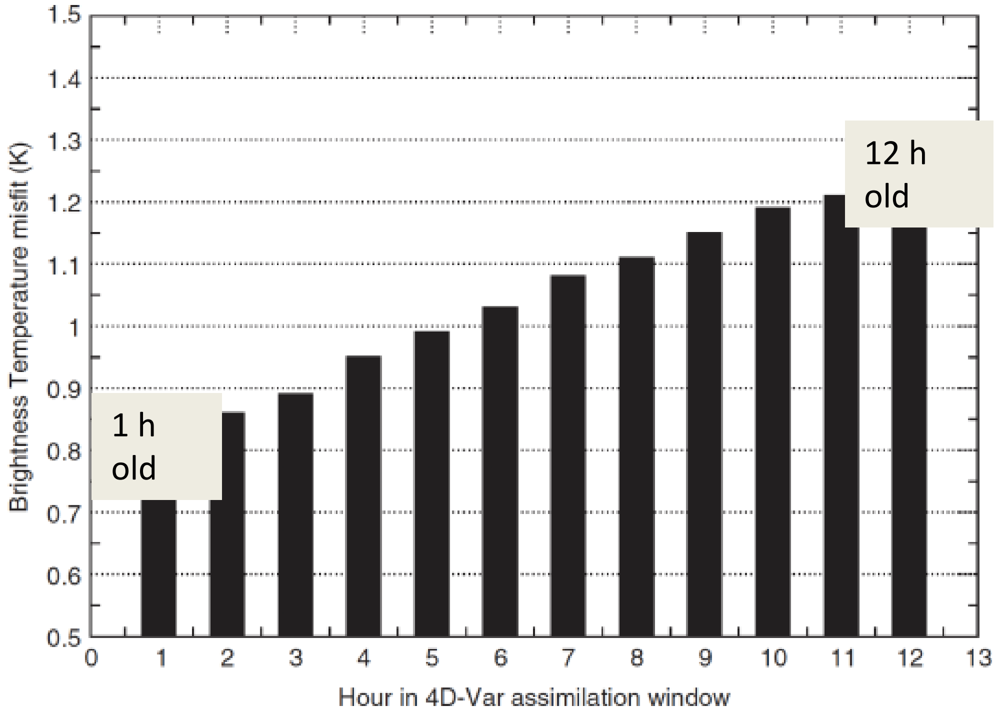


FIGURE 2 Brightness temperature misfits (expressed in terms of standard deviation of departure in K on the vertical axis) between HIMAWARI water vapour radiance observations and values computed from the background model state (using the observation operator) binned hourly (from 1 to 12 along the horizontal axis) according to the observation position in the 0000 UTC and 1200 UTC LWDA assimilation windows. Statistics have been evaluated over a (randomly) selected week (1–7 October 2016)

McNally QJRMS 2019

NOAA definitions of data levels:

Level 0
•Unprocessed raw instrument data as received from the observing platform excluding communication artifacts introduced by ground system.
Level 1a
•Telemetry data that have been extracted but not decommutated from level 0 and formatted into time-sequenced datasets for easier processing. Level 1a formats are NOAA's internal formats and are only used for NOAA processing. They only exist briefly for the purpose of creating the level 1b datasets
Level 1b
•Discrete, instrument-specific datasets derived from level 1a containing unprocessed data at full resolution, time-referenced, and annotated with ancillary information including data quality indicators, calibration coefficients and georeferencing parameters.
Level 2
•Derived geophysical variables at the same resolution and locations as the level 1 source data.
Level 3
•Products mapped on uniform space-time grid scales, usually with some completeness and consistency.
Level 4
•Model output or results from analysis of lower level data e.g.variables derived from multiple measurements.
https://www.ngdc.noaa.gov/wiki/index.php/NOAA_Processing_Levels

LEO Sounding Satellite (Soundersat) Concept Exploration Broad Area Announcement BAA-NOAA-LEO-2019 Oct. 3, 2019

GNSS-RO Soundings Requirements Ranges

Attribute	Lower Bound (Threshold)	Target (Baseline)	Maximum (Objective)	Current Program of Record (COSMIC-2)
SNR (40-80 km altitude range)	800 V/V	1600 V/V	2000 V/V	1600 V/V
Compatibility with Global Navigation Satellite System	GPS	GPS and European Galileo	All GNSS systems available	GPS, GLONASS, and Galileo
Lifetime of the Sensor (in years)	3	5	7	7

Lower bound threshold of 800 V/V too high. More realistic SNR ranges 100, 800, 1600

Participants in May 12 virtual meeting

Rick Anthes (UCAR COSMIC, NOAA SAT)
Ben Ruston (JCSDA)
Lidia Cucurull (NOAA AOML)
Frank Gallagher (NOAA NESDIS)
Sean Healy (ECMWF)

Bill Schreiner (UCAR COSMIC)

Harald Anlauf (DWD)
Patricia Weir (NOAA CDP)
Christian Marquardt (Eumetsat)
Axel von Engeln (Eumetsat)
Daniel Lee (Eumetsat)
Martin McHugh (NOAA Affiliate)
Neill Bowler (Met Office)
Nick Pedatella (UCAR COSMIC)
Ben Ho (NOAA STAR)
Uli Foelsch (Wegener Center, co-Chair IROWG)
Hui Shao (NOAA JCSDA, co-Chair IROWG)

Tony Mannucci (JPL)
Andrea Steiner (Wegener Center)
Terry Onsager (NOAA SWPC)
Eric DeWeaver (NSF AGS Climate Dynamics)
Bill Kuo (UCAR COSMIC)

Jan Weiss (UCAR COSMIC)

John Dreher (US Air Force)

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Privé N.C., R.M. Errico and A. El Akkraoui, 2022: Investigation of the potential saturation of information from Global Navigation Satellite System Radio Occultation observations with an observing system simulation experiment. Mon. Wea. Rev. DOI: https://doi.org/10.1175/MWR-D-21-0230.1

WMO Unified Policy for International Exchange of Earth System Data

“Members shall provide on a free and unrestricted basis the ***core*** data that are necessary for the provision of services in support of the protection of life and property and for the well-being of all nations, at a minimum those data described in Annex 1 to this resolution which are required to monitor and predict seamlessly and accurately weather, climate, water and related environmental conditions.”

Core data include radio occultation. Or at least according to Vision for the WMO Integrated Global Observing System in 2040 Backbone data.

Radio occultation is also an essential-climate-variable (ECV)

WMO Resolution 4.1/1 (Cg-Ext(2021)) approved October 2021

https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/ckeditor/files/Cg-Ext2021-d04-1-WMO-UNIFIED-POLICY-FOR-THE-INTERNATIONAL-approved_en_0.pdf?4pv38FtU6R4fDNtwqOxjBCndLIfntWeR

WMO International Working Group on Radio Occultation (IROWG) Recommendations

- IROWG-7 Denmark 19-25 September 2019.
- At least 20,000 occultations per day, globally distributed and providing good sampling of diurnal cycle (important for NWP, climate, space weather)
- Any commercial data should be purchased with a world license, so the data are available to all.
- Ensure that all information necessary for independent processing centers to process raw level 0 data (phase, amplitude, orbit data, including metadata and associated documentation) to climate products is freely available (applies to government and commercial RO data). This includes long-term archiving.
- Strong support for a "backbone" of agency (government) funded RO missions with long-term commitment.

NWP Sub-group recommendations

- At least 20,000 occultations per day, global coverage and all local times of at least COSMIC -1 quality
- COSMIC-1 quality
  - 80% penetrate below 2 km altitude

Climate Sub-group recommendations

- Ensure continuity and long-term availability of climate quality RO measurements with global coverage over all local times.
- Operational RO missions for continuous global climate observations need to be established and maintained as a backbone to ensure continuity with at least 20,000 occultations per day.

Space Weather Sub-group recommendations

- Acquire high quality near real-time RO space weather measurements, spanning level-0 data to retrieval products, at middle to high latitudes with full local time coverage in standard formats with needed metadata and documentation.
- The quality of these data and products should meet COSMIC-2 requirements
  - Absolute TEC (3 TCU)
  - Relative TEC (0.3 TECU)
  - S4 amplitude scintillation index (0.1)
  - Sigma-phi phase scintillation index (0.1 rad)
- Latency COSMIC-2 requirements of 30 min with goal of 15 min

xxx

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Key issues of relevance to CGMS:

- ...
- .
- Reference to HLPP….

To be considered by CGMS:

- ...
- For endorsement…
- For actioning…