Prepared by IROWG
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CRITICAL IMPACT OF THE POTENTIAL DELAY OR DESCOPING OF THE COSMIC-2/FORMOSAT-7 PROGRAMME

Assessment by the IROWG, September 2013

1. Introduction

The 41st session of the Coordination Group for Meteorological Satellites (CGMS) was informed on the risk that the polar component of the COSMIC-2/FORMOSAT-7 radio-occultation constellation, which is planned to be provided by the United States, might not be funded in due time. Considering the major data gap that this would generate, CGMS requested the IROWG to re-assess the planned availability of radio-occultation data worldwide taking this risk into account, and to review the consequences of this situation at the Third IROWG Workshop on 5-11 September 2013. This note summarizes the conclusions of IROWG on this issue.

In a nutshell, the importance of the polar constellation in the COSMIC-2/FORMOSAT-7 daily coverage is illustrated in Figures 1 and 2, where Figure 1 shows the expected coverage of the equatorial and polar constellation within 24 hours and Figure 2 shows the coverage without the polar component. In the latter case, mid- and high latitudes would not be covered.

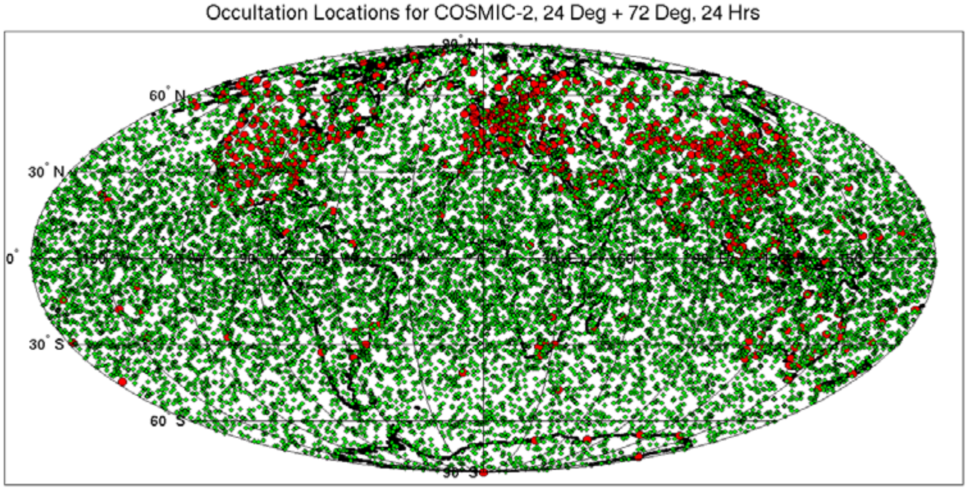

Figure 1 *COSMIC-2/FORMOSAT-7 Equatorial and Polar Component Daily Coverage. Green dots are COSMIC profiles, red dots are daily radiosondes, displayed for comparison.*

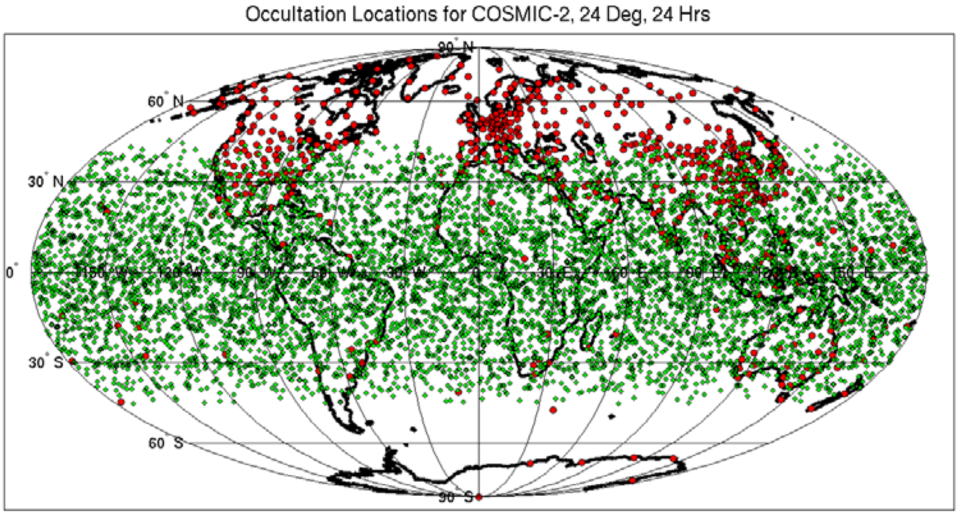

Figure 2 *COSMIC-2/FORMOSAT-7 Daily Coverage without Polar Component. Green dots are COSMIC profiles, red dots are daily radiosondes, displayed for comparison.*

2. Use of radio-occultation

Global Navigation Satellite System (GNSS) radio-occultation (RO) is a limb-sounding technique whereby the signal emitted by a satellite of a GNSS constellation (e.g. GPS, GLONASS, Galileo or BeiDou), is tracked by a receiver on a low Earth orbit satellite. An occultation event occurs when the satellite carrying an RO payload rises or sets behind the Earth. The propagation of the signal between the two satellites being tangent to the Earth is subject to refraction by the atmosphere, this causes a tiny bending angle, which depends on the refractivity of the atmosphere around the tangent point. The bending angle is calculated from a precise measurement of the frequency and phase shift of the received signal. In recording the bending angle during an occultation event a vertical profile of refractivity can be reconstructed, from which a vertical profile of temperature and humidity of the atmosphere can be derived, as well as the electron content.

Since its early demonstration in the nineties, GNSS RO has proved to be a very powerful observation technique providing high quality data, mainly for Numerical Weather Prediction (NWP), climate monitoring, and ionosphere monitoring. Nowadays, most of the operational RO data are provided by either the COSMIC-1/FORMOSAT-3 constellation or the Metop-A and -B satellites, supplemented by a few opportunity missions (GRACE, TerraSAR-X). Other RO missions have been launched but are not providing usable data. As the COSMIC-1/FORMOSAT-3 constellation is aging and its performance degrading, its follow-on, COSMIC-2/FORMOSAT-7, is expected to be the cornerstone of future RO observations. An updated review and assessment of the available and planned RO capabilities has been completed by the IROWG[1].

Three major applications are relying on GNSS-RO: Numerical Weather Prediction (NWP), climate monitoring and ionosphere monitoring. The potential impact of a delayed or de-scoped

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[1] Status of the Global Observing System for Radio Occultation (Update 2013), IROWG/DOC/2013/02, available at http://www.irowg.org/workshops.html

implementation of the polar component of COSMIC-2/FORMOSAT-7 on these applications is summarized below.

3. Importance of radio-occultation for Numerical Weather Prediction

GNSS-RO measurements are now considered a critical component of the Global Observing System used for NWP, because they complement the information provided by satellite radiances. This is because GNSS-RO measurements have excellent vertical resolution, and they can be assimilated without bias correction.

All the major NWP centres have reported a positive impact of GNSS-RO in their systems. For example, see Figure 3 for an example of impacts in the NOAA/NCEP system. The Fifth WMO Workshop on Impact of the Various Observing Systems (Sedona, May 2012) [2] has established that GNSS-RO is now among the top-five data sources for NWP (Figure 4). In addition, calculations of the Forecast Error Contribution (FEC) at multiple NWP centers have shown that GNSS-RO have a larger impact per observation than any other satellite measurement.

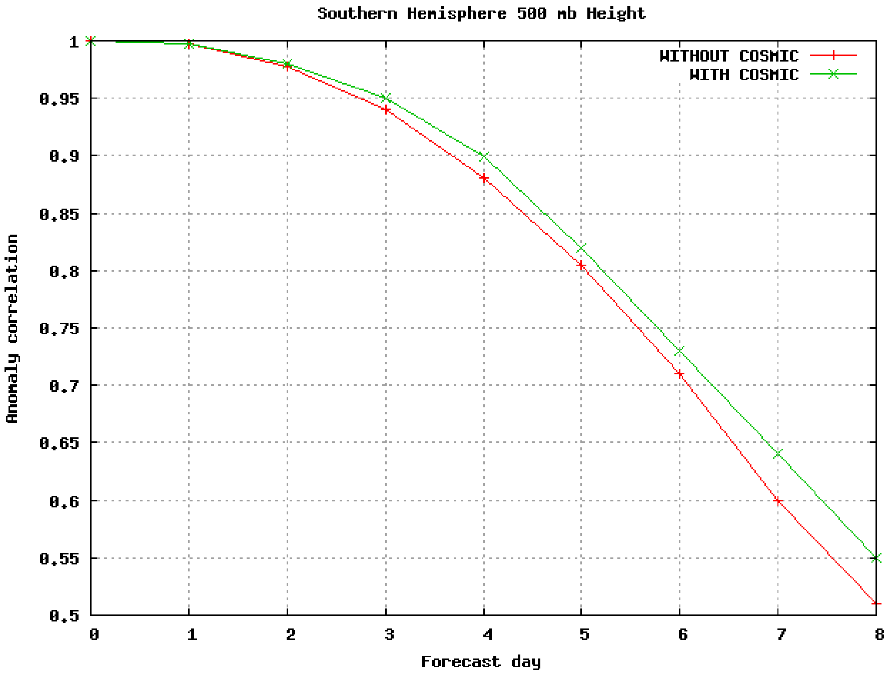

Figure 3 *Anomaly correlation score as a function of the forecast length for the geopotential heights at 500 hPa for the Southern Hemisphere (20S-80S) as a result of assimilating COSMIC-1/FORMOSAT-3 data. Loss of COSMIC-2/FORMOSAT-7 polar constellation would allow a gap in this heritage data – and hence a loss of this forecast skill. These results are filtered to represent the structures with total wave number 1-20. The experiments make use of the NOAA/NCEP's global data assimilation system and cover the period of April 2008.*

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[2] Final Report of the Fifth WMO Workshop on the Impact of Various Observing Systems on Numerical Weather Prediction, Sedona, AZ, USA, 22-25 May 2012, WMO, WIGOS Technical Report No. 2012 – 1 (http://www.wmo.int/pages/prog/www/OSY/Meetings/NWP5_Sedona2012/Final_Report.pdf)

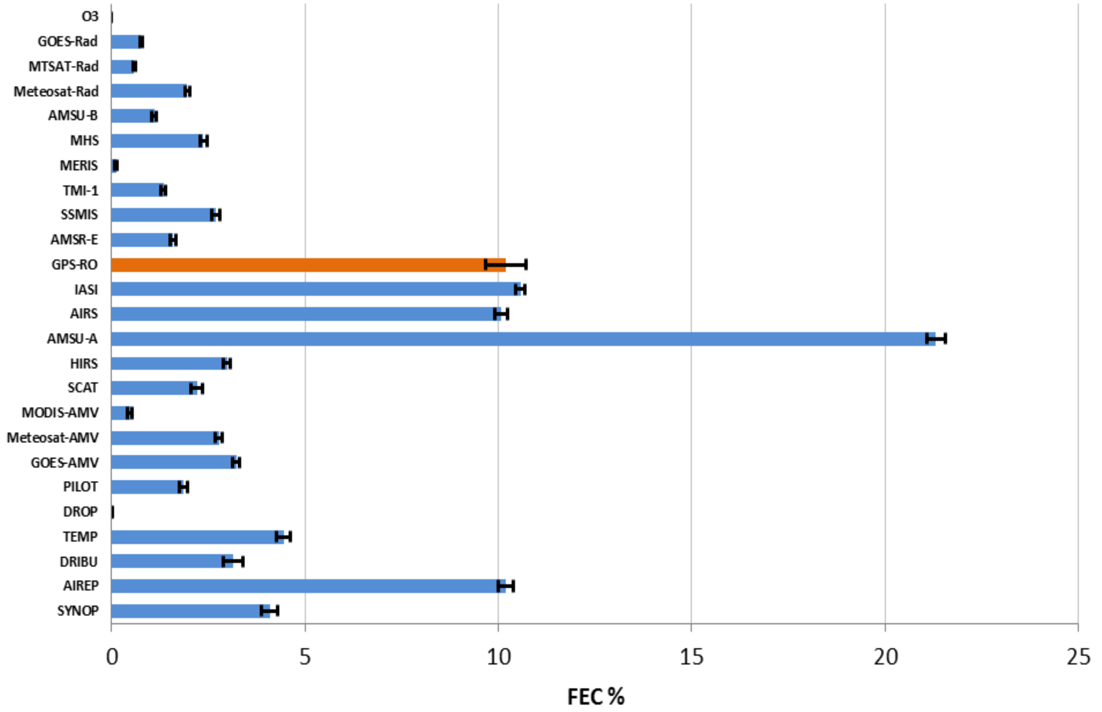

Figure 4 *The Forecast Error Contribution (FEC) for the operational ECMWF system in June, 2011. This shows percentage contribution of each observing system to the reduction of 24 hour forecast errors, for a weighted sum of surface pressure, wind and temperature errors. The error bars denote the statistical uncertainty in the computation.*

Consequently, there is now concern within the NWP community that this substantial impact is under threat because the GNSS-RO data volumes are currently declining as the COSMIC-1/FORMOSAT-3 system is approaching the end of its lifetime.

GNSS-RO has become a critical part of the global observing systems, both directly as a source of vertically resolved temperature and humidity information, and indirectly through the absolute anchoring of the temperature analysis for the high troposphere and the stratosphere. The anchoring is very effective in determining the bias correction for radiances and other observation types that require calibration. It is also important when developing and using data assimilation systems which estimate “model error” as part of the assimilation process.

When comparing the current NWP forecast impact of GNSS-RO observations with that of conventional (ATOVS) and hyperspectral satellite nadir sounders at ECMWF, it is found that GNSS-RO data have a smaller impact than either class of nadir sounders. However, even with the current GNSS-RO numbers, they are still able to account for a considerable fraction (30% to 70%) of the global forecast error reduction afforded by the use of the full observing system, over a system which only uses conventional observations. Furthermore, when the forecast verification is performed against radiosonde observations, GNSS-RO is found to be the most valuable satellite observing system in the lower stratosphere. This is considered remarkable in view of the relative sparseness of the GNSS-RO spatial and temporal coverage, and an indication of the potential improvements that a denser GNSS-RO observing network would be able to provide.

In the Implementation Plan for Evolution of Global Observing Systems[3] WMO has thus set an objective to acquire at least 10,000 occultations/day, and called for studies to further refine this figure. The latest simulations show that the impact would be greater with more observations, and suggested revising the objective to 16,000 occultation/ day, with the additional requirement that these observations be regularly distributed around the globe.[4]

The assessment of GNSS-RO capabilities by IROWG[5] shows that this objective can only be reached with the full implementation of COSMIC-2/FORMOSAT-7 (up to 12,000 occultations/day) supplemented by the operational RO sensors of Metop (1,300 for 2 satellites) and FY-3 (up to 1,400 for 2 satellites) plus a few opportunity missions. If, however, the polar component of COSMIC-2/FORMOSAT-7 was not implemented as planned the total number of occultations/day would fall well below 10,000. Moreover, there would be a poor sampling of the mid to high latitudes.

Severe Weather Impacts

The GNSS-RO data from the polar component of COSMIC-2/FORMOSAT-7 is also extremely valuable for the prediction and track forecasting of significant weather systems such as extratropical cyclones, polar lows, frontal systems and their associated severe weathers, and the extratropical transformation of tropical cyclones. It should also be noted that the polar component of COSMIC-2/FORMOSAT-7 would add considerable GNSS-RO soundings over the tropics, which is crucial for prediction the genesis, track, intensity and precipitation associated with tropical cyclones.

4. Importance of radio-occultation for climate monitoring

GNSS-RO offer a unique opportunity for climate studies and for “anchoring” analysis, re-analysis, and climate model runs since they:

- require no calibration (they are essentially time measurements) and offer thus long-term stability;
- have by nature a high vertical resolution, and, depending on the orbits, a global distribution, and an appropriate diurnal sampling;
- have high accuracy and precision;
- are minimally affected by clouds and precipitation.

The first characteristic above allows for example to combine different sensors to generate a long term data set without requiring inter-calibration. It is however required to process the different sensors in a consistent manner to avoid the introduction of processing differences (called

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[3] Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP), WMO Integrated Global Observing System, Technical Report No. 2013 - 4

[4] F. Harnisch, S. B. Healy, P. Bauer, and S. J. English, Scaling of GNSS radio occultation impact with observation number using an ensemble of data assimilations, AMS Monthly Weather Review 2013, doi: http://dx.doi.org/10.1175/MWR-D-13-00098.1

[5] Status of the Global Observing System for Radio Occultation (Update 2013), IROWG/DOC/2013/02, available at http://www.irowg.org/workshops.html

Structural Uncertainty – SU [6]) since every processing center uses slightly different processing assumptions, e.g. with respect to quality control (See Figure 5).

RO offers continuous data from 2001 onwards and first atmosphere and climate studies have already been performed; results have been published in peer-review journals. The initial focus was on the CHAMP mission, which provided data from 2001 to 2008. Many more observations have been provided by COSMIC, from April 2006 onwards. RO instruments offer products at the various processing levels (1) bending angles, (2) refractivity, (3) temperature and water vapour profiles. Recent studies showed that although the derived variables including bending angle, refractivity, pressure, geopotential height, and temperature are not yet readily traceable to SI units of time, the high precision nature of the raw RO observables is preserved in the inversion chain.

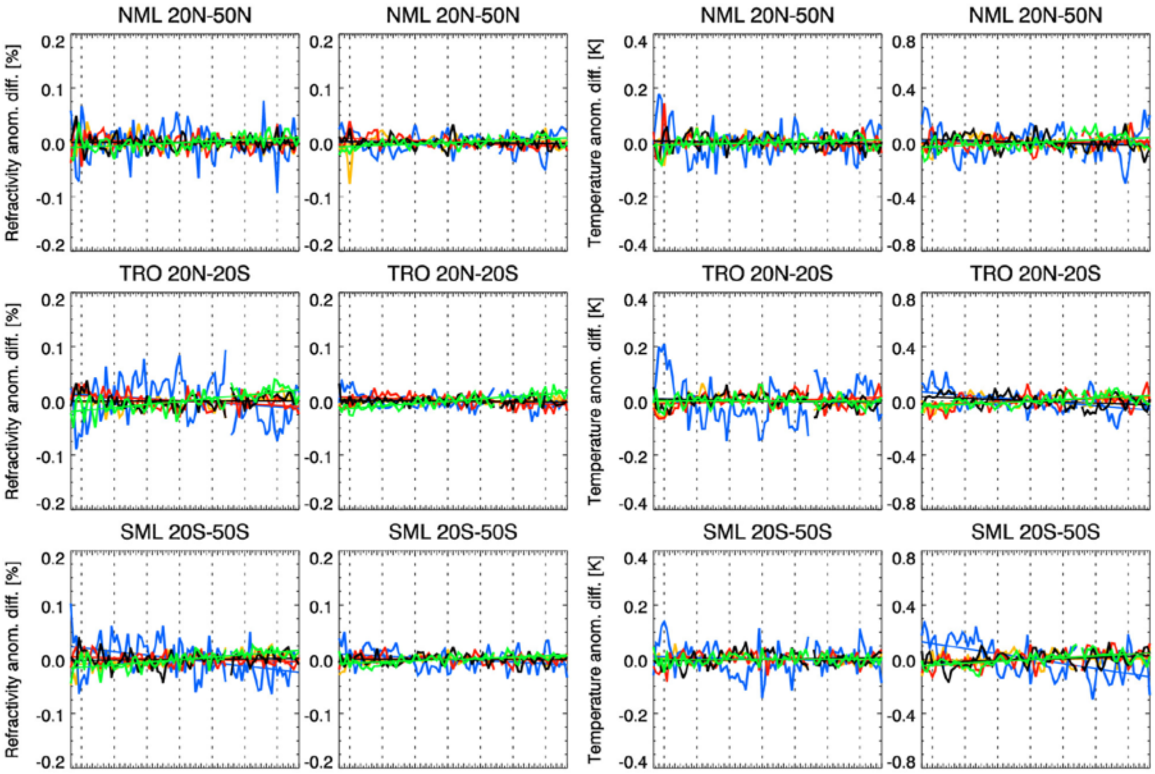

Figure 5 *Consistency in time series of refractivity (left) and temperature (right) from five RO processing centers, differences and trends shown for the upper troposphere (left subpanels) and the lower stratosphere (right subpanels) for northern mid-latitudes, tropics and southern mid-latitudes (top to bottom)* [7].

RO does not only provide information on temperature and water vapour, but it also acts as an "anchor" for drifting radiance instruments. More recently, RO data have also been used to correct other observation types, e.g., radio-sondes which show different bias structures depending on the

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[6] Ho, S.-P et al. (2012), Reproducibility of GPS radio occultation data for climate monitoring: Profile-to-profile inter-comparison of CHAMP climate records 2002 to 2008 from six data centers, J. Geophys. Res., 117, D18111, doi:10.1029/2012JD017665

[7] Steiner et al. (2013), Quantification of structural uncertainty in climate data records from GPS radio occultation, Atmos. Chem. Phys., 13, 1469-1484, doi:10.5194/acp-13-1469-2013.

manufacturer of the sonde, RO can be a valuable comparison and validation record for the GCOS Reference Upper Air Network (GRUAN). The "anchoring" feature and the very different measurement principle is also an excellent benefit for validation of other satellite observations such as radiance measurements, and could also be beneficial for constraining climate models. The high vertical resolution of RO also allows it to "distinguish" between stratospheric cooling and tropospheric warming, unlike e.g., the MSU4/AMSU-9 channel which are used for stratospheric trend detection, but the channel straddles the tropopause in the tropics, essentially averaging out the stratospheric cooling and tropospheric warming.

Although bending angles or refractivity are not "standard" ECVs (Essential Climate Variables), analysis of this data - as well as temperature, pressure, geopotential height profiles derived from RO observations - have shown high potential for climate monitoring. In particular, different variables can be complementary, e.g. refractivity can be unaffected if temperature and pressure changes compensate each other, but further processing to temperature allows separating the two. Geopotential height of pressure levels and the ECV upper-air temperature are well suited for producing RO-based fundamental climate data records (FCDR) in the upper troposphere and lower stratosphere region, including trend detection of tropopause heights.

GNSS RO has been demonstrated to be a very important data record for the global climate observing system providing essential climate variables of benchmark quality. It is of highest importance to assure the continuity of RO measurements with global coverage and coverage of all local times. A monthly mean record with a horizontal resolution of about 300 km and an adequate resolution of the diurnal cycle requires about 20,000 occultations per day. Since the first satellites of the planned COSMIC-2 mission will be in low inclination orbits and will cover low latitudes only, there is an urgent need for the second COSMIC-2 constellation, in high inclination orbits, to provide coverage of mid- and high latitudes at all local times.

5. Importance of radio-occultation for ionosphere monitoring

The ionosphere influences the radio wave propagation through reflection, refraction, absorption, and scattering. The accurate specification of the ionosphere, particularly the electron density, is thus necessary to support a wide range of operational services such as fixed or mobile radio-communications, the operation of low Earth orbit (LEO) satellites flying at ionospheric altitudes, ground radar systems, or GNSS. The GNSS itself is used worldwide e.g. for precise location of vehicles and persons on Earth, ships, or aircrafts; for satellite positioning, advanced farming, geological exploration, and as time signal for automated financial operations.

Electron distribution in the ionosphere is caused by a number of processes, including ionization by solar extreme ultraviolet (EUV) radiation and particle precipitation, chemical reactions including charge exchange and reactions with the neutral gas, transport by neutral winds and ion drifts, and ambipolar diffusion. The ionosphere becomes disturbed as it reacts to certain types of activity such as solar flare, geomagnetic storm, and planetary wave and tide from the lower atmosphere.

Total Electron Content (TEC) observations are supplied chiefly by ground-based and space-based measurements of the signals from GNSS satellites, supplemented by some ionosonde observations[8]. GNSS-RO data provide valuable ionospheric information for sopace weather specification and forecasting. The number of observations per day depends on the number of GNSS-RO receivers in orbit that are designed and configured to scan the whole ionosphere altitude range. The data latency, which is critical for ionosphere nowcasting, depends on the number of ground stations implemented around the world.

Table 1 in Annex lists the current and planned missions with a RO capability to scan the ionosphere. Apart from experimental missions which are not providing any data regularly and current opportunity missions with limited data amount, the RO observations of the ionosphere entirely rely today on the aging COSMIC-1/FORMOSAT-3 constellation. In the future, a contribution should be available from GNOS sensors of the Chinese FY-3 programme as well, however this new sensor has not yet been demonstrated and the experience shows that many years are generally necessary until a fully operational level can be reached. Moreover, the number of occultations per day that can be received by GNOS is one order of magnitude below that of one COSMIC-2/FORMOSAT-7 constellation. COSMIC-2/FORMOSAT-7 is therefore expected to be by far the main operational source of RO data in the years to come for monitoring the ionosphere (See Figure 1).

Both components of COSMIC-2/FORMOSAT-7 are important: the equatorial one (6 spacecraft on 24° inclination orbits) and the polar (6 spacecraft on 72° inclined orbits. The observing system simulations reported by Yue et al.[9] show that when radio-occultation observations from only the six 24° satellites are assimilated, there is significant error in the specification of the ionosphere over the middle and the high latitude area due to the lack of sampling at these latitudes. The error is particularly larger in the southern American area, due to the equatorial ionization anomaly (EIA) there. When both the 24° and 72° constellations provide observations simultaneously, they complement each other well and globally optimize the ionosphere specification (see Figure 6).

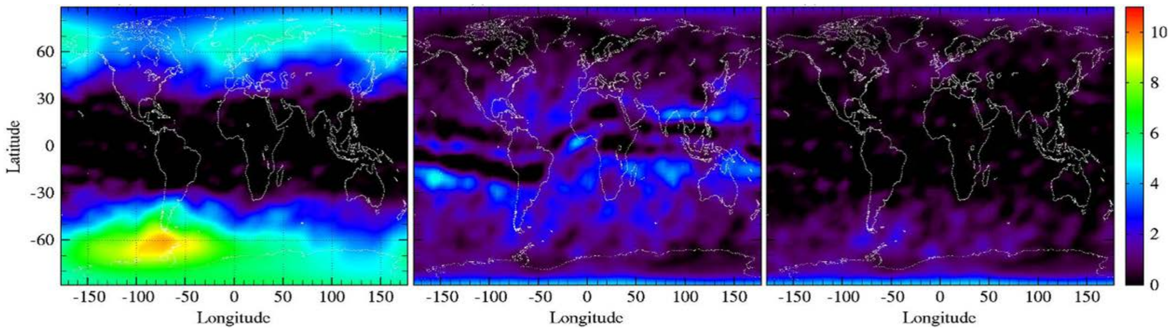

Figure 6 *Longitude and latitude variations of the daily average error (in tecu) of the vertical TEC for the following cases: ROs of six 24° inclination satellites (left), ROs of six 72° inclination satellites (center), and ROs of six 24° and six 72° satellites (right).*

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[8] Statement of Guidance for Space Weather Observations, WMO, 2012, http://www.wmo.int/pages/prog/www/OSY/SOG/SoG-SW.doc

[9] Yue, X., Schreiner, W., Kuo, Y.-H., Braun, J., Lin, Y.-C., and Wan, W., 2013, Observing System Simulation Experiment Study on Imaging the Ionosphere by Assimilating Observations From Ground GNSS, LEO-Based Radio Occultation and Ocean Reflection, and Cross Link, IEEE Transactions on Geoscience and Remote Sensing. DOI 10.1109/TGRS.2013.2275753.

The impact of both constellations in specifying the ionosphere can be quantified by the global average error of vertical TEC for assimilating only 24°, only 72°, and both the 24° and 72° satellites, respectively. In this simulation, when observations from only six 24° satellites are used, the global mean error is ~2.6 tecu, while it is ~1.3 tecu for 72° inclination satellites. When both are assimilated simultaneously, the error will be reduced to ~0.5 tecu (see Figure 7).

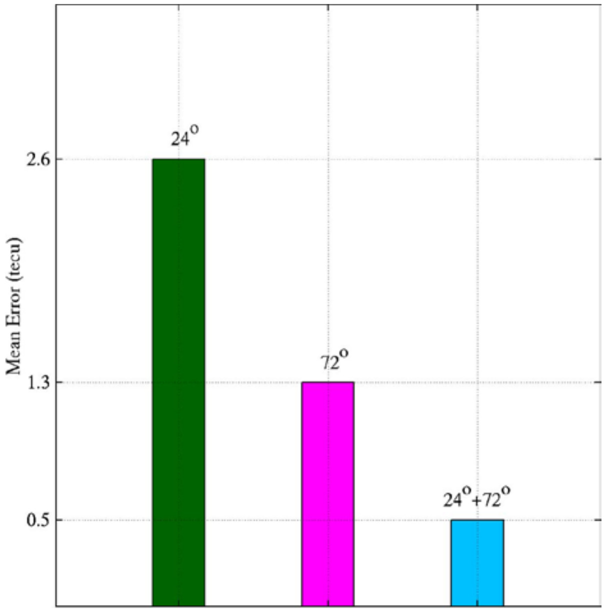

Figure 7 *Global mean error in terms of vertical TEC (tecu) for only assimilating ROs from 24°, 72°, and 24° + 72° satellites, respectively.*

Bearing in mind that COSMIC-2/FORMOSAT-7 is expected to be by far the main operational radio-occultation system observing the ionosphere beyond the current COSMIC-1/FORMOSAT-3, which has already exceeded its lifetime, the implementation of the high-inclination (72°) constellation of the COSMIC-2/FORMOSAT-7 programme is of utmost importance for ionospheric monitoring.

6. Conclusions

COSMIC-2/FORMOSAT-7 is expected to be a cornerstone of future global observing systems for weather, climate and ionospheric activity. It is severely needed to replace the aging COSMIC-1/FORMOSAT-3, which has already exceeded its lifetime, and to raise the performance of the global RO system to the level required for NWP in particular. Within the COSMIC-2/FORMOSAT-7 programme, the implementation of the high-inclination (72°) constellation is of utmost importance, not only because it will provide half of the data but also because of the evenly distributed coverage it will provide, thus enhancing the value of the whole system.

ANNEX TO SECTION 5

TABLE 1: Summary of the current and planned radio-occultation missions having the capability to scan above 100 km with hyperlinks to the relevant OSCAR pages .

Sensor	Satellite mission	Orbit	current	2014		2016		2018		2020		2022		2024		2026		2028		2030
Operational missions or planned missions building on a solid technical heritage																				
IGOR	COSMIC (6 sats)	72 °	X	X																	
Tri-G	Cosmic-2 (1-6)	24 °				X	X	X	X	X	X	X	X								
Tri-G	Cosmic-2 (7-12)	72 °						X	X	X	X	X	X	X	X						
Tri-G	JASON-CS-A	66°							X	X	X	X	X	X	X	X					
Tri-G	JASON-CS-B	66°												X	X	X	X	X	X	X
Planned operational missions (with continuity) with new instrument and processing still to be demonstrated.																				
GNOS	FY-3C	10:00 desc		X	X	X															
GNOS	FY-3D	14:00 asc			X	X	X	X													
GNOS	FY-3E	06:00 desc				X	X	X	X												
GNOS	FY-3F	14:00 asc						X	X	X	X										
GNOS	FY-3G	06:00 desc								X	X	X	X								
Opportunity missions – limited data amount																				
IGOR	TanDEM-X	06:00 desc	X	X	X																
IGOR	TerraSAR-X	06:00 desc	X																		
IGOR	TerraSAR-X2	06:00 desc			X	X	X	X	X	X	X	X									
Other missions: current missions with no regular data or potential missions still to be confirmed and demonstrated.																				
CORISS	C/NOFS	13 °	X																		
ROSA	Megha-Tropiques	20 °	X	X	X	X															
AOPOD	KOMPSAT-5	06:00 asc	X	X	X	X	X	X													
ROSA	SAC-D	06:00 desc	X	X	X	X															
ROSA	OceanSat-2	12:00 desc	X	X																	
Radiomet	Meteor-MP N1	15:30 asc					X	X	X	X	X	X									
Radiomet	Meteor-MP N2	09:30 desc						X	X	X	X	X	X								
Radiomet	Meteor-M N3	12:00 desc					X	X	X	X	X	X									