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The Second GPS Radio Occultation Data Users Workshop: Summary and Aftermath

NOAA-WP-15 describes the state of readiness of the operational and research communities that will use Global Positioning System Radio Occultation (GPSRO) observations for numerical weather prediction, climate monitoring, and space weather analysis provided by real-time platforms such has COSMIC and METOP/GRAS. A summary of the Second GPSRO Data Users is provided, and progress subsequently made is described. The continuity of full data availability after the COSMIC demonstration period ends in April 2008 is identified as the most significant outstanding issue.

The Second GPS Radio Occultation Data Users Workshop: Summary and Aftermath

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1. Introduction

With the launches of FORMOSAT-3/COSMIC and METOP/GRAS scheduled for the Spring and Summer of 2006, the GPS radio occultation (RO) technique for sounding the atmosphere and ionosphere has arrived at the threshold separating research from real-time, operational status. In recognition of the imminent transition from research to operations, the NOAA/NESDIS Office of Research and Applications (ORA) and the University Corporation for Atmospheric Research (UCAR) jointly sponsored the Second GPSRO Data Users Workshop, which was hosted by the National Conference Center in Lansdowne, VA, August 22-24, 2005. J. Yoe of NOAA and B. Kuo of UCAR organized and co-chaired the workshop.

This document provides a brief overview of the Workshop and summarizes the extent to which the users of GPSRO observations for several applications are prepared to take advantage of the operational or quasi-operational data streams becoming available. It describes the prospects for new and improved GPSRO hardware, retrieval methodologies and applications, and techniques for using in numerical environmental models and analyses ranging from weather and climate to space weather. It also provides a list of the recommendations that came out of the Workshop. Finally, it reviews the events that have ensued since the Workshop, and re-assesses the priorities for the data user community based on these events.

2. Summary of the Workshop

The First GPSRO Data Users Workshop (October 2003) in Camp Springs, MD, was hosted by NESDIS/ORA and organized by J. Yoe. This initial meeting was relatively small, with about 25 participants, almost all of whom were scientists and engineers focused on the prospects and difficulties associated with the use of neutral atmospheric soundings for NWP and climate investigations. This workshop helped define a number of the key issues that guided many of the efforts reported on more recently at Lansdowne.

The 2005 Lansdowne Workshop included almost 60 participants, including international scientists engineers representing research and operational government agencies, industry, and academia, and government program managers from the United States and Taiwan. The format consisted primarily of invited and contributed oral presentations made to the entire audience. These talks were grouped in the following categories:

- GPS RO Mission Status Reports
- Recent Advances in RO Techniques
- Retrievals of Geophysical Parameters

- Data Management and Quality Control
- Data Assimilation and Impact Studies
- Climate Applications
- Space Weather Applications

Time was provided at the conclusion of each session for a group discussion, which helped define the state of the art and the outstanding issues associated with each of these areas. In addition to the oral presentations, small poster session consisting of ~ 10 student papers was held. The progress made and issues identified for each category are summarized below.

Due to limitations of space and time, no attempt is made to provide distillations of the individual presentations. However, the Workshop Agenda and the complete set of ~ 35 oral presentations may be obtained by following the world wide web link:

http://www.cosmic.ucar.edu/gpsro2/agenda.html

2.1 Mission Status Reports

Reports on the mission readiness for upcoming RO missions were encouraging. Assembly of the COSMIC receivers and satellites from kits was almost complete, and preparations for integration of the six packages on the single launch vehicle were on schedule with no major difficulties foreseen. Communications links to the downlink and ancillary groundstation facilities were in order. The COSMIC Data Archive and Analysis Center (CDAAC) successfully processed, formatted, and distributed (to NOAA) CHAMP data to test the procedure and communications that will be used to support the COSMIC product flow. Likewise, reports on the sensor hardware, spacecraft integration, communications, and preparation of the Satellite Applications Facility (SAF) for GRAS indicated no show-stoppers, with launch of METOP-1 expected in mid-2006. The performance reports of RO sensors currently on orbit, in particular CHAMP, were also positive, with strong prospects for continued operation and data availability for the immediate future.

Of equal interest but less certainty were the prospects for continued COSMIC operation past 2008, and for a follow on constellation mission to replace COSMIC after the 5-year satellite life expectancy has been exceeded. Presentations on the future of GPSRO pointed to improved instrumentation that will exploit GALILEO and possibly GLONASS as well as GPS were made, and predictions of increased user dependency on RO data were made

2.2 Advances in RO Techniques

Considerable attention was devoted to the potential of the use of open-loop (OL) tracking instead of phase-locked loop (PLL) tracking of the GPS signal by the receivers during occultation. The use of OL is predicted to result in better penetration of the lower troposphere, including the capability to acquire rising occultation events, and to reduce the negative refractivity bias in the lower troposphere relative to that

observed using PLL. The trade-off cost may be seen in the larger analysis-observation values (standard deviations) observed for OL.

2.3 Retrievals

Despite the primary focus on the assimilation of intermediate-level data products (bending angle and refractivity) for NWP, there is also considerable user community interest in higher-order derived products. Of particular emphasis are temperature profiles, which can be derived from refractivity for the upper troposphere and lower stratosphere with superior vertical resolution and accuracy comparable to the best satellite and conventional (i.e. radiosonde) measurements. While it is possible to use GPSRO refractivity and ancillary temperature information to derive humidity profiles for the troposphere, caution must be exercised due to the short horizontal scales that often characterize moisture gradients, compared to the effective along-track resolution of RO limb soundings. In this context, perhaps the most promising prospect is the use of simultaneous application pf GPSRO and microwave and IR sounder observations to produce combined retrievals of temperature and humidity.

2.4 Data Management and Quality Control

Data management, or more precisely, data access and distribution, rose to the forefront of GPSRO-related issues. The need for data to be delivered to operational NWP centers in BUFR format had been emphasized at the 2003 Data Users Workshop and at the GRAS SAF Users Workshop in Denmark in 2003. Subsequently the UKMO led an international effort to define BUFR specifications for RO data and to have it sanctioned by the WMO. Both the GRAS SAF and the CDAAC were producing and distributing synthetic or proxy BUFR data, and operational centers including the JCSDA and NCEP were able to decode and ingest the data. Wider distribution of the BUFR'ed data, particularly COSMIC, was a question not completely resolved. Given the small volume of COSMIC data (compared to conventional satellite observations), distribution by NESDIS/OSDPD posed no technical challenge. However, NESDIS would not deliver COSMIC data via the GTS or any other mechanism without the consent of the Taiwanese National Space Program Office, which bore so much of the mission costs. Likewise, the UCAR CDAAC would not distribute the raw COSMIC observations without permissions in place. Clarification of the approval process for data dissemination was identified as an issue to be pursued vigorously as COSMIC moved toward launch.

Significant progress has been made to characterize the instrument and retrieval error of refractivity and bending angle profiles based on signal characteristics. While this promising work has a firm theoretical basis, however, to date is has proved difficult to apply for NWP, in which more restrictive empirical quality control procedures have been used more successfully.

2.5 Data Assimilation and Impact Studies

Representatives of a number of the national weather services or consortiums presented reports on their efforts to develop, test, and implement assimilation procedures for GPSRO in operational NWP. Among these were the US, Canada,

Japan, and the ECMWF. Observation System Experiments (OSEs) using both bending angle (local and non-local) have been at least marginally successful. Improved forward operators and better quality control procedures are expected to increase the beneficial impact of RO data for global NWP. Moreover, improved soundings of the lower troposphere via PLL, and increase numbers of occultation events, are also anticipated to extend the impact.

2.6 Climate Applications

The common expectation of those familiar with the GPSRO methodology and applications is that that the most immediate impact of high density, operationally-delivered RO profiles will be realized in the realm of NWP. However, there are many who contend that the most significant long-term impact of RO observations will be in the realm of climate studies. Stratospheric temperature data and refractivity profiles themselves were discussed as climate data records (CDRs). An invited presentation argued that GPSRO and high-spectral resolution IR measurements together offered the most potent set of CDRs.

2.7 Space Weather Applications

Space weather modeling is considerably less mature than conventional NWP. The situation is aggravated by the relative paucity of ionospheric observations. This means that COSMIC-derived electron density measurements, which reflect responses to space weather events, represent a unique source of data to be incorporated in the NWS' Space Environment Center's analyses. The temporal scales of interest for space weather are typically much shorter than those relevant for tropospheric phenomena. Even a mature ionospheric/thermospheric model, therefore, might require a much shorter data latency (15 minutes or less) than will be possible for COSMIC. However, it is anticipated that COSMIC data will still be of considerable value when used ingested for retrospective analyses.

3. Aftermath

3.1 Satellites and GPSRO Receivers

The most significant event following the conclusion of the Workshop is also the most obvious: On April 14, 2006, COSMIC was successfully launched. All six COSMIC satellites are functional and all receivers are operating at or better than specification, and the benefits of PLL tracking are being realized. Of particular note, the open-loop tracking for COSMIC is permitting occultations to be completed routinely at least to the top of the planetary boundary layer. The initial configuration of the COSMIC constellation permits multiple receivers to record nearly simultaneous and collocated soundings, both of ionospheric electron density and tropospheric refractivity. The internal consistency of these paired soundings has met expectations. As the satellites are moved into separate orbits, more evenly distributed soundings will result, and downlink bottlenecks will be reduced, permitting the full complement of ~ 3000 soundings/day to be obtained. The launch of METOP-1 and the GRAS sensor

was postponed in July 2006 and is currently scheduled for October 7, 2006. This delay was attributed to the launch system itself and not to GRAS or any of the other environmental sensors onboard.

The CHAMP satellite and sensor continue to be fully functional. Indeed, processing of CHAMP data in near-real time has been achieved and neutral atmosphere profiles apparently are now available to some centers for operational assimilation into NWP analyses and forecasts. The Joint Center for Satellite Data Assimilation (JCSDA) and the NWS/NCEP are seeking to gain access to the real-time CHAMP data to augment the impact of COSMIC (and eventually GRAS) in the Global Forecast System (GFS).

3.2 Progress and Prospects for Data Assimilation for NWP

Working at the JCSDA, L. Cucurull has led the effort to complete and test codes for the forward, tangent linear, and adjoint models to assimilate BUFR'ized CHAMP observations in an environment parallel to the NCEP GFS and demonstrated positive impact in anomaly correlation scores, particularly near 200 mb, where the resolution and accuracy of GPSRO are expected to provide information not available from conventional radiometric satellite soundings. The same codes are applicable for assessing the impact of the COSMIC data, which will be more voluminous and available for real-time assimilation once the offline evaluation is successfully completed.

The BUFR formatting and piping from UCAR to NESDIS/OSDPD and onto the JCSDA and NCEP, developed and tested using non-real time CHAMP data in 2005, expedited the capability for CDAAC to produce and NOAA to acquire COSMIC data in BUFR form, within 2-3 months after launch. Accumulation of occultation data set extending over a month is nearly complete and a retrospective impact experiment will be run and assessed by December 2006. Pending success of this experiment, COSMIC data will be assimilated operationally in the NCEP GFS following the next system upgrade, which will include the transition from the SSI to the GSI analysis, since preparations and testing for COSMIC were made using the GSI to avoid the need for re-coding. The issue of wider distribution of COSMIC BUFR data has abated, and it appears that NOAA will be able to distribute the BUFR files via the GTS. A draft Transition to Operations plan for COSMIC has been developed within NOAA.

3.3 Progress and Prospects for Improved Retrievals

A collaboration has been undertaken between the NESDIS ORA and the University of Wisconsin (CIMMS) to include COSMIC and GRAS soundings (refractivity and derived "dry" temperature) as part of the validation data set for NPOESS sounding products. Indeed, GPSRO soundings could and should be incorporated as part of ORA's comprehensive satellite calibration/validation program.

Issue: Mission and Data Continuity

The success of the building, launching, and operating GPSRO sensors, and exploiting the occultation data streams for various applications, the physical

ruggedness of the individual sensors and the robustness of the system of sensors collectively, indicate that the technical issues are relatively minor. The most significant threat on the horizon remains in fact programmatic: The operation of the CDAAC, which processes and delivers COSMIC data to the NESDIS Office of

Satellite Data Processing and Distribution, is funded only through launch plus two years, that is, until April, 2008. The risk to data availability and continuity is sobering. Although METOP satellites will each include a GRAS, the six COSMIC spacecraft collectively deliver approximately 6 times as many soundings for NWP, climate monitoring, and satellite sounder inter-validation. Moreover, with six satellites and receivers, COSMIC may be expected to fail gracefully, since the loss of any given sensor still leaves the system at almost full strength. Finally, it must be noted that ionospheric electron density retrievals have never been a requirement and will not be delivered for GRAS. For the Space Weather community, COSMIC is the only viable option.

A NOAA Small Business Innovative Research (SBIR) Phase One Proposal was competitively selected in the Spring of 2006 to investigate concepts for an advanced RO that would take advantage of GALILEO and be appropriate for deployment on a COSMIC follow-on constellation.