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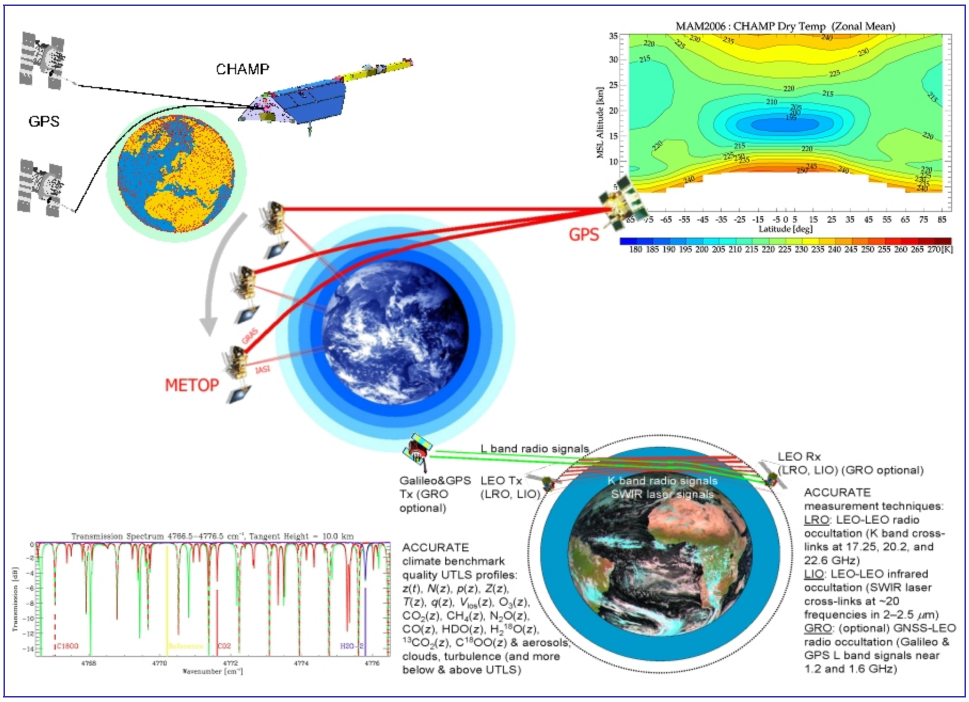
Project: ProdexCN2–Radio and Optical Occultation: EGOPS System Development
(ESA Prodex Arrangement No. 90152-CN2)

ProdexCN2 Project Summary Report

Radio and Optical Occultation: EGOPS System Development

Project Team Members:
G. Kirchengast (Project Leader), J. Fritzer (Leader EGOPS Development), M. Pock, and
M. Gorbunov (WegCenter Vis. Scientist and Inst. of Atmos. Physics, Moscow, Russia)
Team Support:
F. Ladstädter, S. Schweitzer, V. Proschek, B. Pirscher, M. Borsche, C. Retscher

Wegener Center for Climate and Global Change (WegCenter),
University of Graz, Graz, Austria



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List of Acronyms

ACTLIMB	Active Limb Sounding study (UniGraz-led ESA study on MWO+ILO 2008–2010)
ATR	Acceptance Test Report (of the EGOPS S/W)
CHAMP	Challenging Minisatellite Payload (German/U.S. research satellite)
COSMIC	Constellation Obs. System for Meteorology, Ionosphere, and Climate (Taiwan/U.S.)
DDD	Detailed Design Document (of the EGOPS S/W)
EGOPS	1996-2002/until EGOPS4: End-to-end GNSS Occultation Performance Simulator; 2003-2007/to EGOPS5.2: End-to-end Generic Occultation Performance Simulator; 2007-/after EGOPS5.2: End-to-end Generic Occultation Performance Simulation and Processing System. (EGOPS® is since 2000 a registered trademark/class software)
ESA	European Space Agency
ESA-Prodex	An ESA Programme line (for an enlisted subgroup of member states, incl. Austria)
FOM	Forward Modeling (subsystem of EGOPS)
FORTRAN	Formula Translation (Language) (a compiler-based programming language)
GADEM	Galileo Data Enhancement Mission (an EU study 2005-06; cf. [Schwaerzetal, 2006])
GNSS	Global Navigation Satellite Systems (Global Positioning System GPS, and Galileo)
GO	Geometrical Optics (in the context of RO geom. optics simulations and processing)
GPS	Global Positioning System
GPS/Met	GPS Meteorology – "proof-of-concept" sat experiment for the GPS RO technique
GRACE	Gravity Recovery and Climate Experiment satellite (carrying a GPS RO sensor)
GRAS	GNSS Receiver for Atmospheric Sounding (GPS RO sensor on MetOp)
GRO	GNSS-LEO Radio Occultation (here Galileo & GPS L band signals, ~1.2 / 1.6 GHz)
GUI	Graphical User Interface
I/F	Interface (e.g., EGOPS User I/F is [graphical] user interface of the EGOPS software)
IDL	Interactive Data Language (a S/W development environment and language)
ILO	Infrared-Laser Occultation
LEO	Low Earth Orbit (or Low Earth Orbit satellite)
LIO	LEO-LEO Infrared-laser Occultation
LMO	LEO-LEO Microwave Occultation
MAP	Mission Analysis/Planning (subsystem of EGOPS)

MetOp	Meteorological Operational satellite (of EUMETSAT Polar System)
MW	Microwave spectral region
MWO	Microwave Occultation
netCDF	Network Common Data Form (a scientific file format; see www.unidata.ucar.edu)
OSM	Observation System Modeling (subsystem of EGOPS)
OPS	Occultation Processing System (subsystem of EGOPS)
ProdexCN2	"Prodex Change Notice 2" project; 2nd continuation project of Prodex #90152 project
RO	Radio Occultation
ROPP	Radio Occultation Processing Package (specialized S/W; see http://garf.grassaf.org)
Rx	Receiver (satellite)
SAC-C	Satélite de Aplicaciones Científicas-C (Argentine satellite carrying a GPS RO sensor)
SUM	Software User Manual (of the EGOPS S/W)
S/W	Software
Tx	Transmitter (satellite)
URD	User Requirements Document (of the EGOPS S/W)
VIR	Visual and InfraRed
WegCenter/ UniGraz	Wegener Center for Climate and Global Change, University of Graz (Austria)
WO	Wave Optics (in the context of RO wave-optics simulations and processing)
WP	Work Package
xEGOPS	Experimental EGOPS system (EGOPS S/W containing new ILO functionalities)

1. Introduction and Project Aims

The ProdexCN2 project comprised four main aims: 1) Integration and development of end-to-end radio occultation (RO) and microwave occultation (MWO) simulation, both GNSS-LEO RO (GRO) and LEO-LEO MWO (LMO), and real RO data processing into a single joint system, 2) Integration of end-to-end simulation of optical infrared-laser occultation (ILO) with GRO and MWO, for LEO-LEO ILO (LIO) developments, where in particular the integration of LIO with LMO retrieval processing system elements is challenging at system development level, 3) Upgrades for use of space-to-ground modeling in addition to the space-to-space modeling both in the forward and observation system modeling parts for simulation of space-to-ground setups similar to those for full space-to-space setups, 4) At S/W system level, streamlining of the EGOPS S/W interfaces, especially of input and output data I/Fs of occultation profile data, complemented by a system test utility already using these improved I/Fs.

The scientific-technical work for implementing the four main aims summarized above was performed within the following four main work packages (WP 1 was Project Management):

WP 2 – EGOPS5 master and EGOPS5 derivatives integration (aims 1 and 2),

WP 3 – Update and harmonize space-to-ground link modeling (aim 2 and 3),

WP 4 – Update and streamline EGOPS file I/Fs and graphical user I/F elements (aim 4),

WP 5 – EGOPS system control, testing, and documentation (aim 4 and integrating WP).

An EGOPS User Requirements Document (URD) [E55-URD, 2009], providing detailed requirements for the S/W, served as the key reference for the S/W functionality to be achieved by the work.

In this summary report we first summarize the work results in each of the WPs 2 to 5 listed above (Section 2) and then summarize the status of the EGOPS S/W by end of the project (Section 3). Finally, an outlook to next development directions is given in Section 4.

2. Summary of Main Work Results

2.1 WP 2 “EGOPS5 master and EGOPS5 derivatives integration”

The WP 2 work included the four tasks *Task 2.1–Enhance by WO and merge-in real RO data processing*, *Task 2.2–Harmonize and streamline geometry simulations*, *Task 2.3–Harmonize and streamline Tx-Rx system modeling*, and *Task 2.4–Coherent GRO/MWO/ILO observation system error modeling*, respectively [ProdexCN2, 2007]. The work of these four tasks was completed in the project as follows.

Task 2.1–Enhance by WO and merge-in real RO data processing: Regarding WO enhancement, the WO subsystem of the retrieval system and associated library modules were upgraded to be capable of processing real RO data from GPS/Met, CHAMP, SAC-C, GRACE, COSMIC, and MetOp/GRAS. Regarding the merging-in of real RO data processing and modules from other EGOPS derivatives, a joint processing chain both for simulated and real data was achieved. The chain can perform GO, WO, or GO&WO combined retrievals. WO and combined GO&WO retrievals have been applied to several days of real test data and GO retrieval (merging finished mid-project, OPSv5.4) has already received EGOPS large-scale application to real data (GPS/Met, CHAMP, SAC-C, GRACE, COSMIC; MetOp for available test data). It has meanwhile processed all CHAMP data (full record 2001-2008), the available GPS/Met, SAC-C and GRACE data (datasets of about months to year length), and about 3 years of COSMIC data (up to mid 2009). For the quality of EGOPS OPSv5.4 processing results see, for example, [Foelscheetal, 2008] and [Steineretal, 2009]; the quality of WO results has been shown in the ProdexCN2 final presentation.

Task 2.2–Harmonize and streamline geometry simulations: The geometry simulations in the mission analysis/planning (MAP) and forward modeling (FOM) parts of EGOPS, which were for airborne/ideal event components attached to the GUI (and written in IDL), were brought into the core computational system (written in FORTRAN). By this we made all geometrical simulations (incl. airborne and space-to-ground) available for core-based batch simulations. Careful tests confirmed that the new FORTRAN system implementations work correctly and that the related IDL GUI is still functioning nominally.

Task 2.3–Harmonize and streamline Tx-Rx system modeling: The Tx-Rx modeling from mission analysis/planning via forward and observation system modeling to occultation processing was cleared from GRO-specifics to render it generic. Thus the complete MAP-FOM-OSM-OPS modeling flow can now function without being partly bound to GRO-specifics, which increased also the S/W robustness of the system.

Task 2.4–Coherent GRO/MWO/ILO observation system error modeling: The streamlining work of this task started with a re-design of the OSM in that joint routines were used for those functionalities that are generic over all wavelength (radio/microwave and optical), such as amplitude/intensity drifts modeling or multiple-sines perturbations modeling, and dedicated routines (sharing lower level routines as appropriate) where modeling of radio/microwave and optical processes is different. The main program structure was also streamlined such that optical OSM (serving experimental capability requirements related to ILO) can run as separate process to the core-radio/microwave-OSM (EGOPS-Kernel, xEGOPS structure; see also Section 3). The OSM error modeling can now run for radio (GRO), microwave (MWO), and optical (ILO) in an equal-footing alternative without partly depending on GRO specifics.

2.2 WP 3 "Update and harmonize space-to-ground link modeling"

The WP 3 work included the two tasks *Task 3.1–Upgrade space-to-ground forward modeling* and *Task 3.2–Upgrade space-to-ground observation system modeling*, respectively [ProdexCN2, 2007]. The work of these two tasks was completed as follows.

Task 3.1–Upgrade space-to-ground forward modeling: The existing space-to-ground link forward modeling (FOM) elements in EGOPS5.2 (start version of ProdexCN2) were upgraded based on EGOPS derivative modules (especially from the project GADEM [Schwaerzetal, 2006]), in a way to enable space-to-ground modeling on an equal footing with space-to-space modeling in the geometric-optics FOM chain. All EGOPS-supported types of signals (GRO, MWO, and ILO) can now be used in FOM in space-to-ground mode in addition to space-to-space mode.

Task 3.2–Upgrade space-to-ground observation system modeling: As a natural subsequent step to Task 3.1 the existing space-to-ground observation system modeling (OSM) elements in EGOPS5.2 were upgraded based on EGOPS derivative modules (especially from GADEM), in a way to enable space-to-ground modeling on an equal footing with space-to-space modeling in the OSM. All EGOPS-supported types of signals (GRO, MWO, and ILO) can now be used in OSM in space-to-ground mode in addition to space-to-space mode.

2.3 WP 4 "Update and streamline EGOPS file I/Fs and GUI elements"

The WP 4 work included the two tasks *Task 4.1–Upgrade EGOPS file I/Fs to generic joint system* and *Task 4.2–Upgrades to the visualization/validation GUI*, respectively [ProdexCN2, 2007]. The work of these two tasks was completed as follows.

Task 4.1–Upgrade EGOPS file I/Fs to generic joint system: The EGOPS profile data file I/Fs were upgraded to generic netCDF-based (with option ASCII conversion) joint formats. This was implemented throughout forward modeling (FOM), observation system modeling (OSM), and occultation processing (OPS) systems and includes input data files (simulated data files, real RO input datastreams) as well as output data files (simulation output and real data processing output). This I/F development was performed compliant with the requirements in the CLIPS (Climatology Processing System) Level 3 processing at WegCenter, which is currently advanced and which uses the EGOPS output profiles and metadata as input for its processing towards value-added (Level 3) gridded climatology products.

Task 4.2–Upgrades to the visualization/validation GUI: In this task we developed, in support of the WP 5 work, the post-processing and visualization part of the EGOPS system test utility (the profilePPV tool), in order to supply a simple script-driven/command-line utility for atmospheric profiles visualization/validation. A description of the profilePPV tool was produced and is available as auxiliary document as part of the EGOPS documentation package delivered to ESA [profilePPV, 2009].

2.4 WP 5 “EGOPS system control, testing, and documentation”

The WP 5 work included work on the two tasks *Task 5.1–System control, testing, and system test utility* and *Task 5.2–Update the set of EGOPS documentation*, respectively [ProdexCN2, 2007]. The work of these two tasks was completed as follows.

Task 5.1–System control, testing, and system test utility: In line with the needs of WPs 2 to 4, the system level engineering coordination, integration control, and system level test function for all EGOPS developments during the project was performed. In parallel, also in support of work in WPs 2 to 4, a myriad of structural improvements in main system level components (such as in the FOM, OSM, and OPS main programs and in EGOPS utility modules) were implemented. Also the final technical authorization and preparation of the EGOPS release by end of project (EGOPS 5.5 package) was part of this task.

Regarding EGOPS system testing activities, these were a continuous task during the project and a system testing utility was developed and employed to aid in the testing. Its description is available as an auxiliary document being part of the EGOPS documentation package delivered to ESA [egopsSystemTest, 2009]. The preparation of the system/acceptance test report is described as part of Task 5.2 below.

Task 5.2–Update the set of EGOPS documentation: Updates to the set of EGOPS documentation (URD, DDD, SUM) were performed throughout the project along with the S/W development. As a substantial task of the documentation work, the conversion of the URD, SUM and DDD documents from Word to the new documentation framework egopsLaTeX were mastered during the project. A description of the latter framework is available as auxiliary document (“EGOPS LaTeX Guide, ELG”), being part of the EGOPS documentation package delivered to ESA [EGOPS5.5-ELG, 2009]. As part of the documentation, in particular the SUM was completely renewed in addition to the URD, which makes the new SUM significantly more informative to the users than the previous one.

Finally, an acceptance test report (ATR) was prepared for properly documenting the system and hand-over testing (final acceptance text) of EGOPS 5.5 by the end of the project.

A summary of the overall status of the S/W, achieved with the EGOPS 5.5 version, follows below in Section 3, which also cites the URD, SUM, DDD, and ATR as main references.

3. Status of the EGOPS S/W by End of Project

The EGOPS software development status at the end of ProdexCN2 is here briefly described by summarizing its capabilities with respect to the four main simulation and processing tasks Mission Analysis and Planning MAP, Forward Modeling FOM, Observation System Modeling OSM and Occultation Processing System OPS, as well as regarding the updated software documentation. Main references are the URD [E55-URD, 2009], the SUM [E55-SUM, 2009], the DDD [E55-DDD, 2009] and the ATR [E55-ATR, 2009].

Mission Analysis and Planning MAP
All features required by the URD concerning MAP are fulfilled. Additionally, concepts have been developed recently to extend the MAP numerical core for generating pseudo Level 1 netCDF event information files containing, besides the tangent point coordinates, also the tangent-point-to-transmitter-platform and tangent-point-to-receiver-platform levers, which can then be directly used for plotting the event geometry with off the shelf scientific data analysis and visualization packages like NCL (http://www.ncl.ucar.edu). The implementation intended can also be included in the FOM L1, and OSM L1a and OPS L1a output routines. When applied to the OPS simulated or observed signal data L1a crosscheck output, it will allow to visualize also the event geometry of processed RO events.

Forward Modeling FOM
All features required by the URD concerning FOM are available. The ILO related parts, comprising experimental requirements concerning the VIR signal propagation simulation, are provided via the eXperimental EGOPS part, termed xEGOPS.
The main function of xEGOPS is to enable and support a seamless and parallel development of the EGOPS-Kernel concurrently with new experimental features that use the kernel provided proven routines. Currently xEGOPS is a software package distinct from the legacy EGOPS software package, implementing the ILO simulation and retrieval functions developed within the frame of the ACTLIMB and ProdexCN2 projects.
The xEGOPS approach was conceived due to the requirement of using EGOPS heritage features in multiple, but thematically different and concurrent projects. Since the concurrent projects often have aims that are not compatible with the strict and focused roadmap of the EGOPS development and maintenance scheme, it was decided to supply the EGOPS core functionality as a source code library termed EGOPS-Kernel. The EGOPS-Kernel supplies its services via the modules which constitute the EGOPS numerical core, i.e., without any GUI and DPP (Data Post-processing) components.
The rationale behind this setup is the not infrequently encountered situation that during implementation of an experimental feature one or more EGOPS-Kernel functions or modules cannot be used without modification, e.g., because some additional parameters are required. In this case, a modification of the EGOPS-Kernel function or module is necessary and a discussion between the partner projects using the EGOPS-Kernel and the EGOPS maintenance team (providing the EGOPS-Kernel) is started on how to best implement the new feature while safeguarding the long-term stability and maintainability of the EGOPS numerical core. For most new features required, it can be readily determined and agreed whether it is best implemented as a local function of the experimental xEGOPS software branch or as a more general and generic function of the EGOPS-Kernel.

Having this scene in mind, the EGOPS-Kernel/xEGOPS approach primarily is not so much a technical topic, but much more a managerial and organizational solution for providing the EGOPS numerical core functions to occultation-related software prototype and breadboard developers on one side, and a style of cooperation for the EGOPS maintenance team, tasked to deliver a rock-solid and stable RO/MWO end-to-end simulation tool and proven operational occultation processing system (OPS), on the other side.

Observation System Modeling OSM
For the RO/MWO spectral region, the EGOPS 5.5 software version provides all intended features except for rigorous handling of transmitter antenna properties in non-boresight tracking mode, the use of which is thus not recommended. The non-boresight handling will be improved as part of future maintenance including partial re-implementation and proper documentation. For the VIS/IR spectral region, the required features are all available within the xEGOPS project, described above.

Occultation Processing System OPS
All RO/MWO based atmospheric and ionospheric retrieval requirements are fulfilled, including the provision of the renewed (ROPP 2.0-package based) 1D-Var optimal estimation moist air profiles retrieval tool. This is integrated with only minor inconveniences remaining. One topic is the configuration of the UDUNITS package (imported by ROPP 2.0), which currently uses a compile-time-configured fixed path to its database, inhibiting the relocation of the executable to a different path. Another topic is that at the moment the ROPP package can only be conveniently compiled and executed with the GFortran and NAG Fortran compilers. It is expected to get rid of these problems by upgrading to ROPP 3.0, currently scheduled to be available by January 2010 in needed form. Processing of real GPS RO data is now supported for all GNSS RO experiments listed in the URD. On VIS/IR, all requirements are fulfilled and available within the xEGOPS project (described in the FOM section).

EGOPS Documentation
The completion of the renewed EGOPS documentation, i.e., the Software User Manual [E55-SUM, 2009], the Detailed Design Document [E55-DDD, 2009], and the Acceptance Test Report [E55-ATR, 2009], as well as the conversion of the URD [E55-URD, 2009] to LaTeX format, was finished. While the SUM received complete renewal it is to be noted that the Detailed Design Document has received only formal renewal, with the content focused and covering the numerical core for end-to-end occultation simulations and occultation data processing/retrieval. The EGOPS GUI is not separately described again, since further GUI development was frozen after the EGOPS 5.2 release and on-going work concerning the IDL GUI was performed for bug-fixing and maintenance purposes only. Readers interested in technical information on the EGOPS GUI are requested to consult the EGOPS 5.2 Architectural Design/Detailed Design Document.

4. Future EGOPS Development Direction and Outlook

In view of the long and extremely successful EGOPS track of 12 years, starting with the first official EGOPS 2.0 Release 1 in 1997 and reaching the EGOPS 5.5 release by end of the ProdexCN2 project in fall 2009, one has also to take note of the partly heterogeneous nature of the numerical core's code base, caused mainly by the relatively large number of team members related with EGOPS development for sometimes limited time periods only. Streamlining the full code base covering MAP, FOM, OSM and OPS would require much more resources than can be expected to be reasonably available in the time frame ahead.

Therefore, the WegCenter EGOPS development team has strategically decided to pursue continued development of the EGOPS-Kernel with focus on the most-important subsystem, OPS, and fundamental components needed by the OPS (e.g., core atmospheric models). The main aim in this context is as good as possible processing of the European MetOp/GRAS data.

The EGOPS development cycle within the frame of the ProdexCN2 project thus concludes the overall EGOPS-Kernel system development in its original approach and freezes the non-OPS requirements to the state defined in the EGOPS 5.5 URD [E55-URD, 2009]. Maintenance is intended to be provided to non-OPS whilst development shall serve the OPS, which is most and critically needed by the WegCenter-internal and the external application communities for weather, climate, validation and other applications. Given the MetOp/GRAS perspective towards 2020, processing these most modern RO data will be the particular focus.

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