GRAS SAF

EUMETSAT
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ROPIC First Assessment

Introduction

The RO technique proved to be a success story during the last years. Its reliable technical concept did meet the expectations of global coverage, all-weather capability, long term stability and high accuracy. Its self calibrating concept makes RO an ideal candidate to conduct climate studies over large time frames; its conceptual simplicity makes the instrument itself, cheap and lightweight. These new observations are attracting attention from the NWP centers too, which will put them into an operational context.

Motivation for ROPIC, The Radio Occultation Processing Intercomparison Campaign

There are worldwide several centers processing RO data, starting from different levels, to bending angles and refractivities, some at an operational or quasi operational level. Most are also generating further processed products like temperature and humidity profiles. The processing chain is composed of a number of algorithms which differ between the centers; even if the same underlying algorithm is used the specific implementations will be different, resulting in slightly different results. As the ROSE campaign pointed out different centers process different subsets of the same pool of RO profiles too (this discrepancy issue has been relaxed by now).
For that reason the idea to undertake a comprehensive processing center intercomparison was born. This project was be realized within the GRAS SAF and carried out as a visiting scientist project scheduled for 2006/2007.

Project objectives

The intention is not the assessment of the absolute accuracy but to reveal possible inconsistencies between the results of different centers and the identification of benefits from using certain algorithms and methods. Most likely the optimal processing method is complex (e.g. it may vary with altitude range and spatial location of the observation).
The aim of this project is thus that we all gain a better understanding and insight in the behavior of our processing chains and to come up for discussion to optimize our procedures.

This project was encouraged by talks of Axel von Engeln during the COSMIC RO workshop at Lansdowne, indicating interest from various participants to conduct such a study.

Armin Löscher

GRAS SAF Visiting Scientist at DMI

1. The ROPIC Project

The primary objective of the ROPIC (Radio Occultation Intercomparison Campaign) project is to analyze the robustness of state of the art Radio Occultation (RO) processing chains. Since the RO technique comprises some characteristics which suggest the usage of this data type to monitor atmospheric variability and on the long term climate change the impact of the used processing method has to be understood thoroughly.
Prior studies (ROSE) showed quite a discrepancy between a given *raw* data set and the set of excess phases data (Level 1a) derived by different centers. The study showed clearly a potential for optimization since different centers where able to process different profiles up to Level 1a. The total overlap at Level 1a from all participating centers (3) was surprisingly small.
To avoid that effect and enable the participation of centers not having the capability to process data to Level 1a, it was decided to prepare a common Level 1a data set for the ROPIC project. Consequently the ROPIC study investigates the RO processing chains from Level 1a to Level 1b and Level 2a respectively.

2. The ROPIC Data Set

The Phase Delay Data

The data set was selected to comprise enough occultation events to perform meaningful statistics on one hand and to cover different atmospheric conditions on the other hand. To satisfy these two requirements the data set had been compiled using two month (cf. Table 1) of CHAMP data covering the winter season (January 2005) and the summer season (July 2005).

Used Time Windows for Data.	**No. of Days.**
Year 2005 total No. of days:	365
January No. of days:	001 – 031
July No. of days:	182 - 212

Table 1 Days used within the ROPIC data set.

2.1 CHAMP Data

To conduct the ROPIC campaign, a fixed set of phase delay and orbit data from CHAMP is distributed to the participants. The data set is generated using the space-based single differencing technique and consists of two month (one winter and one summer month) to cover changing atmospheric conditions. The data set is distributed using FTP access for the participants (http://grassaf.dmi.dk/ROPIC).

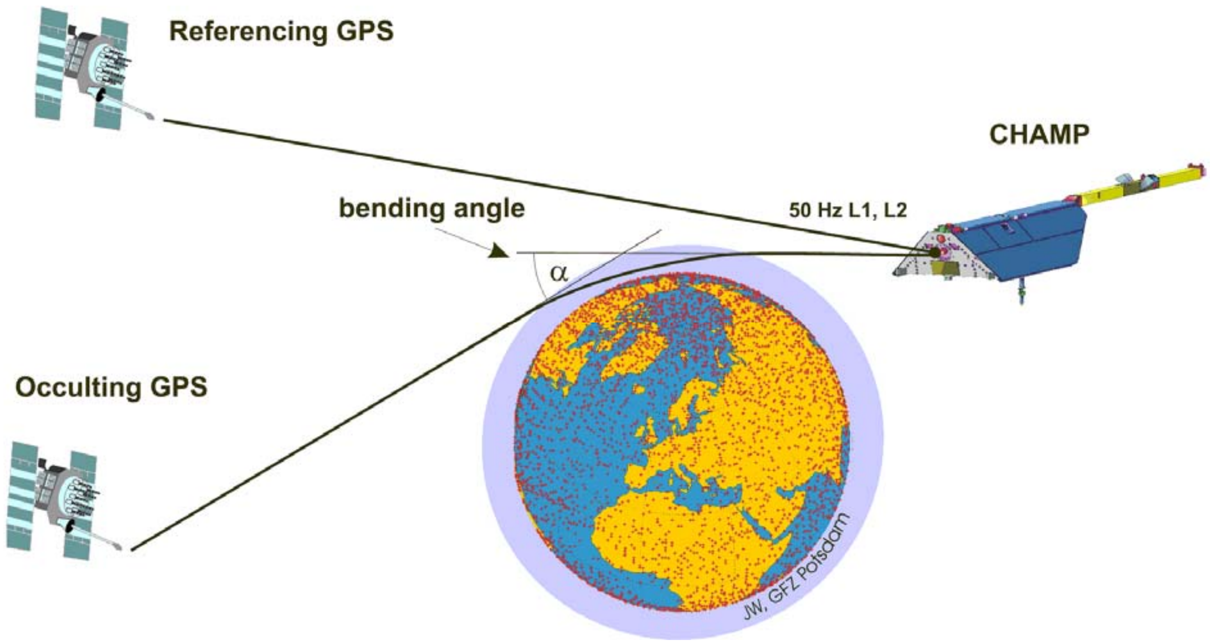


Figure 1 Space based single differencing geometry for the analysis of the CHAMP occultation data for ROPIC. The 50 Hz occultation measurements (L1 and L2 from occulting GPS satellite) are differenced with measurements from a referencing GPS satellite to eliminate the CHAMP satellite clock error [adapted from Wickert, 2002].

The GeoForschungsZentrum (GFZ) Potsdam provides the data of the CHAMP GPS radio occultation experiment and also generates the phase delay data set for ROPIC (technical contact: Dr. Jens Wickert; jens.wickert@gfz-potsdam.de; www.gfz-potsdam.de/atmo). The data set is available either in GFZ ASCII or ROPP NetCDF format for the participants of the intercomparison campaign via the dedicated ROPIC web page http://grassaf.dmi.dk/ropic (technical contact Dr. Armin Löscher, arl@dmi.dk).

The corresponding *raw* satellite data (input for the excess phase derivation) is available via GFZ's Information System and Data Center (ISDC, http://isdc.gfz-potsdam.de/champ). If access to the raw data is required, please contact Dr. Jens Wickert.

2.2 CHAMP Excess Phase Data Set for ROPIC

To clarify the notation and avoid confusion Tab. 2 shows some data level definitions used for the excess phase (PD) and corresponding orbit data.

GFZ	GRAS-SAF	UCAR	EUMETSAT
Level 2	Level 1a	Level 2	Level 1b

Table 2 Definition of data levels.

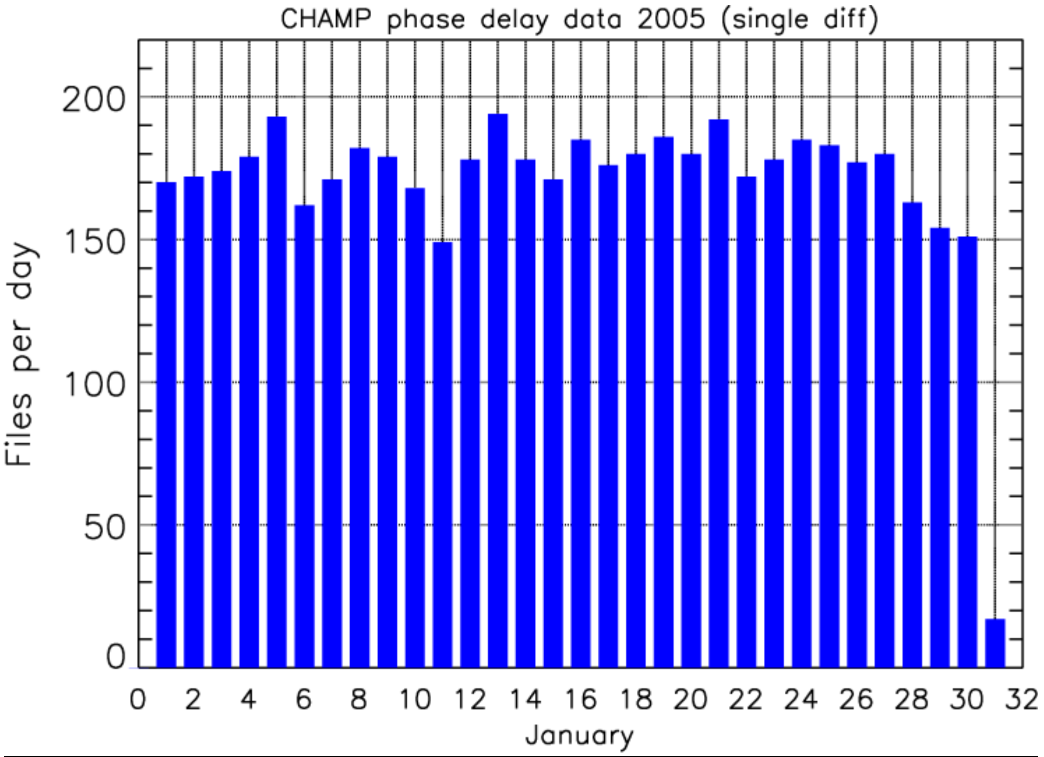


Figure 2 Daily number of occultations from 01.01.2005 to 31.01.2005; 5246 in total.

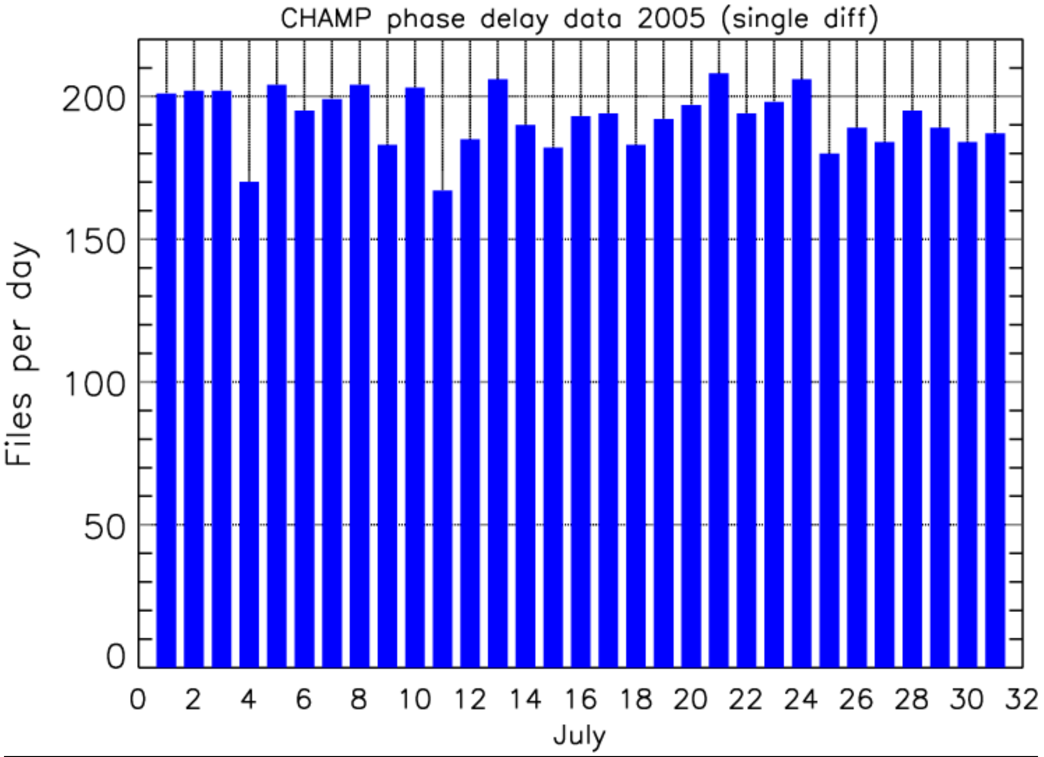


Figure 3 Daily number of occultations from 01.07.2005 to 31.07.2005; 5928 in total.

The ROPIC data set consists of the Level 1a (ROPP format, Level 2 in GFZ format), stored as ROPP NetCDF files and GFZ ASCII files. The processing from raw to excess phase level had been performed by GFZ using the single differencing technique.
The data set consists of two month (January & July 2005) to cover the atmospheric variability throughout the summer and winter seasons. It comprises 5246 profiles from 01.01.2005 to 31.01.2005 and 5928 profiles from 01.07.2005 to 31.07.2005; in total 11174 profiles. Due to problems in the attitude stabilization of CHAMP no precise orbits are provided between January 30, 22 UTC and January 31, 22 UTC, thus only a limited number of occultation could be processed.

2.3 Provided CHAMP occultation Phase Delay (PD) Data & Orbits

- Atmospheric excess phase and orbit data for each occultation (CH-AI-2-PD, GFZ-Level 2).
- Table of occultation events per day (CH-AI-2-TAB, GFZ-Level 2).

2.4 Input data for the excess phase generation

- High rate (50 Hz) GPS occultation data from CHAMP (CH-AI-1-HR, GFZ-Level 1).
- CHAMP and GPS satellite orbits (CH-OG-3-RSO).

The high rate GPS occultation data are provided in standard RINEX format (*http://igscb.jpl.nasa.gov/igscb/data/format/rinex2.txt*). A format description of the CHAMP orbit data is available online at *http://op.gfz-otsdam.de/champ/more/index_MORE.html*. GPS orbits are provided in sp3 standard data format (*http://www.ngs.noaa.gov/GPS/SP3_format.html*). These raw data sets are available via GFZ's Information System and Data Center (ISDC, *http://isdc.gfz-potsdam.de/champ*).

2.5 Retrieval and operational data processing

2.5.1 Derivation of the atmospheric excess phase delay (CH-AI-2-PD)

A single difference technique is used to eliminate the CHAMP satellite clock error and to derive the atmospheric excess phase data for ROPIC (see Fig.1). The GPS clock errors are corrected for by using 5 min clock solutions, provided by the GFZ orbit processing facility [König et al., 2005]. Details of the GFZ RO data analysis using single differences are given by Wickert et al. [2002]. Further references related to the derivation of the atmospheric excess phase from GPS RO data are, e.g., [Hajj et al., 2002], [Wickert et al., 2001] and [Schreiner et al., 1998].
A modified ionosphere correction of the reference link was introduced for the derivation of

excess phase data version 002 in contrast to the generation of the 001 product. The ionospheric contribution of the reference link is corrected for based on a "Smoothing (L1 - L2) technique" [Wickert et al., 2004; Schreiner et al., 1998]. Corresponding formulas are also given by Beyerle et al. [2005].

2.5.2 Occultation tables (CH-AI-2-TAB)

The occultation table contains a complete list of occultation events (tracking of occulting and referencing GPS satellite in parallel > 20 s). Additional information is given: PRN of occulting and referencing GPS satellite, start and end time of the occultation, estimated location and ground station information for double differencing. The given location is estimated by an software tool (ROST, Radio occultation simulation and Tracking tool, Wickert [2002]), which is used to determine appropriate ground stations for the double difference processing in advance (currently the standard GFZ processing).

2.5.2. Automated data processing at GFZ

CHAMP's orbit and occultation data are analyzed using dedicated occultation and orbit processing systems [König et al., 2005; Schmidt et al., 2005; Wickert et al., 2004; Wickert, 2002]. Both systems are operated at GFZ Potsdam in automatic mode to generate atmospheric data products. The occultation processing system currently uses as standard the double difference technique [Wickert et al., 2001] with input data from the Precise Orbit Determination (POD) facility (CH-OG-3-RSO data products), the fiducial GPS ground network (CH-AI-1-FID), the occultation data from CHAMP (CH-AI-1-HR) and ancillary meteorological data (ECMWF). The system was operated in manual mode using the single difference technique (without direct use of the GPS ground data) to generate the data set for ROPIC.

The Processed Data

Processed data had been provided by three (3) processing centers, namely The Danish Meteorological Institute (DMI), Deutscher Wetter Dienst (DWD) and The Wegener Center for Climate Research (WEGC).
A fourth data set which was compiled using a matching algorithm by A. v. Engeln from available CHAMP data processed at The University Cooperation for Atmospheric Research (UCAR) was added to complement the basic data set. It has to be noted that this profiles had been processed using the double differencing technique and is not based on our phase delay data set, but it still offers an interesting opportunity for comparison and evaluation. One interesting feature of this data set is the overall low number of matches which is 6121, compared to a total of 11174 profiles in our phase delay set, a problem addressed in the ROSE campaign.

	January	July	Total
GFZ Phase	5246	5928	11174

Table 3 GFZ ROPIC phase & orbits data set.

	January		July		Total	
	Passed	**Failed**	**Passed**	**Failed**	**Passed**	**Failed**
DMI	4232	-	4767	-	8999	-
DMI 5%	4132	100	4679	88	8811	188
DMI 10%	4167	65	4706	61	8873	126
DMI Q	4424	-	5043	-	9467	-
DMI Q 5%	4233	191	4905	138	9138	329
DMI Q 10%	4272	152	4932	111	9204	263
DWD	4439	-	5066	-	9505	-
WEGC	3828	1425	4539	1427	8367	2879
UCAR	2476	-	3645	-	6121	-
UCAR 10%	2476	0	3645	0	6121	0

Table 4 Processed ROPIC data set where failed indicates profiles which could be processed but didn't pass quality checks. The difference between passed and the numbers in Tab. 3 indicates profiles which couldn't be processed to bending angles.

DMI Data Set

The DMI data set was produced using the in-house processing chain which is based on wave optics retrieval. It comes in six (6) different versions which had been produced to support this study.

The Q indicates that the quality control flag had been set in the processing, which basically means that the profiles are cut off as soon as they don't meet internal quality criteria. The result is that the processed profiles in general not penetrating the atmosphere as deep as without setting this flag.

The 5% or 10% margin mean an external quality control which had been applied after the processing. The rule is as follows: Any profile which deviates from the background on average between 10 [km] and 20 [km] more than 10% respectively 5% is considered an outlier and flagged as failed, from 10 [km] down every point of the profile is checked against the background, if the deviation exceeds 10% respectively 5% the first time the point and all consecutive points are set to missing values. The same procedure is applied to all points from 20 [km] up. This external quality check is applied in refractivity space.

The 10% margin is seen as reasonable allowing for some variation; the 5% margin is seen as too small but included for study purposes. The interval from 10 [km] to 20 [km] for the outlier check had been chosen since the quality of the data seems to best within this interval.

The reason that there are more profiles with quality check Q than without (which appears odd at the first glance) is that if the 1DVAR is not converging the profile is automatically discarded. Since without the internal Q quality check the 1DVAR problem is ill posed for more profiles more profiles are rejected in the end.

Parameter	Description	Range	Units	YES/NO
Processing Centre	Text indicating processing centre (40 characters)	[A-Z,0-9]	-	YES
Software Version	String indicating software version	[A-Z,0-9]	-	YES
Level 1 b algorithm	Text strings (40 characters) indicating algorithms used to derive bending angle, refractivity and meteorological data	[A-Z,0-9]	-	NO
Level 2 a algorithm		[A-Z,0-9]	-	YES
Level 2 b algorithm		[A-Z,0-9]	-	YES

Table 5 DMI ROPIC data set processing.

Parameter	Description	Range	Units	YES/NO
Background Source	Source of meteorological or atmospheric data used as background (ancillary) data	[A-Z,0-9]	-	YES
Verification Time	Verification time of background data (if applicable)	1999 01 01 00 00 - 2099 12 31 23 59	-	YES

Table 6 DMI ROPIC data set background meta data.

Parameter	Description	Range	Units	YES/NO
Time since start	Time since start of occultation to the time when georeferencing data and radius of curvature are determined	0 – 999.999	s	YES
Latitude	Position of tangent point as used for georeferencing	-90 … 90	deg	YES
Longitude		-180 … 180	deg	YES
Radius of Curvature	Radius of curvature	6.2 – 6.6 x 10^6	m	YES
Centre of Curvature	Centre of curvature coordinates (ECF; X, Y, Z)	± 10000	m	YES
Line of sight	GNSS to LEO azimuth direction w.r.t. North	0 – 360	deg	NO
Geoid Undulation	Difference between ellipsoid (WGS-84) and geoid (EGM-96) heights	± 150	m	NO

Table 7 DMI ROPIC data set georeferencing.

Parameter	Description	Range	Units	YES/NO
Product Confidence[1]	Product confidence data	Bit flags within a single 32-bit / 4-byte integer		**NO**
Data Quality	Overall summary data quality	0 - 100	%	**NO**

1 only used in the NetCDF ROPP format

Table 8 DMI ROPIC data set quality.

Parameter	Description	Range	Units	YES/NO
Latitude	Longitude and Latitude w.r.t. the WGS 84 ellipsoid of the tangential point of the generic bending angle	-90 … 90	deg	**NO**
Longitude		-180 … 180	deg	**NO**
Azimuth	GNSS to LEO azimuth w.r.t. North at tangent point	0 - 360	deg	**NO**
Impact Parameter L1	Impact parameter derived from L1	$6.2 \times 10^6 – 6.6 \times 10^6$	m	**YES**
Impact Parameter L2	Impact parameter derived from L2	$6.2 \times 10^6 – 6.6 \times 10^6$	m	**YES**
Impact Parameter	Impact parameter generic	$6.2 \times 10^6 – 6.6 \times 10^6$	m	**YES**
Bending Angle L1	Bending angle derived from L1	-10^{-4} – 0.05	rad	**YES**
Bending Angle L2	Bending angle derived from L2	-10^{-4} – 0.05	rad	**YES**
Bending Angle	Bending angle generic	-10^{-4} – 0.05	rad	**YES**
Bending Angle Errors L1	Estimated errors (one σ) of bending angle values L1	0 – 0.02	rad	**NO**
Bending Angle Errors L2	Estimated errors (one σ) of bending angle values L2	0 – 0.02	rad	**NO**
Bending Angle Errors	Estimated errors (one σ) of bending angle values generic	0 – 0.02	rad	**NO**
Bending Angle Quality L1	Percentage confidence value for bending angles L1	0 - 100	%	**NO**
Bending Angle Quality L2	Percentage confidence values for bending angles L2	0 - 100	%	**NO**
Bending Angle Quality	Percentage confidence values for bending angles generic	0 - 100	%	**NO**

Table 9 DMI ROPIC data set Level 1b.

Parameter	Description	Range	Units	YES/NO
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m	**YES**
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm	**YES**
Refractivity	Derived refractivity	0 - 500	N-units	**YES**
Refractivity Error	Estimated errors (one σ) of refractivity values	0 - 100	N-units	**YES**
Refractivity Quality	Percentage confidence value	0 - 100	%	**NO**

Table 10 DMI ROPIC data set Level 2a.

Parameter	Description	Range	Units	YES/NO
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm	**YES**
Geopotential Height Error	Estimated errors (one σ) of geopotential height values		gpm	**NO**
Pressure	Retrieved pressure	0.1 - 1100	hPa	**YES**
Pressure Error	Estimated errors (one σ) of pressure values	0 - 50	hPa	**NO**
Temperature	Retrieved temperature	150 - 350	K	**YES**
Temperature Error	Estimated errors (one σ) of temperature values	0 - 50	K	**NO**
Specific Humidity	Retrieved specific humidity	0 - 50	g/kg	**YES**
Specific Humidity Error	Estimated errors (one σ) of specific humidity values	0 - 10	g/kg	**NO**
Quality	Overall percentage confidence value	0 - 100	%	**NO**

Table 11 DMI ROPIC data set Level 2b.

Parameter	Description	Range	Units	YES/NO
Geopotential Height Surface	Geopotential height of surface above geoid (EGM 96)	-1000 - 100000	gpm	**YES**
Surface Pressure	Retrieved surface (or reference) pressure	900 - 1100	hPa	**YES**
Surface Pressure Error	Estimated errors (one σ) of surface pressure values	0 - 50	hPa	**NO**
Quality	Percentage confidence value	0 - 100	%	**NO**

Table 12 DMI ROPIC data set Level 2c.

Parameter	Description	Range	Units	YES/NO
Temperature	ECMWF temperature	150 - 350	K	YES
Dry Temperature	ECMWF dry temperature	150 - 350	K	NO
Specific Humidity	ECMWF specific humidity	0 - 50	g/kg	YES
Pressure	ECMWF derived pressure	0.1 - 1100	hPa	YES
Geopotential Height	ECMWF derived geopotential height	-1000 - 100000	gpm	YES
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m	YES
Refractivity	ECMWF derived refractivity	0 - 500	N-units	YES
Surface Pressure	ECMWF surface pressure	900 - 1100	hPa	YES
Surface Height	ECMWF surface height	-1000 - 100000	m	YES
Surface Geopotential	ECMWF surface geopotential	-1000 - 8000	gpm	YES
Surface Temperature	ECMWF surface temperature	0 - 500	K	NO
Skin Temperature	ECMWF skin temperature	0 - 500	K	NO
Surface Humidity	ECMWF surface humidity	0 – 0.05	g/kg	NO

Table 13 DMI ROPIC data set background data.

Parameter	Description	Range	Units	YES/NO
Dry Temperature	Retrieved dry temperature	150 – 350	K	YES
Optimized Bending Angle	Retrieved optimized bending angle	-10^{-4} – 0.05	rad	NO
Reference Bending Angle Inverse Able	From background derived (inverse able) bending angle	-10^{-4} – 0.05	rad	NO
Reference Bending Angle Retraced	From background derived (raytraced) bending angle	-10^{-4} – 0.05	rad	NO
Density	Retrieved density	0 - 1100	Kg/m^3	NO

Table 14 DMI ROPIC data set additional data.

WEGC Data Set

The Wegener Center used geometric optics processing to derive the data set. All profiles which didn't have the quality flag 00 (the flags are assigned by the internal WEGC quality control which is composed of several internal and external checks) are assumed failed. The bending angle in Level 1b is UNOPTIMIZED (in the other data sets it is the optimized one), the OPTIMIZED bending angle is stored under Additional Data Bending Angle Optimized.

Parameter	Description	Range	Units	YES/NO
Processing Centre	Text indicating processing centre (40 characters)	[A-Z,0-9]	-	**YES**
Software Version	String indicating software version	[A-Z,0-9]	-	**NO**
Level 1 b algorithm	Text strings (40 characters) indicating algorithms used to derive bending angle, refractivity and meteorological data	[A-Z,0-9]	-	**NO**
Level 2 a algorithm		[A-Z,0-9]	-	**NO**
Level 2 b algorithm		[A-Z,0-9]	-	**NO**

Table 15 WEGC ROPIC data set processing.

Parameter	Description	Range	Units	YES/NO
Background Source	Source of meteorological or atmospheric data used as background (ancillary) data	[A-Z,0-9]	-	**YES**
Verification Time	Verification time of background data (if applicable)	1999 01 01 00 00 - 2099 12 31 23 59	-	**YES**

Table 16 WEGC ROPIC data set background meta data.

Parameter	Description	Range	Units	YES/NO
Time since start	Time since start of occultation to the time when georeferencing data and radius of curvature are determined	0 – 999.999	s	**YES**
Latitude	Position of tangent point as used for georeferencing	-90 … 90	deg	**YES**
Longitude		-180 … 180	deg	**YES**
Radius of Curvature	Radius of curvature	$6.2 – 6.6 \times 10^6$	m	**YES**
Centre of Curvature	Centre of curvature coordinates (ECF; X, Y, Z)	± 10000	m	**NO**
Line of sight	GNSS to LEO azimuth direction w.r.t. North	0 – 360	deg	**NO**
Geoid Undulation	Difference between ellipsoid (WGS-84) and geoid (EGM-96) heights	± 150	m	**YES**

Table 17 WEGC ROPIC data set georeferencing.

Parameter	Description	Range	Units	YES/NO
Product Confidence[1]	Product confidence data	Bit flags within a single 32-bit / 4-byte integer		**NO**
Data Quality	Overall summary data quality	0 - 100	%	**NO**

1 only used in the NetCDF ROPP format

Table 18 WEGC ROPIC data set quality.

Parameter	Description	Range	Units	YES/NO
Latitude	Longitude and Latitude w.r.t. the WGS 84 ellipsoid of the tangential point of the generic bending angle	-90 … 90	deg	**NO**
Longitude		-180 … 180	deg	**NO**
Azimuth	GNSS to LEO azimuth w.r.t. North at tangent point	0 - 360	deg	**NO**
Impact Parameter L1	Impact parameter derived from L1	$6.2 \times 10^6 – 6.6 \times 10^6$	m	**NO**
Impact Parameter L2	Impact parameter derived from L2	$6.2 \times 10^6 – 6.6 \times 10^6$	m	**NO**
Impact Parameter	Impact parameter generic	$6.2 \times 10^6 – 6.6 \times 10^6$	m	**YES**
Bending Angle L1	Bending angle derived from L1	-10^{-4} – 0.05	rad	**YES**
Bending Angle L2	Bending angle derived from L2	-10^{-4} – 0.05	rad	**YES**
Bending Angle	Bending angle generic	-10^{-4} – 0.05	rad	**YES**
Bending Angle Errors L1	Estimated errors (one σ) of bending angle values L1	0 – 0.02	rad	**NO**
Bending Angle Errors L2	Estimated errors (one σ) of bending angle values L2	0 – 0.02	rad	**NO**
Bending Angle Errors	Estimated errors (one σ) of bending angle values generic	0 – 0.02	rad	**NO**
Bending Angle Quality L1	Percentage confidence value for bending angles L1	0 - 100	%	**NO**
Bending Angle Quality L2	Percentage confidence values for bending angles L2	0 - 100	%	**NO**
Bending Angle Quality	Percentage confidence values for bending angles generic	0 - 100	%	**NO**

Table 19 WEGC ROPIC data set Level 1b.

Parameter	Description	Range	Units	YES/NO
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m	**YES**
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm	**YES**
Refractivity	Derived refractivity	0 - 500	N-units	**YES**
Refractivity Error	Estimated errors (one σ) of refractivity values	0 - 100	N-units	**NO**
Refractivity Quality	Percentage confidence value	0 - 100	%	**NO**

Table 20 WEGC ROPIC data set Level 2a.

Parameter	Description	Range	Units	YES/NO
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm	**NO**
Geopotential Height Error	Estimated errors (one σ) of geopotential height values		gpm	**NO**
Pressure	Retrieved pressure	0.1 - 1100	hPa	**YES**
Pressure Error	Estimated errors (one σ) of pressure values	0 - 50	hPa	**NO**
Temperature	Retrieved temperature	150 - 350	K	**NO**
Temperature Error	Estimated errors (one σ) of temperature values	0 - 50	K	**NO**
Specific Humidity	Retrieved specific humidity	0 - 50	g/kg	**NO**
Specific Humidity Error	Estimated errors (one σ) of specific humidity values	0 - 10	g/kg	**NO**
Quality	Overall percentage confidence value	0 - 100	%	**NO**

Table 21 WEGC ROPIC data set Level 2b.

Parameter	Description	Range	Units	YES/NO
Geopotential Height Surface	Geopotential height of surface above geoid (EGM 96)	-1000 - 100000	gpm	**NO**
Surface Pressure	Retrieved surface (or reference) pressure	900 - 1100	hPa	**NO**
Surface Pressure Error	Estimated errors (one σ) of surface pressure values	0 - 50	hPa	**NO**
Quality	Percentage confidence value	0 - 100	%	**NO**

Table 22 WEGC ROPIC data set Level 2c.

Parameter	Description	Range	Units	YES/NO
Temperature	ECMWF temperature	150 - 350	K	**YES**
Dry Temperature	ECMWF dry temperature	150 - 350	K	**YES**
Specific Humidity	ECMWF specific humidity	0 - 50	g/kg	**YES**
Pressure	ECMWF derived pressure	0.1 - 1100	hPa	**YES**
Geopotential Height	ECMWF derived geopotential height	-1000 - 100000	gpm	**YES**
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m	**YES**
Refractivity	ECMWF derived refractivity	0 - 500	N-units	**YES**
Surface Pressure	ECMWF surface pressure	900 - 1100	hPa	**YES**
Surface Height	ECMWF surface height	-1000 - 100000	m	**YES**
Surface Geopotential	ECMWF surface geopotential	-1000 - 8000	gpm	**NO**
Surface Temperature	ECMWF surface temperature	0 - 500	K	**YES**
Skin Temperature	ECMWF skin temperature	0 - 500	K	**YES**
Surface Humidity	ECMWF surface humidity	0 – 0.05	g/kg	**YES**

Table 23 WEGC ROPIC data set background data.

Parameter	Description	Range	Units	YES/NO
Dry Temperature	Retrieved dry temperature	150 – 350	K	**YES**
Optimized Bending Angle	Retrieved optimized bending angle	-10^{-4} – 0.05	rad	**YES**
Reference Bending Angle Inverse Able	From background derived (inverse able) bending angle	-10^{-4} – 0.05	rad	**NO**
Reference Bending Angle Retraced	From background derived (raytraced) bending angle	-10^{-4} – 0.05	rad	**NO**
Density	Retrieved density	0 - 1100	Kg/m^3	**NO**

Table 24 WEGC ROPIC data set additional data.

DWD Data Set

The Deutscher Wetter Dienst used a similar wave optics processing as DMI. The data set also contains reference bending angles derived from then background data using the Inverse Able Transform.

Parameter	Description	Range	Units	YES/NO
Processing Centre	Text indicating processing centre (40 characters)	[A-Z,0-9]	-	**YES**
Software Version	String indicating software version	[A-Z,0-9]	-	**YES**
Level 1 b algorithm	Text strings (40 characters) indicating algorithms used to derive bending angle, refractivity and meteorological data	[A-Z,0-9]	-	**YES**
Level 2 a algorithm		[A-Z,0-9]	-	**YES**
Level 2 b algorithm		[A-Z,0-9]	-	**YES**

Table 25 DWD ROPIC data set processing.

Parameter	Description	Range	Units	YES/NO
Background Source	Source of meteorological or atmospheric data used as background (ancillary) data	[A-Z,0-9]	-	**YES**
Verification Time	Verification time of background data (if applicable)	1999 01 01 00 00 - 2099 12 31 23 59	-	**YES**

Table 26 DWD ROPIC data set background meta data.

Parameter	Description	Range	Units	YES/NO
Time since start	Time since start of occultation to the time when georeferencing data and radius of curvature are determined	0 – 999.999	s	**YES**
Latitude	Position of tangent point as used for georeferencing	-90 … 90	deg	**YES**
Longitude		-180 … 180	deg	**YES**
Radius of Curvature	Radius of curvature	6.2 – 6.6 x 10^6	m	**YES**
Centre of Curvature	Centre of curvature coordinates (ECF; X, Y, Z)	± 10000	m	**YES**
Line of sight	GNSS to LEO azimuth direction w.r.t. North	0 – 360	deg	**NO**
Geoid Undulation	Difference between ellipsoid (WGS-84) and geoid (EGM-96) heights	± 150	m	**YES**

Table 27 DWD ROPIC data set georeferencing.

Parameter	Description	Range	Units	YES/NO
Product Confidence[1]	Product confidence data	Bit flags within a single 32-bit / 4-byte integer		NO
Data Quality	Overall summary data quality	0 - 100	%	YES

1 only used in the NetCDF ROPP format

Table 28 DWD ROPIC data set quality.

Parameter	Description	Range	Units	YES/NO
Latitude	Longitude and Latitude w.r.t. the WGS 84 ellipsoid of the tangential point of the generic bending angle	-90 … 90	deg	YES
Longitude		-180 … 180	deg	YES
Azimuth	GNSS to LEO azimuth w.r.t. North at tangent point	0 - 360	deg	NO
Impact Parameter L1	Impact parameter derived from L1	$6.2 \times 10^6 - 6.6 \times 10^6$	m	YES
Impact Parameter L2	Impact parameter derived from L2	$6.2 \times 10^6 - 6.6 \times 10^6$	m	YES
Impact Parameter	Impact parameter generic	$6.2 \times 10^6 - 6.6 \times 10^6$	m	YES
Bending Angle L1	Bending angle derived from L1	$-10^{-4} - 0.05$	rad	YES
Bending Angle L2	Bending angle derived from L2	$-10^{-4} - 0.05$	rad	YES
Bending Angle	Bending angle generic	$-10^{-4} - 0.05$	rad	YES
Bending Angle Errors L1	Estimated errors (one σ) of bending angle values L1	0 – 0.02	rad	NO
Bending Angle Errors L2	Estimated errors (one σ) of bending angle values L2	0 – 0.02	rad	NO
Bending Angle Errors	Estimated errors (one σ) of bending angle values generic	0 – 0.02	rad	YES
Bending Angle Quality L1	Percentage confidence value for bending angles L1	0 - 100	%	YES
Bending Angle Quality L2	Percentage confidence values for bending angles L2	0 - 100	%	YES
Bending Angle Quality	Percentage confidence values for bending angles generic	0 - 100	%	YES

Table 29 DWD ROPIC data set Level 1b.

Parameter	Description	Range	Units	YES/NO
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m	**YES**
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm	**NO**
Refractivity	Derived refractivity	0 - 500	N-units	**YES**
Refractivity Error	Estimated errors (one σ) of refractivity values	0 - 100	N-units	**YES**
Refractivity Quality	Percentage confidence value	0 - 100	%	**YES**

Table 30 DWD ROPIC data set Level 2a.

Parameter	Description	Range	Units	YES/NO
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm	**YES**
Geopotential Height Error	Estimated errors (one σ) of geopotential height values		gpm	**NO**
Pressure	Retrieved pressure	0.1 - 1100	hPa	**YES**
Pressure Error	Estimated errors (one σ) of pressure values	0 - 50	hPa	**NO**
Temperature	Retrieved temperature	150 - 350	K	**YES**
Temperature Error	Estimated errors (one σ) of temperature values	0 - 50	K	**NO**
Specific Humidity	Retrieved specific humidity	0 - 50	g/kg	**YES**
Specific Humidity Error	Estimated errors (one σ) of specific humidity values	0 - 10	g/kg	**NO**
Quality	Overall percentage confidence value	0 - 100	%	**NO**

Table 31 DWD ROPIC data set Level 2b.

Parameter	Description	Range	Units	YES/NO
Geopotential Height Surface	Geopotential height of surface above geoid (EGM 96)	-1000 - 100000	gpm	**NO**
Surface Pressure	Retrieved surface (or reference) pressure	900 - 1100	hPa	**NO**
Surface Pressure Error	Estimated errors (one σ) of surface pressure values	0 - 50	hPa	**NO**
Quality	Percentage confidence value	0 - 100	%	**NO**

Table 32 DWD ROPIC data set Level 2c.

Parameter	Description	Range	Units	YES/NO
Temperature	ECMWF temperature	150 - 350	K	**YES**
Dry Temperature	ECMWF dry temperature	150 - 350	K	**NO**
Specific Humidity	ECMWF specific humidity	0 - 50	g/kg	**YES**
Pressure	ECMWF derived pressure	0.1 - 1100	hPa	**YES**
Geopotential Height	ECMWF derived geopotential height	-1000 - 100000	gpm	**YES**
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m	**YES**
Refractivity	ECMWF derived refractivity	0 - 500	N-units	**YES**
Surface Pressure	ECMWF surface pressure	900 - 1100	hPa	**YES**
Surface Height	ECMWF surface height	-1000 - 100000	m	**NO**
Surface Geopotential	ECMWF surface geopotential	-1000 - 8000	gpm	**YES**
Surface Temperature	ECMWF surface temperature	0 - 500	K	**NO**
Skin Temperature	ECMWF skin temperature	0 - 500	K	**NO**
Surface Humidity	ECMWF surface humidity	0 – 0.05	g/kg	**NO**

Table 33 DWD ROPIC data set background data.

Parameter	Description	Range	Units	YES/NO
Dry Temperature	Retrieved dry temperature	150 – 350	K	**NO**
Optimized Bending Angle	Retrieved optimized bending angle	-10^{-4} – 0.05	rad	**NO**
Reference Bending Angle Inverse Able	From background derived (inverse able) bending angle	-10^{-4} – 0.05	rad	**YES**
Reference Bending Angle Retraced	From background derived (raytraced) bending angle	-10^{-4} – 0.05	rad	**YES????**
Density	Retrieved density	0 - 1100	Kg/m^3	**NO**

Table 34 DWD ROPIC data set additional data.

UCAR Data Set

The UCAR data had been retrieved from the CDAAC in the GFZ ASCII format; the collocated ECMWF background profiles and derived quantities had been retrieved at DMI using the local scripts. The same external quality check as used for the DMI data had been used at the 10% level to generate a second data set (no profile was rejected).

Parameter	Description	Range	Units	YES/NO
Processing Centre	Text indicating processing centre (40 characters)	[A-Z,0-9]	-	YES
Software Version	String indicating software version	[A-Z,0-9]	-	YES
Level 1 b algorithm	Text strings (40 characters) indicating algorithms used to derive bending angle, refractivity and meteorological data	[A-Z,0-9]	-	NO
Level 2 a algorithm		[A-Z,0-9]	-	NO
Level 2 b algorithm		[A-Z,0-9]	-	NO

Table 35 UCAR ROPIC data set processing.

Parameter	Description	Range	Units	YES/NO
Background Source	Source of meteorological or atmospheric data used as background (ancillary) data	[A-Z,0-9]	-	YES
Verification Time	Verification time of background data (if applicable)	1999 01 01 00 00 - 2099 12 31 23 59	-	NO

Table 36 UCAR ROPIC data set background meta data.

Parameter	Description	Range	Units	YES/NO
Time since start	Time since start of occultation to the time when georeferencing data and radius of curvature are determined	0 – 999.999	s	YES
Latitude	Position of tangent point as used for georeferencing	-90 … 90	deg	YES
Longitude		-180 … 180	deg	YES
Radius of Curvature	Radius of curvature	6.2 – 6.6 x 10^6	m	NO
Centre of Curvature	Centre of curvature coordinates (ECF; X, Y, Z)	± 10000	m	NO
Line of sight	GNSS to LEO azimuth direction w.r.t. North	0 – 360	deg	NO
Geoid Undulation	Difference between ellipsoid (WGS-84) and geoid (EGM-96) heights	± 150	m	NO

Table 37 UCAR ROPIC data set georeferencing.

Parameter	Description	Range	Units	YES/NO
Product Confidence[1]	Product confidence data	Bit flags within a single 32-bit / 4-byte integer		**NO**
Data Quality	Overall summary data quality	0 - 100	%	**NO**

1 only used in the NetCDF ROPP format

Table 38 UCAR ROPIC data set quality.

Parameter	Description	Range	Units	YES/NO
Latitude	Longitude and Latitude w.r.t. the WGS 84 ellipsoid of the tangential point of the generic bending angle	-90 … 90	deg	**YES**
Longitude		-180 … 180	deg	**YES**
Azimuth	GNSS to LEO azimuth w.r.t. North at tangent point	0 - 360	deg	**NO**
Impact Parameter L1	Impact parameter derived from L1	$6.2 \times 10^6 - 6.6 \times 10^6$	m	**NO**
Impact Parameter L2	Impact parameter derived from L2	$6.2 \times 10^6 - 6.6 \times 10^6$	m	**NO**
Impact Parameter	Impact parameter generic	$6.2 \times 10^6 - 6.6 \times 10^6$	m	**YES**
Bending Angle L1	Bending angle derived from L1	$-10^{-4} - 0.05$	rad	**NO**
Bending Angle L2	Bending angle derived from L2	$-10^{-4} - 0.05$	rad	**NO**
Bending Angle	Bending angle generic	$-10^{-4} - 0.05$	rad	**NO**
Bending Angle Errors L1	Estimated errors (one σ) of bending angle values L1	0 – 0.02	rad	**NO**
Bending Angle Errors L2	Estimated errors (one σ) of bending angle values L2	0 – 0.02	rad	**NO**
Bending Angle Errors	Estimated errors (one σ) of bending angle values generic	0 – 0.02	rad	**NO**
Bending Angle Quality L1	Percentage confidence value for bending angles L1	0 - 100	%	**NO**
Bending Angle Quality L2	Percentage confidence values for bending angles L2	0 - 100	%	**NO**
Bending Angle Quality	Percentage confidence values for bending angles generic	0 - 100	%	**NO**

Table 39 UCAR ROPIC data set Level 1b.

Parameter	Description	Range	Units	YES/NO
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m	**YES**
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm	**NO**
Refractivity	Derived refractivity	0 - 500	N-units	**YES**
Refractivity Error	Estimated errors (one σ) of refractivity values	0 - 100	N-units	**NO**
Refractivity Quality	Percentage confidence value	0 - 100	%	**NO**

Table 40 UCAR ROPIC data set Level 2a.

Parameter	Description	Range	Units	YES/NO
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm	**NO**
Geopotential Height Error	Estimated errors (one σ) of geopotential height values		gpm	**NO**
Pressure	Retrieved pressure	0.1 - 1100	hPa	**YES**
Pressure Error	Estimated errors (one σ) of pressure values	0 - 50	hPa	**NO**
Temperature	Retrieved temperature	150 - 350	K	**NO**
Temperature Error	Estimated errors (one σ) of temperature values	0 - 50	K	**NO**
Specific Humidity	Retrieved specific humidity	0 - 50	g/kg	**NO**
Specific Humidity Error	Estimated errors (one σ) of specific humidity values	0 - 10	g/kg	**NO**
Quality	Overall percentage confidence value	0 - 100	%	**NO**

Table 41 UCAR ROPIC data set Level 2b.

Parameter	Description	Range	Units	YES/NO
Geopotential Height Surface	Geopotential height of surface above geoid (EGM 96)	-1000 - 100000	gpm	**NO**
Surface Pressure	Retrieved surface (or reference) pressure	900 - 1100	hPa	**NO**
Surface Pressure Error	Estimated errors (one σ) of surface pressure values	0 - 50	hPa	**NO**
Quality	Percentage confidence value	0 - 100	%	**NO**

Table 42 UCAR ROPIC data set Level 2c.

Parameter	Description	Range	Units	YES/NO
Temperature	ECMWF temperature	150 - 350	K	YES
Dry Temperature	ECMWF dry temperature	150 - 350	K	NO
Specific Humidity	ECMWF specific humidity	0 - 50	g/kg	YES
Pressure	ECMWF derived pressure	0.1 - 1100	hPa	YES
Geopotential Height	ECMWF derived geopotential height	-1000 - 100000	gpm	YES
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m	YES
Refractivity	ECMWF derived refractivity	0 - 500	N-units	YES
Surface Pressure	ECMWF surface pressure	900 - 1100	hPa	YES
Surface Height	ECMWF surface height	-1000 - 100000	m	YES
Surface Geopotential	ECMWF surface geopotential	-1000 - 8000	gpm	YES
Surface Temperature	ECMWF surface temperature	0 - 500	K	NO
Skin Temperature	ECMWF skin temperature	0 - 500	K	NO
Surface Humidity	ECMWF surface humidity	0 – 0.05	g/kg	NO

Table 43 UCAR ROPIC data set background data.

Parameter	Description	Range	Units	YES/NO
Dry Temperature	Retrieved dry temperature	150 – 350	K	YES
Optimized Bending Angle	Retrieved optimized bending angle	-10^{-4} – 0.05	rad	NO
Reference Bending Angle Inverse Able	From background derived (inverse able) bending angle	-10^{-4} – 0.05	rad	NO
Reference Bending Angle Retraced	From background derived (raytraced) bending angle	-10^{-4} – 0.05	rad	NO
Density	Retrieved density	0 - 1100	Kg/m^3	YES

Table 44 UCAR ROPIC data set additional data.

Data Analysis

Used Statistics

To calculate the statistics the IDL routine MOMENT was used. The MOMENT function computes the mean, variance, skewness, and kurtosis of a sample population contained in an *n*-element vector **X**. When **x** = (x_0, x_1, x_2, ..., x_{n-1}), the various moments are defined as follows:

$$\text{Mean} = \bar{x} = \frac{1}{N}\sum_{j=0}^{N-1} x_j \quad (1)$$

$$\text{Variance} = \tilde{x} = \frac{1}{N-1}\sum_{j=0}^{N-1} (x_j - \bar{x})^2 \quad (2)$$

$$\text{Skewness} = \frac{1}{N}\sum_{j=0}^{N-1}\left(\frac{x_j - \bar{x}}{\sqrt{\tilde{x}}}\right)^3 \quad (3)$$

$$\text{Kurtosis} = \frac{1}{N}\sum_{j=0}^{N-1}\left(\frac{x_j - \bar{x}}{\sqrt{\tilde{x}}}\right)^4 - 3 \quad (4)$$

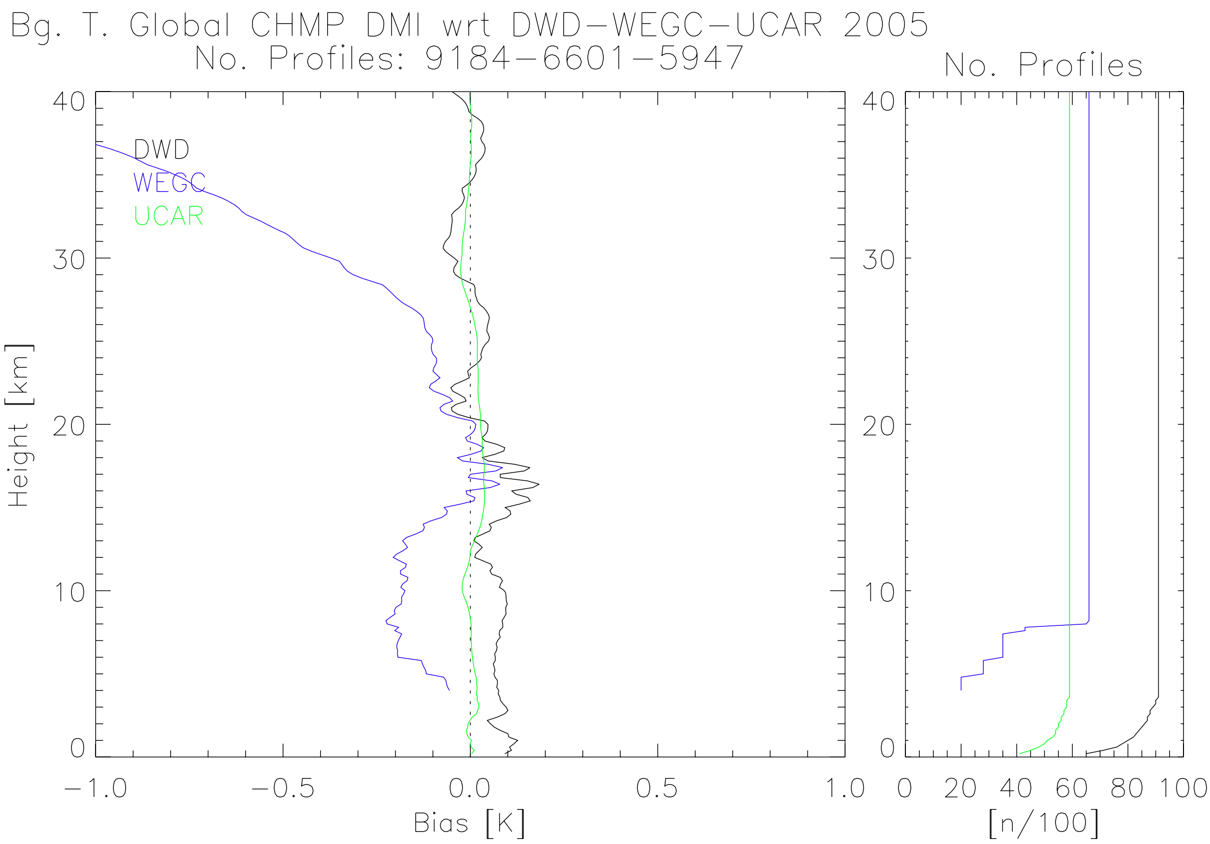
$$\text{Mean Absolute Deviation} = \frac{1}{N}\sum_{j=0}^{N-1}\left|x_j - \bar{x}\right| \quad (5)$$

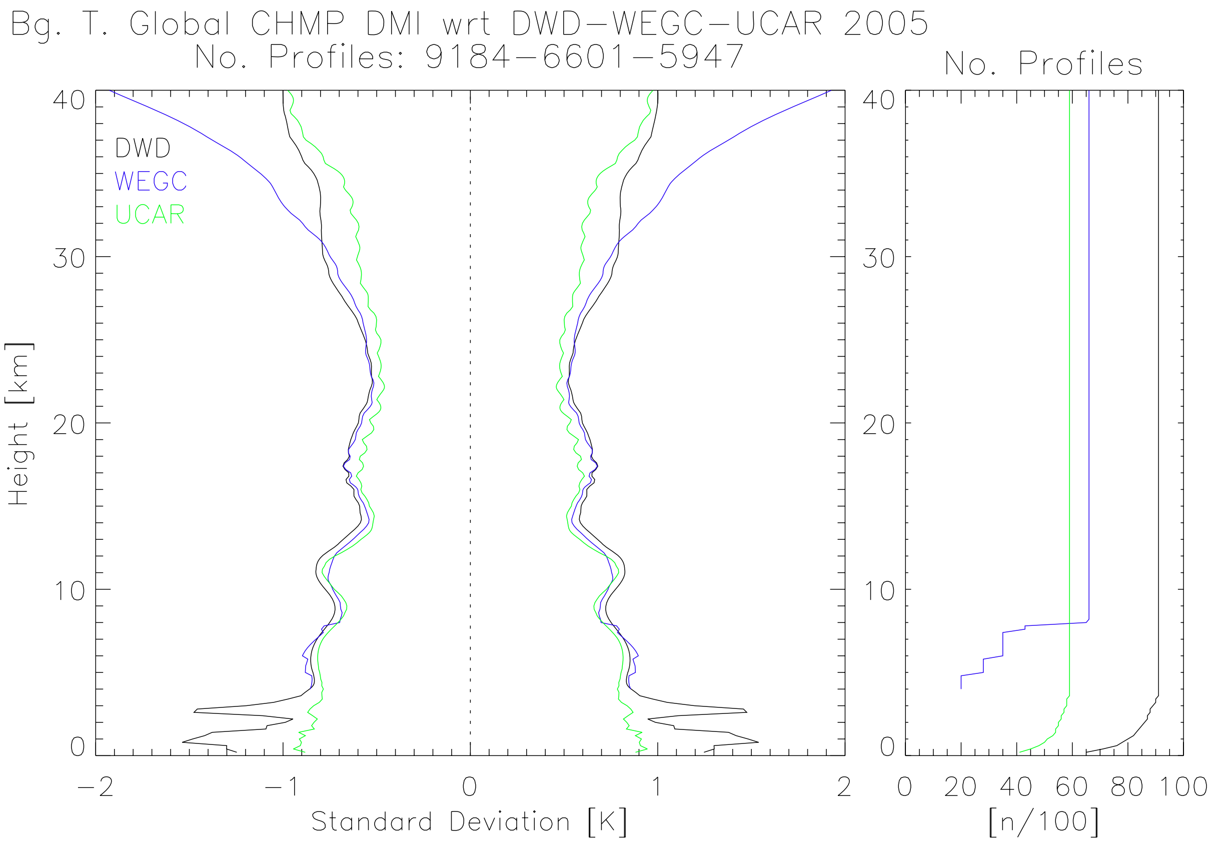
$$\text{Standard Deviation} = \sqrt{\tilde{x}} \quad (6)$$

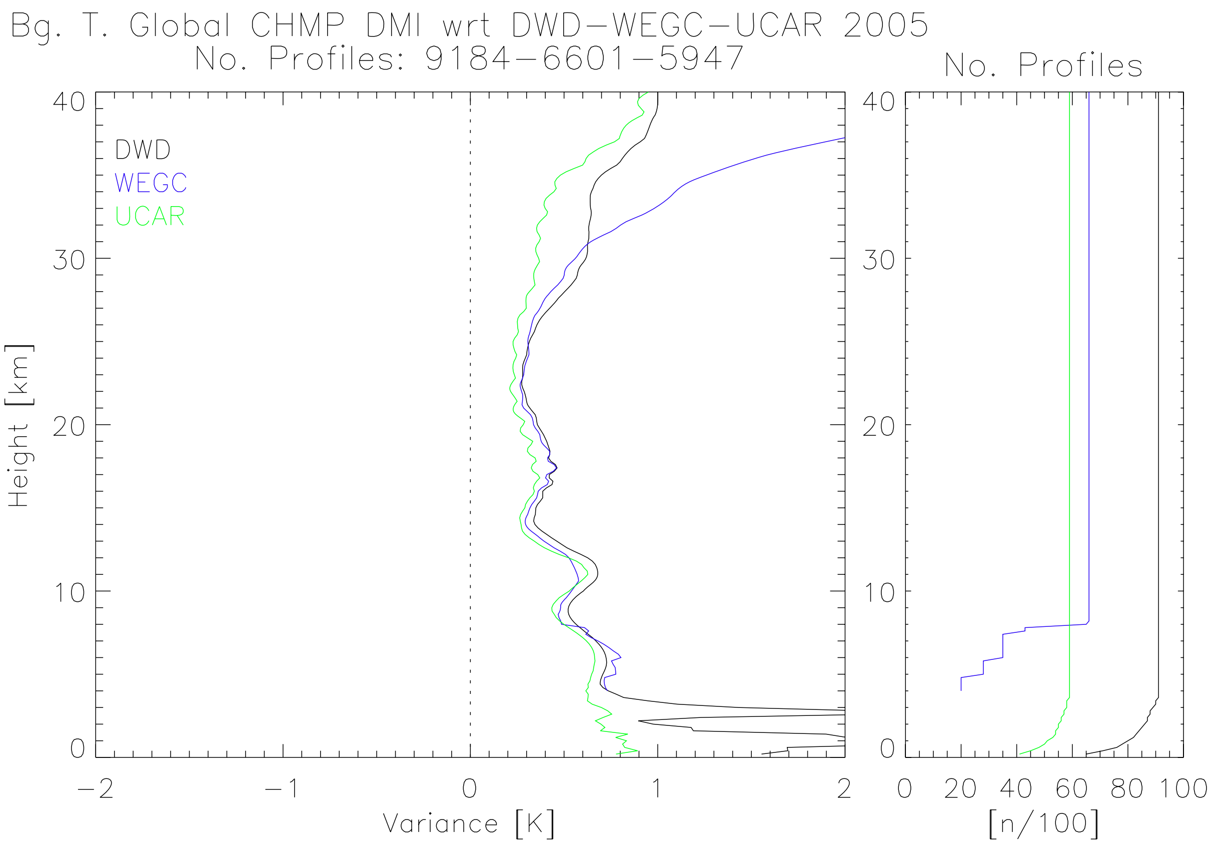
Validation

To perform an initial assessment of the provided data sets some simple validation steps are conducted. As a first step the background data of the different data sets is compared to find any possible inconsistencies within the data sets concerning the retrieval procedures of the background data and the derivation of atmospheric quantities. In general the statistics are computed from DMI minus the other centers results.

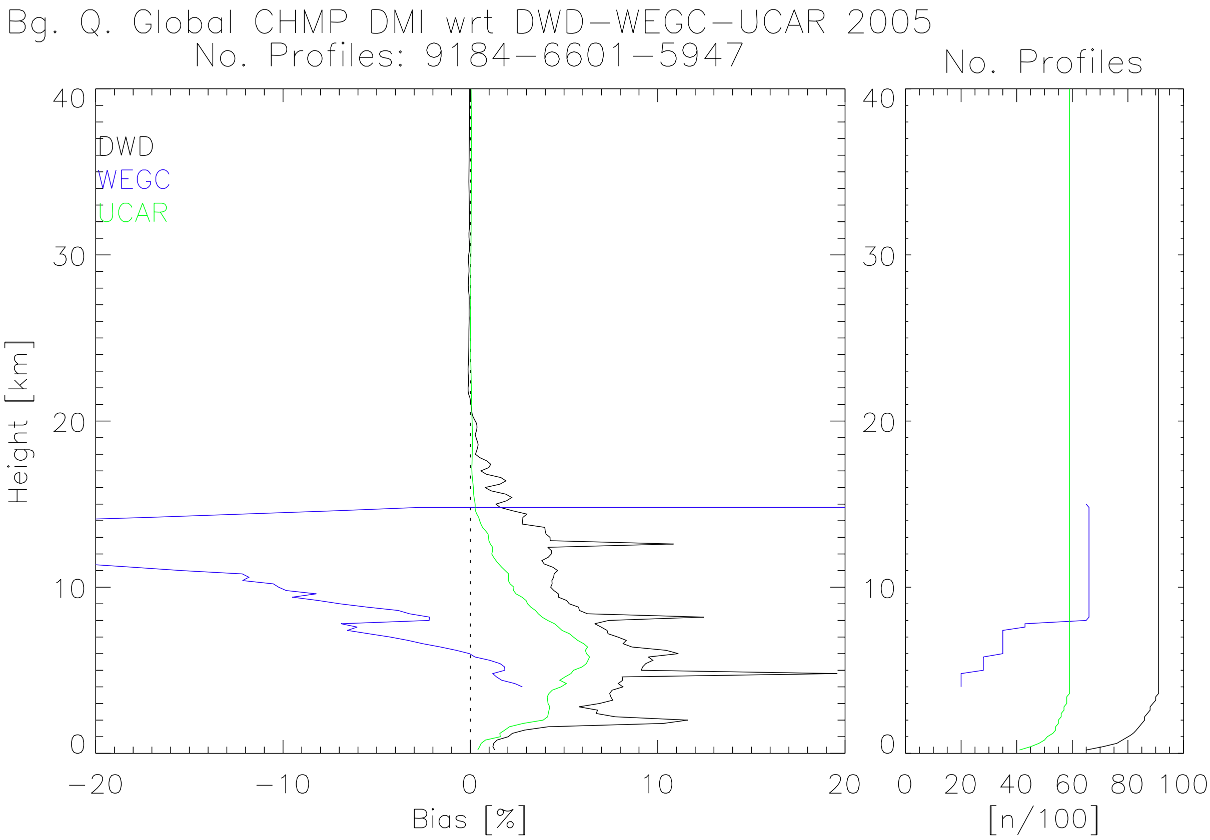
Background Temperature

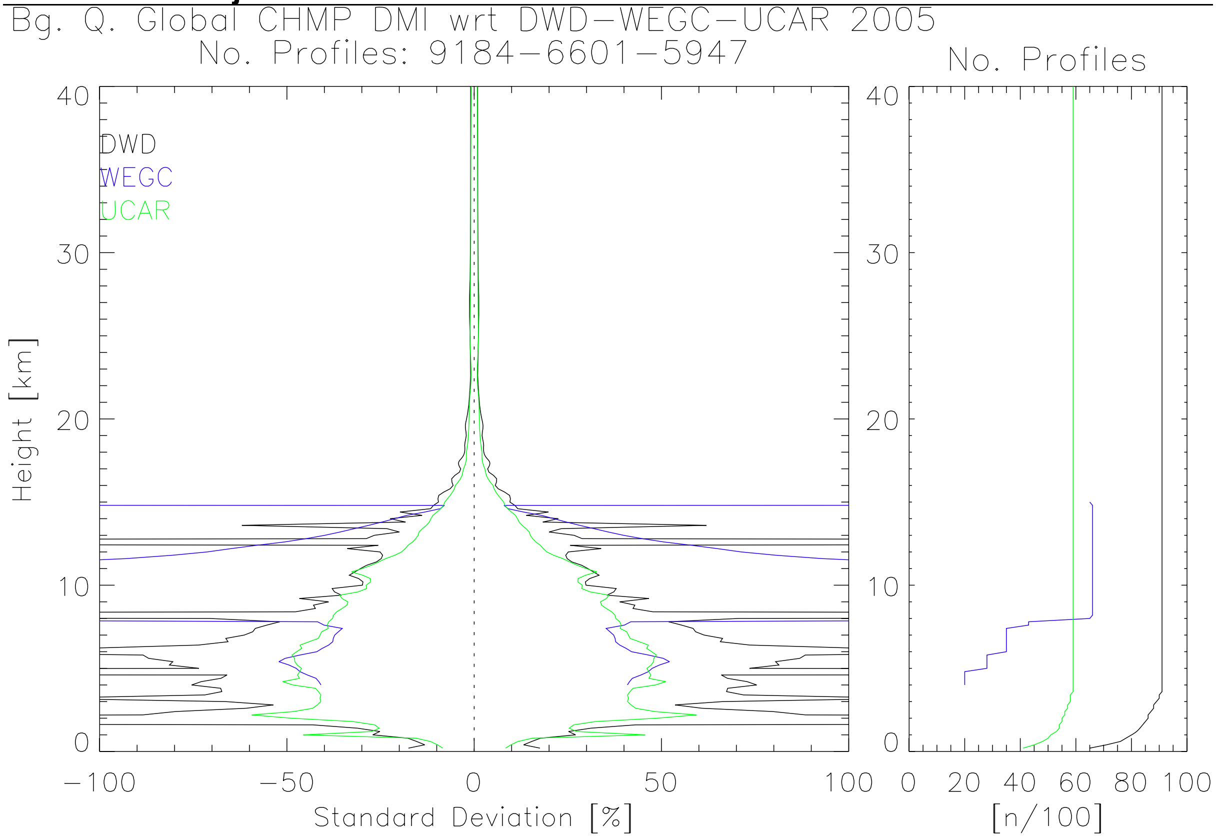


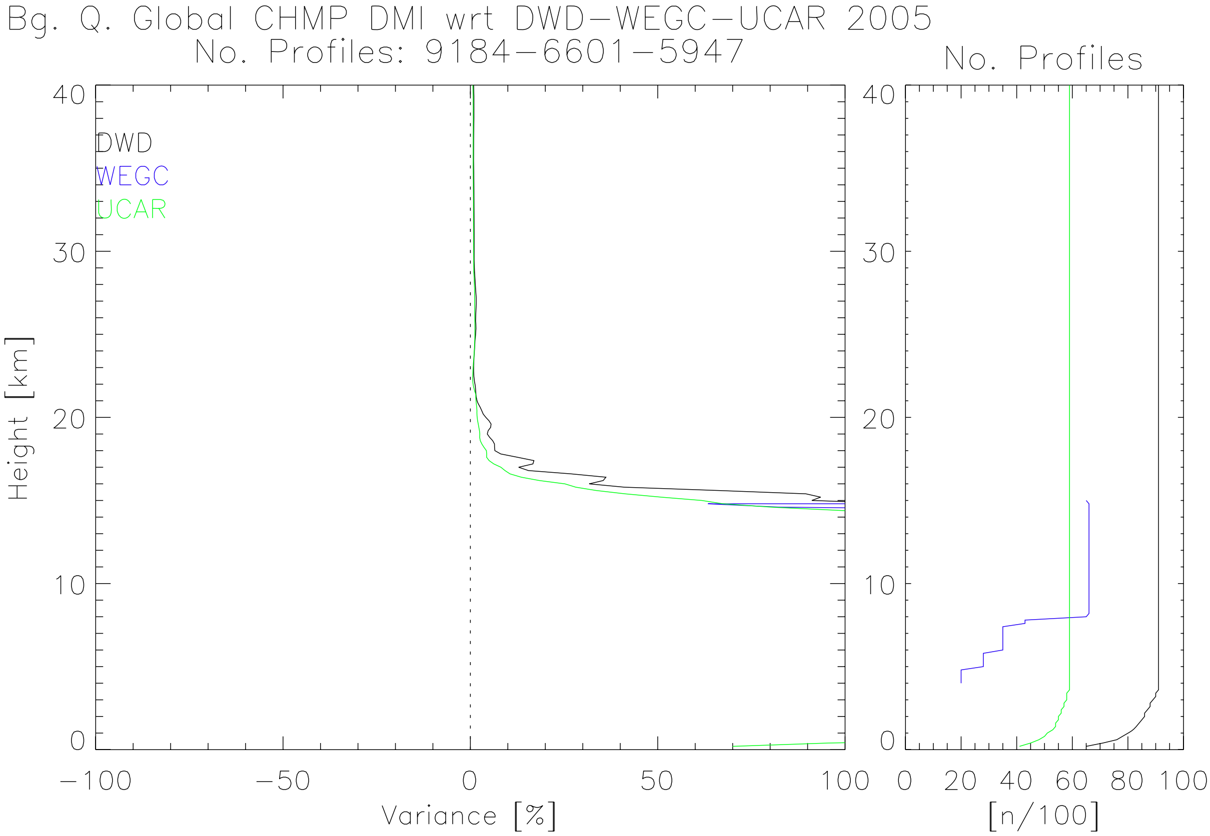

Bg. T. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
Standard Deviation [K]
[n/100]


Bg. T. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
Variance [K]
[n/100]

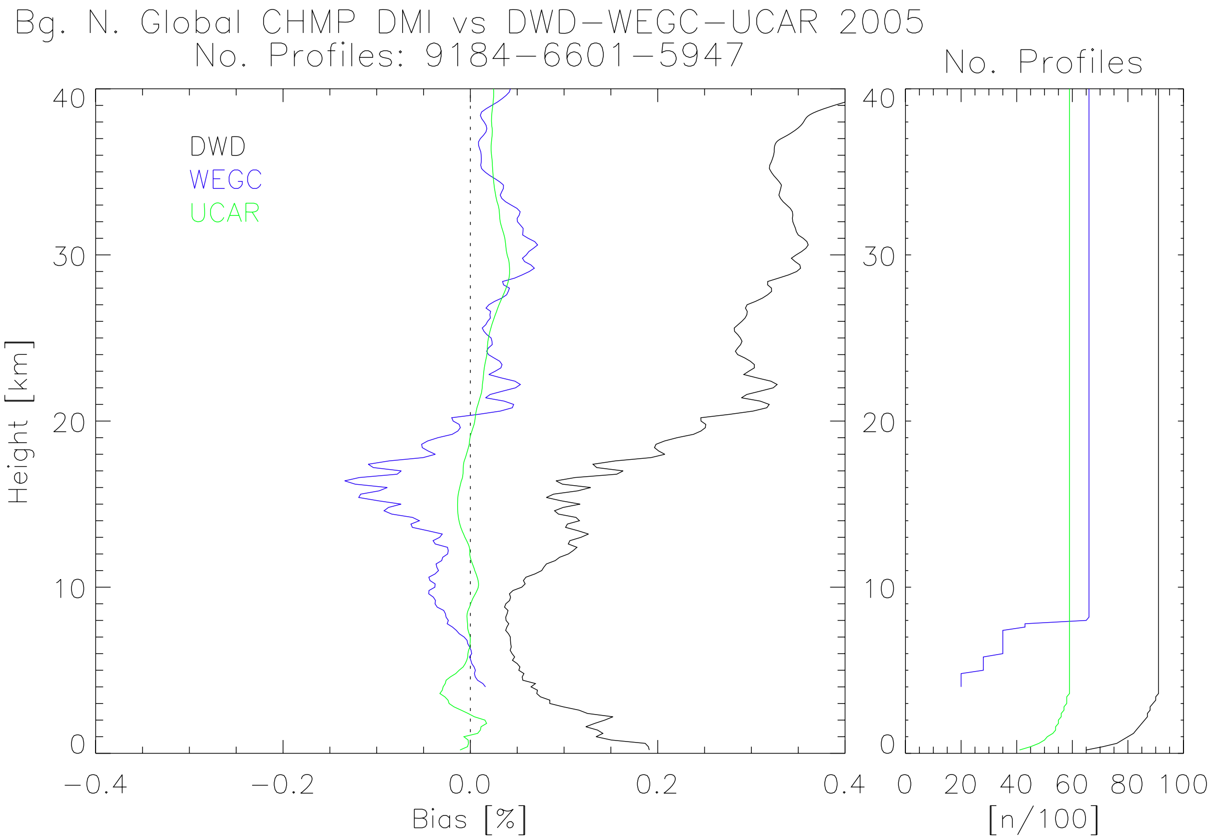
Background Specific Humidity

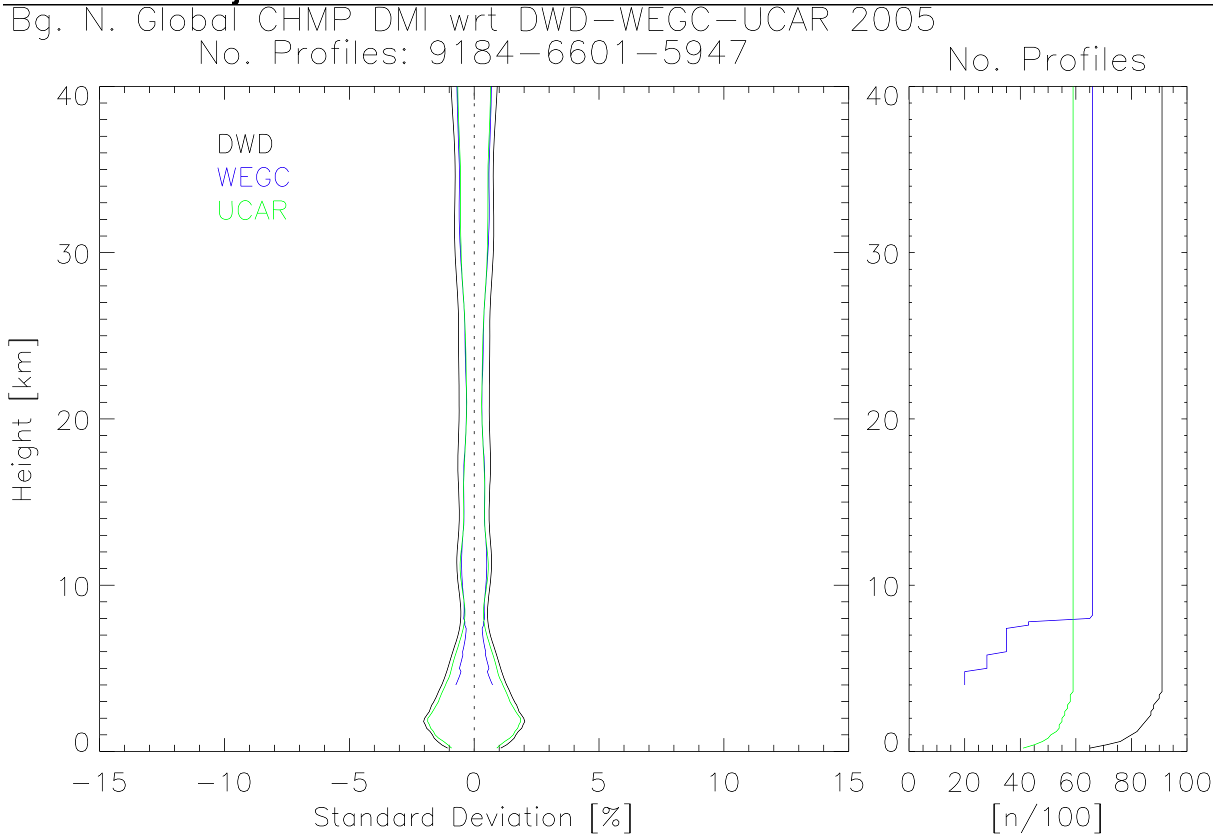


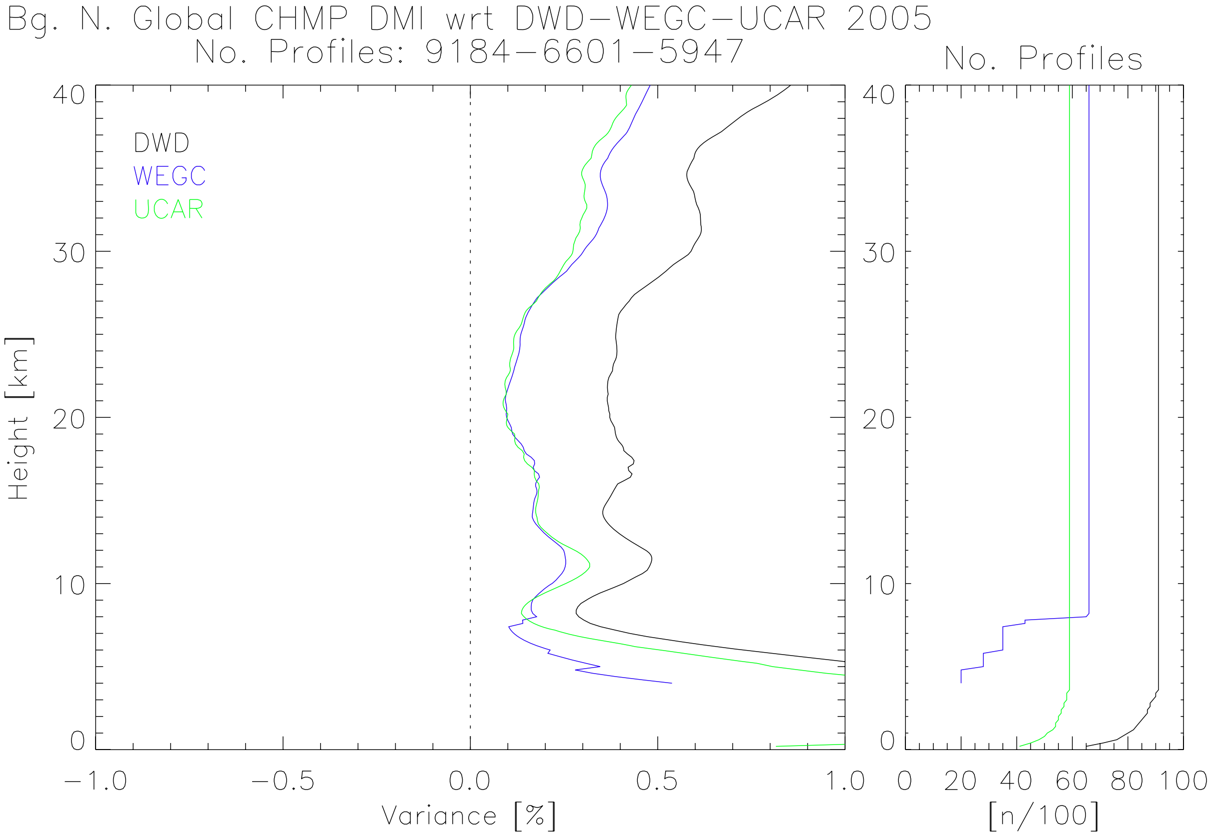

Bg. Q. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
Standard Deviation [%]
[n/100]


Bg. Q. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
Variance [%]
[n/100]

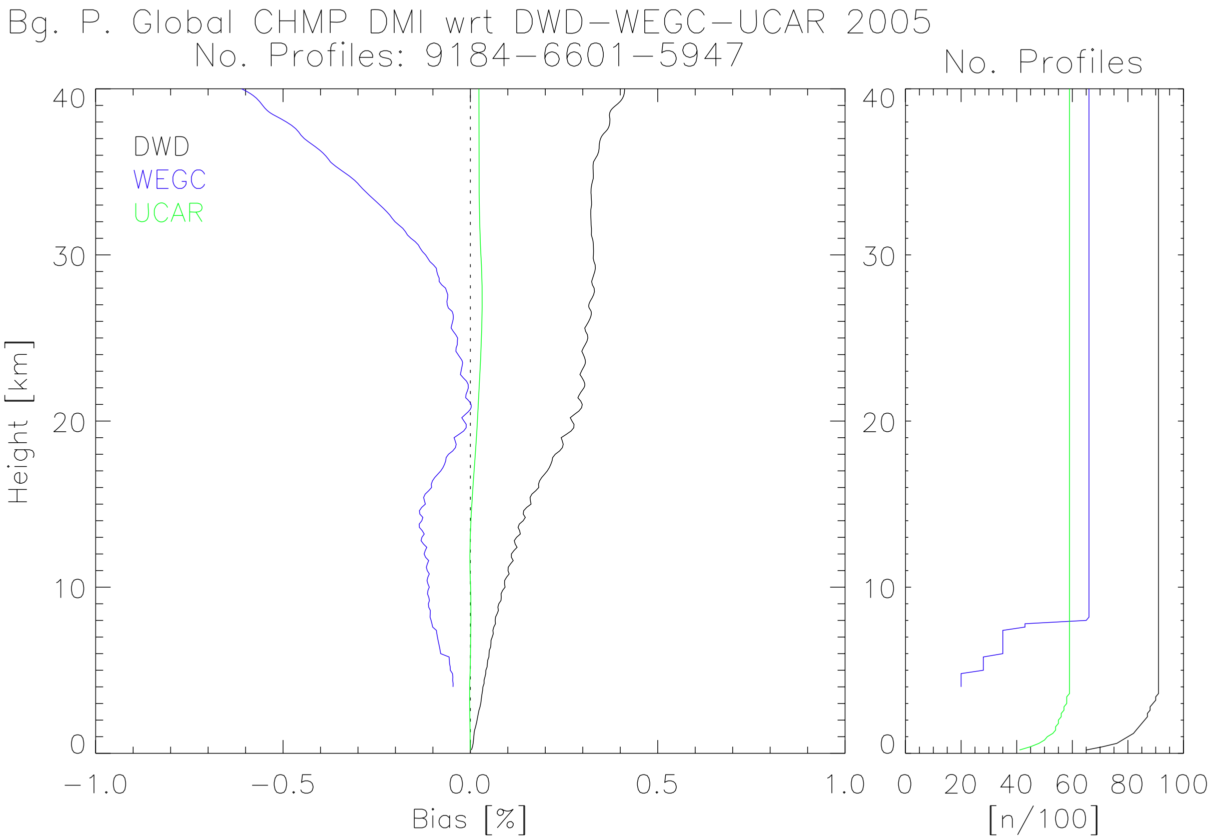
Refractivity

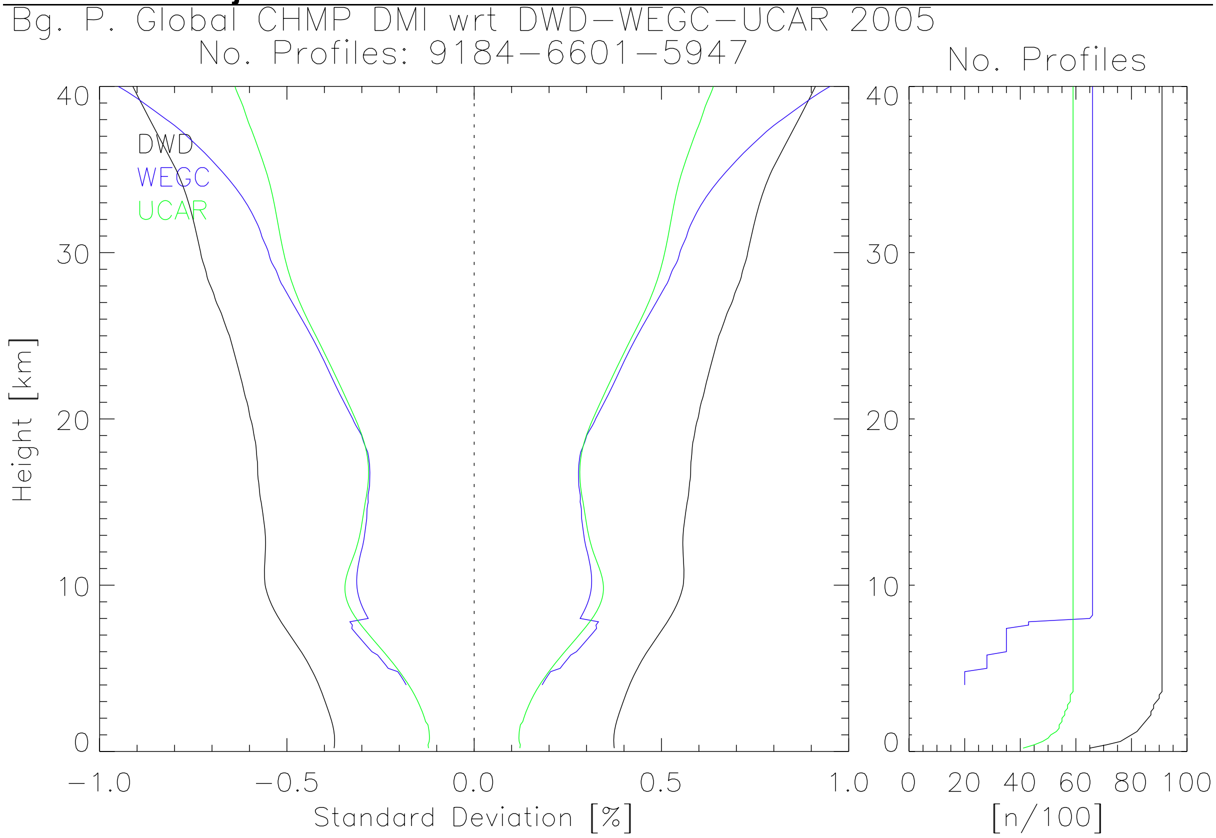


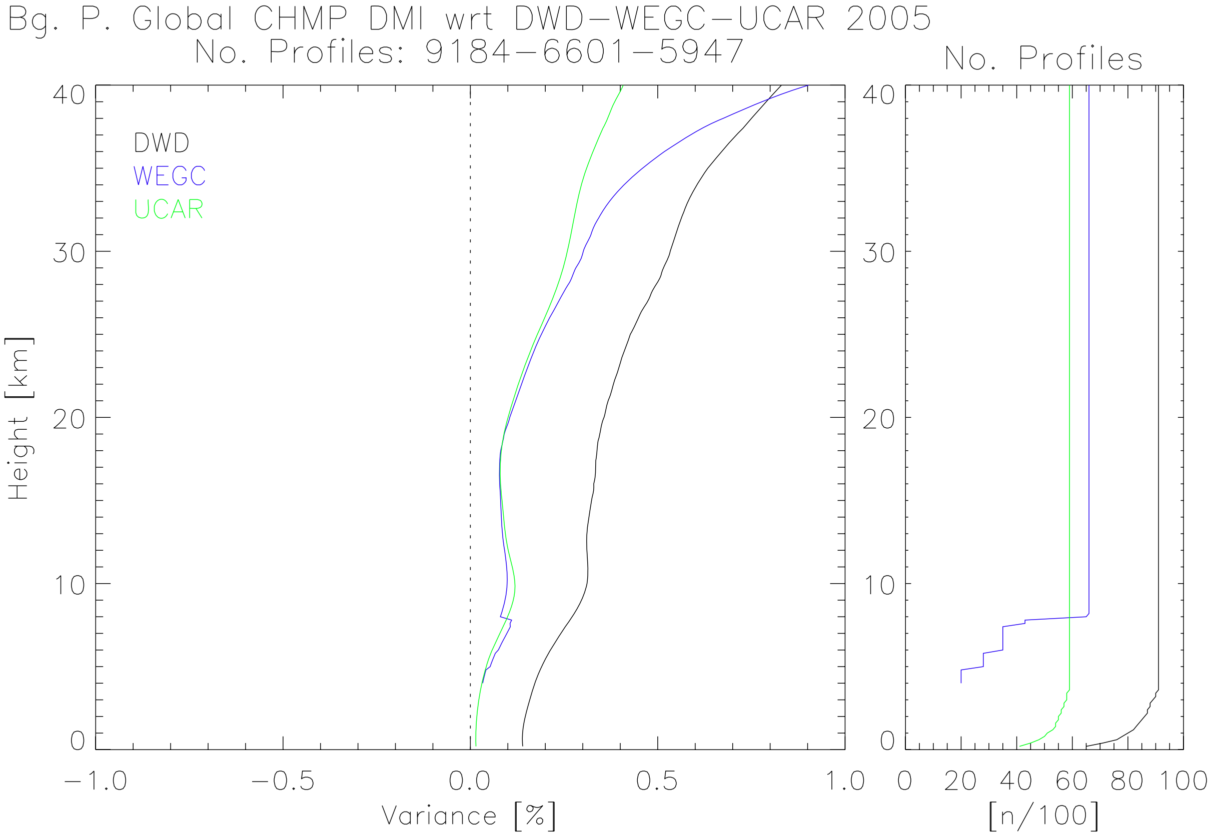

Bg. N. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
Standard Deviation [%]
[n/100]


Bg. N. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
Variance [%]
[n/100]

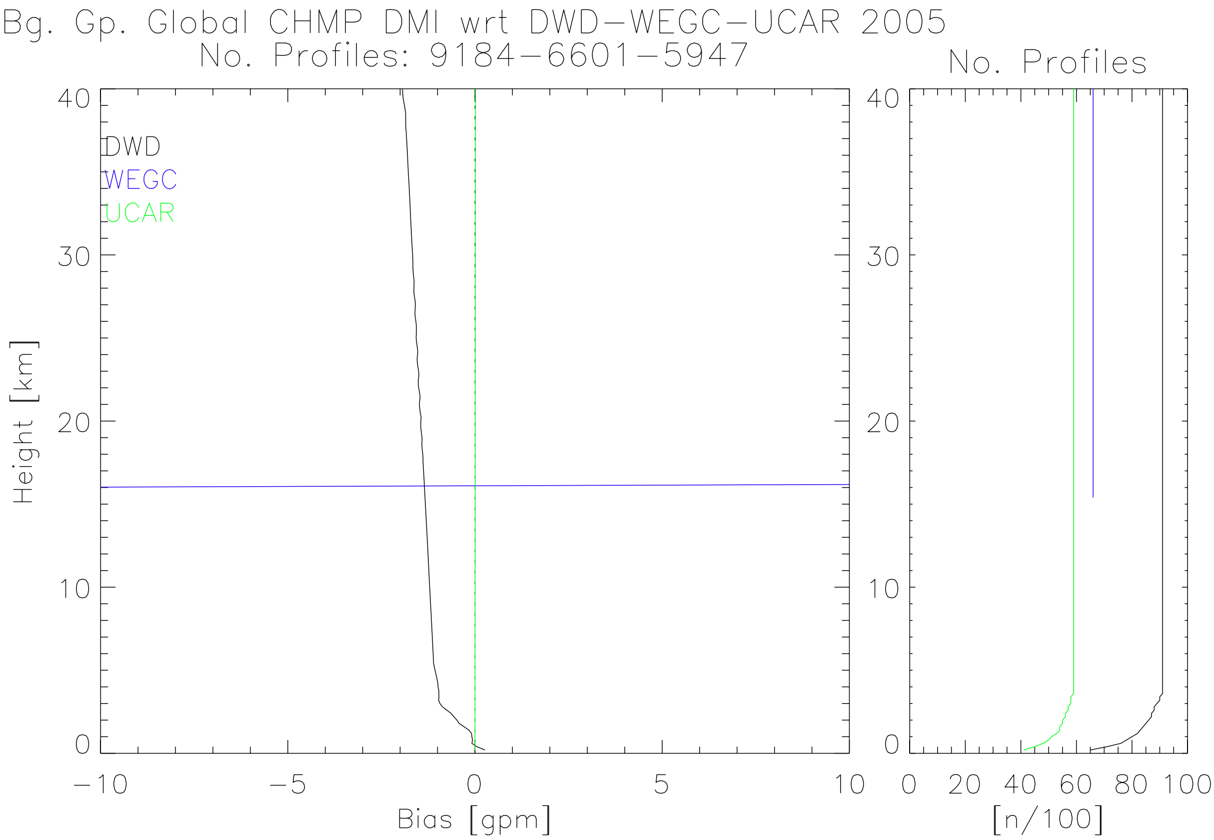
Pressure

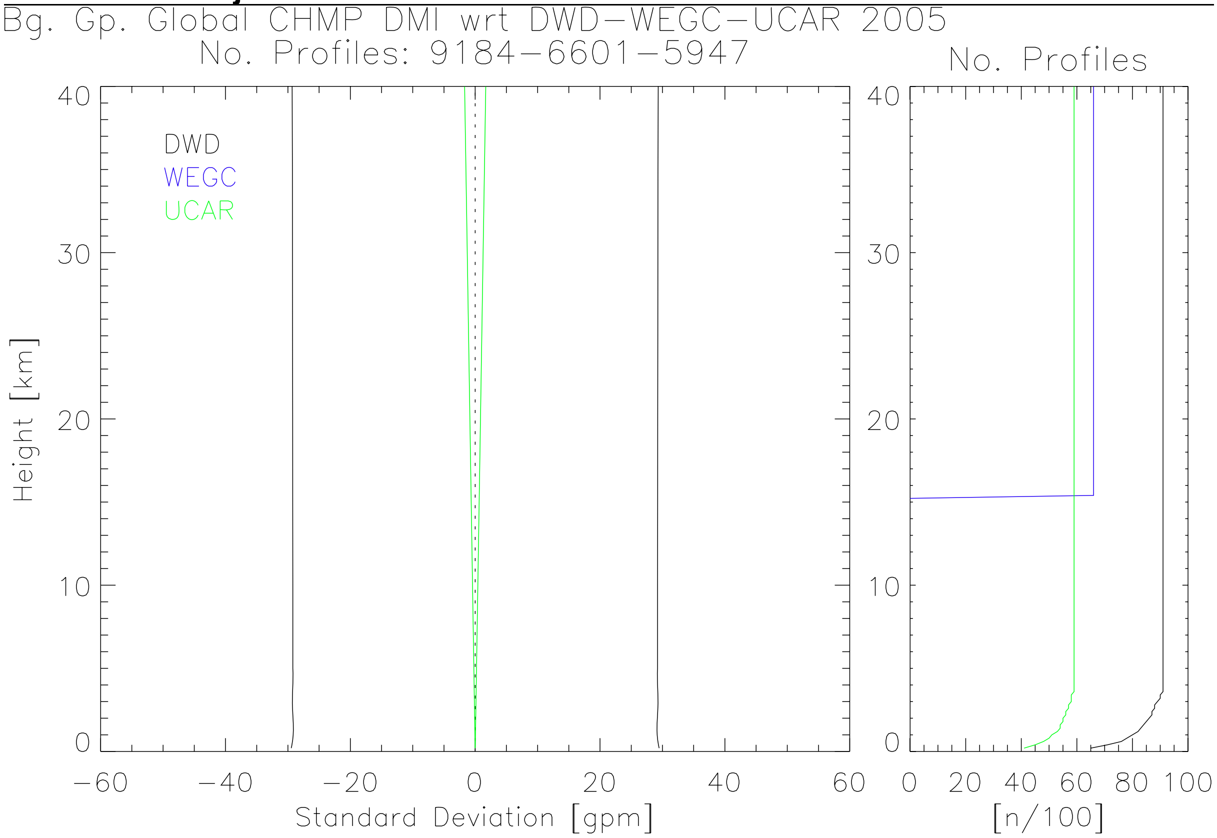

Bg. P. Global CHMP DMI wrt DWD–WEGC–UCAR 2005
No. Profiles: 9184–6601–5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
Bias [%]
[n/100]
0
10
20
30
40
–1.0
–0.5
0.0
0.5
1.0
0
20
40
60
80
100

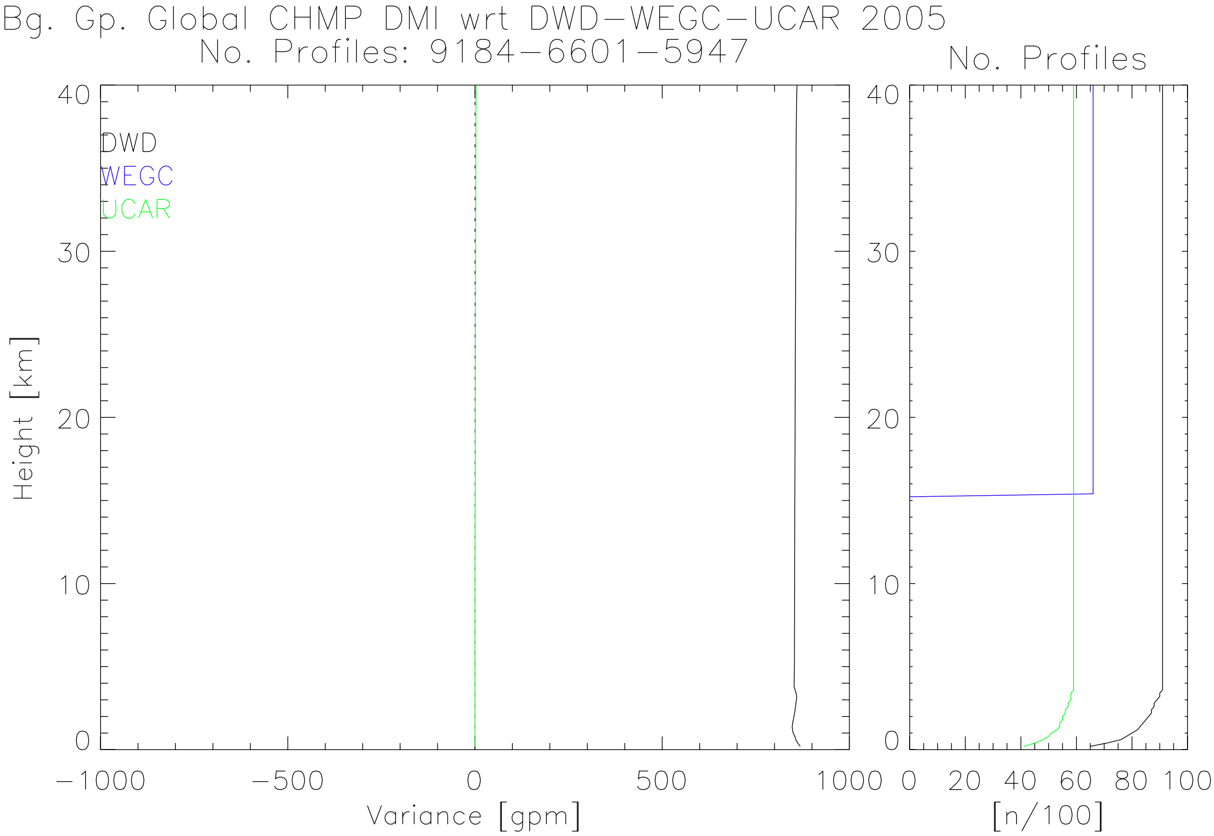

Bg. P. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0
Standard Deviation [%]
0 20 40 60 80 100
[n/100]


Bg. P. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0
Variance [%]
0 20 40 60 80 100
[n/100]

Geopotential



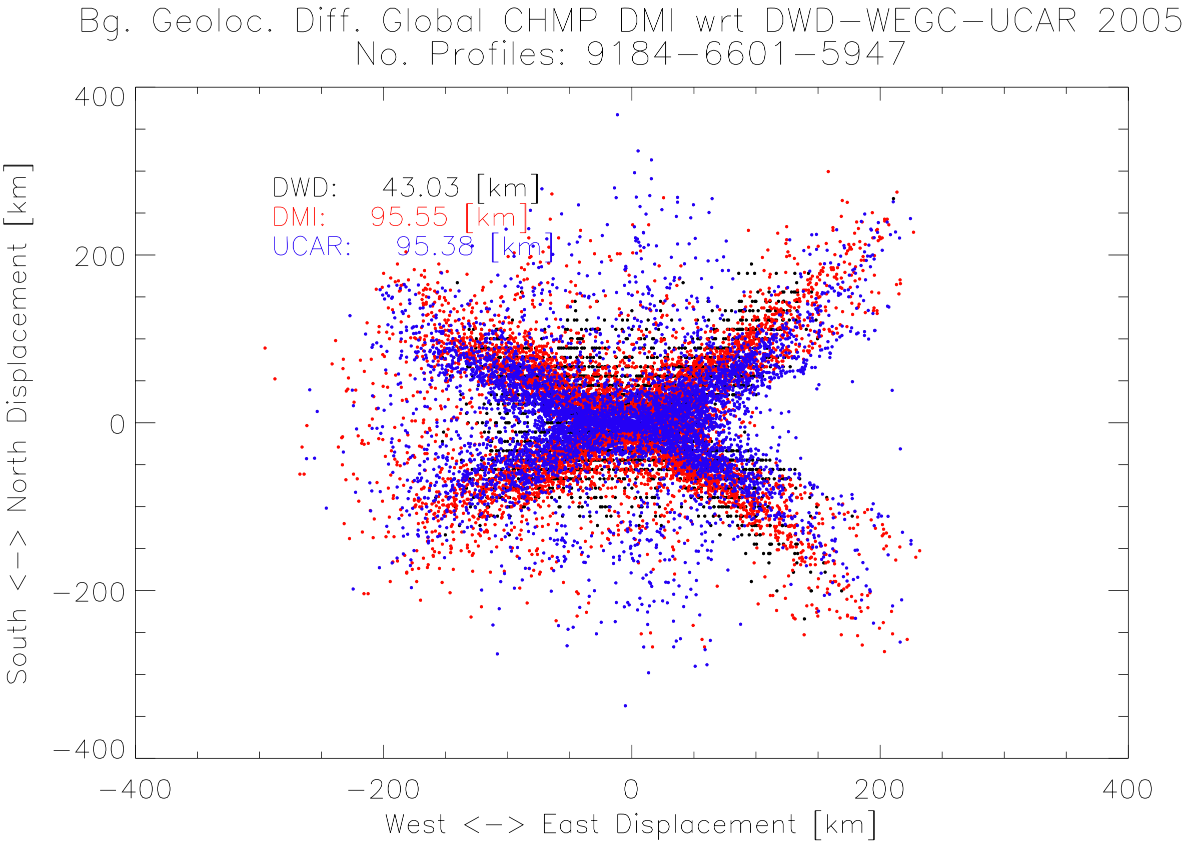

Bg. Gp. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
Standard Deviation [gpm]
[n/100]


Bg. Gp. Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Height [km]
Variance [gpm]
[n/100]

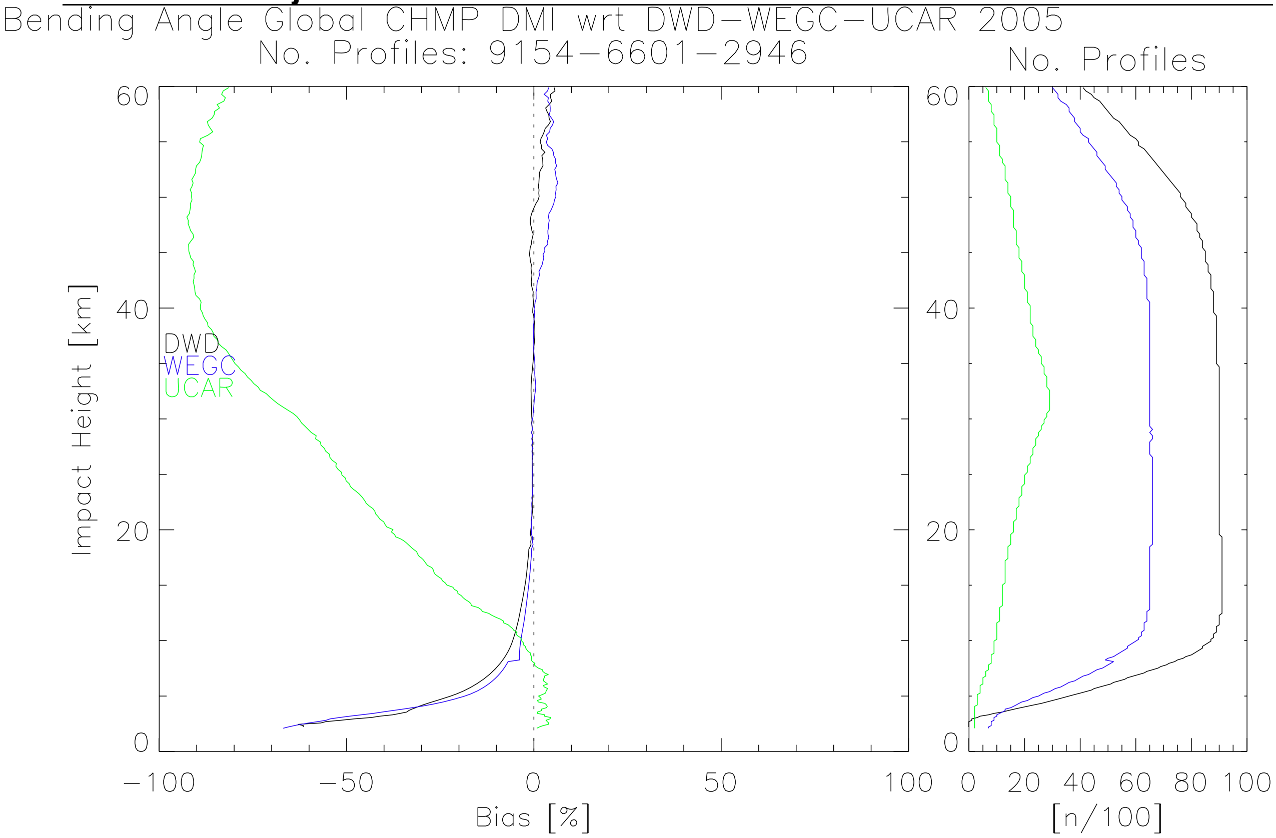
Retrieved Data

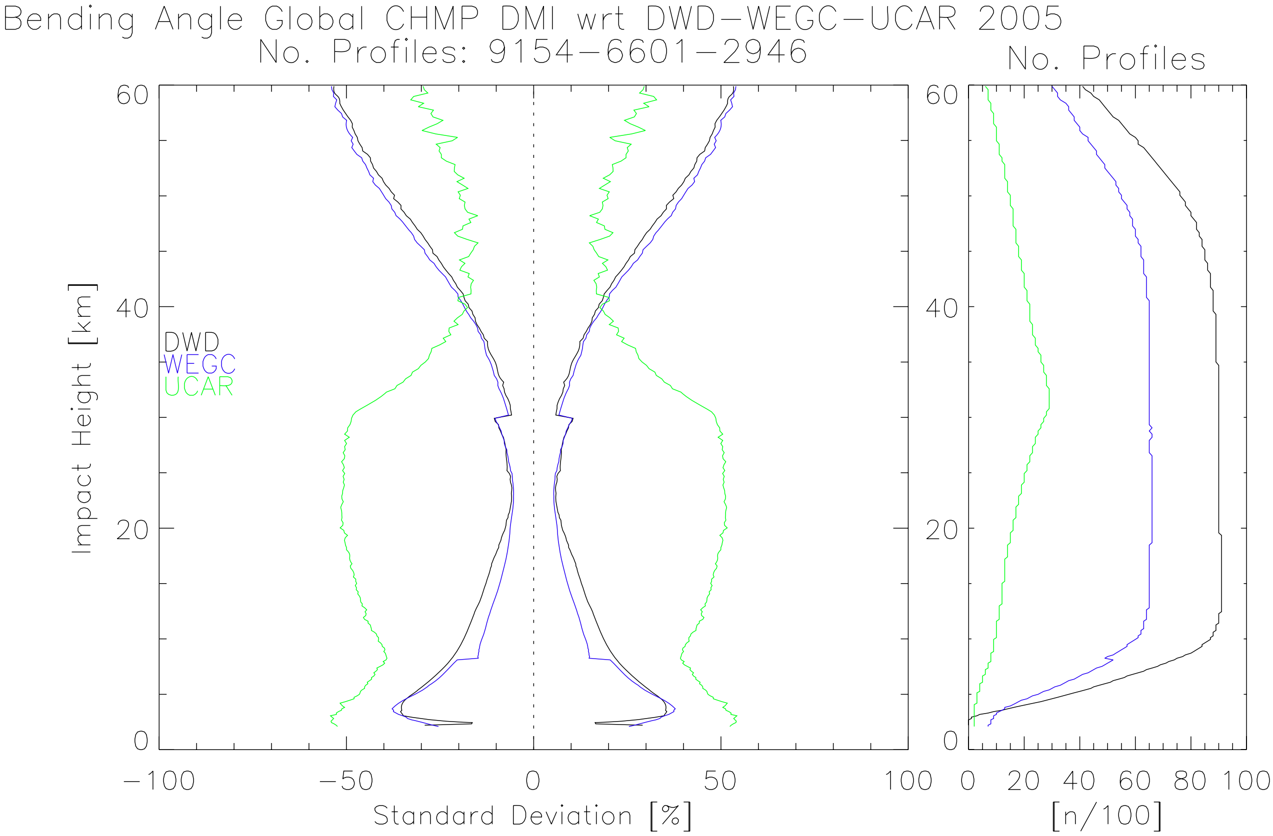
Geolocation

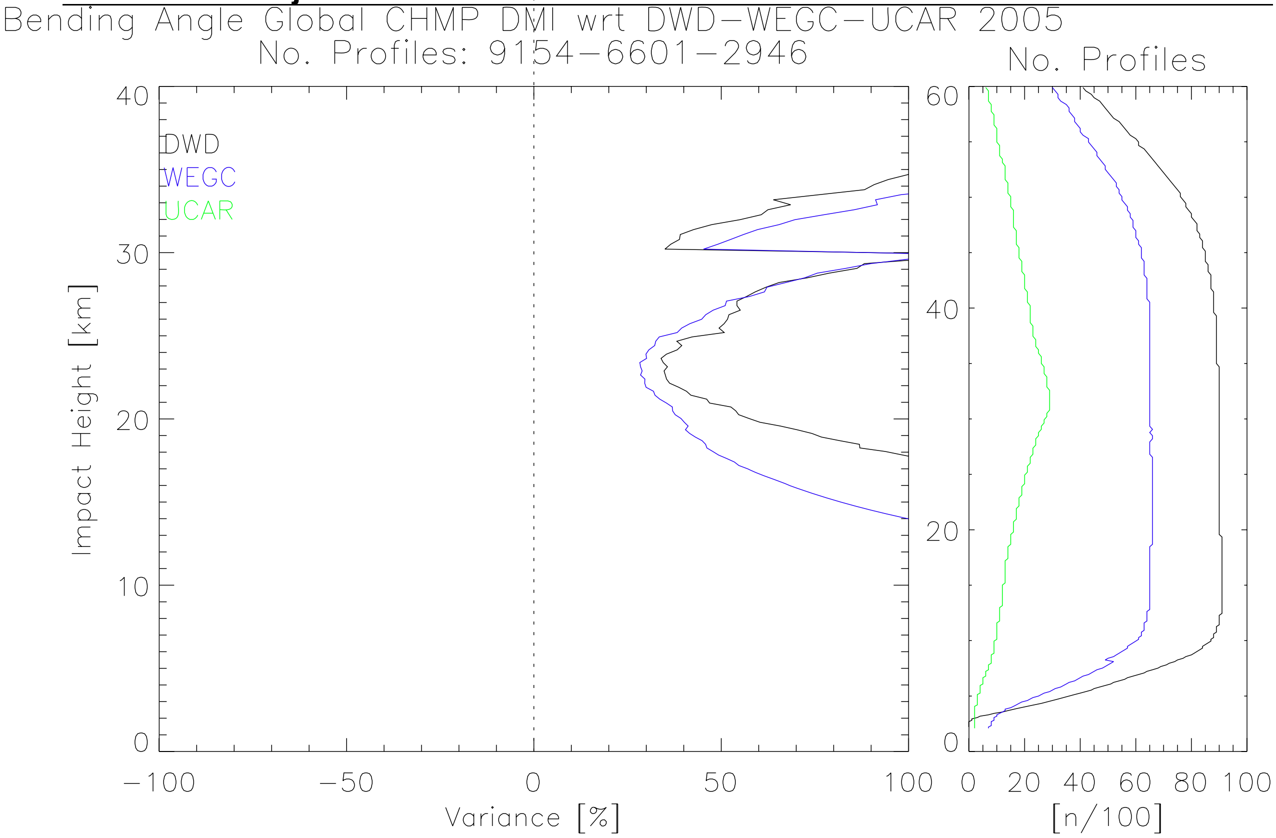
The geolocation difference for the same profiles derived by different centers had been calculated by the IDL function MAP_2POINTS



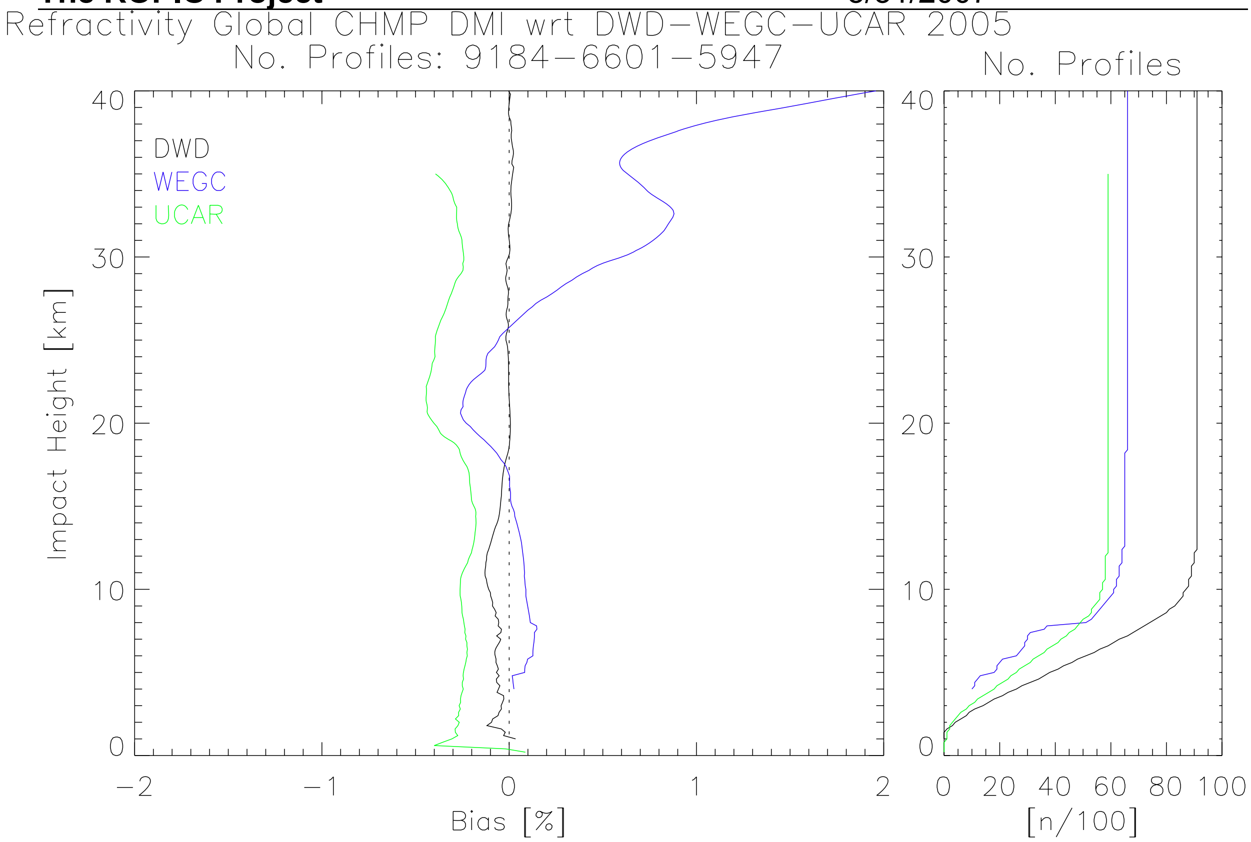
Bending Angles

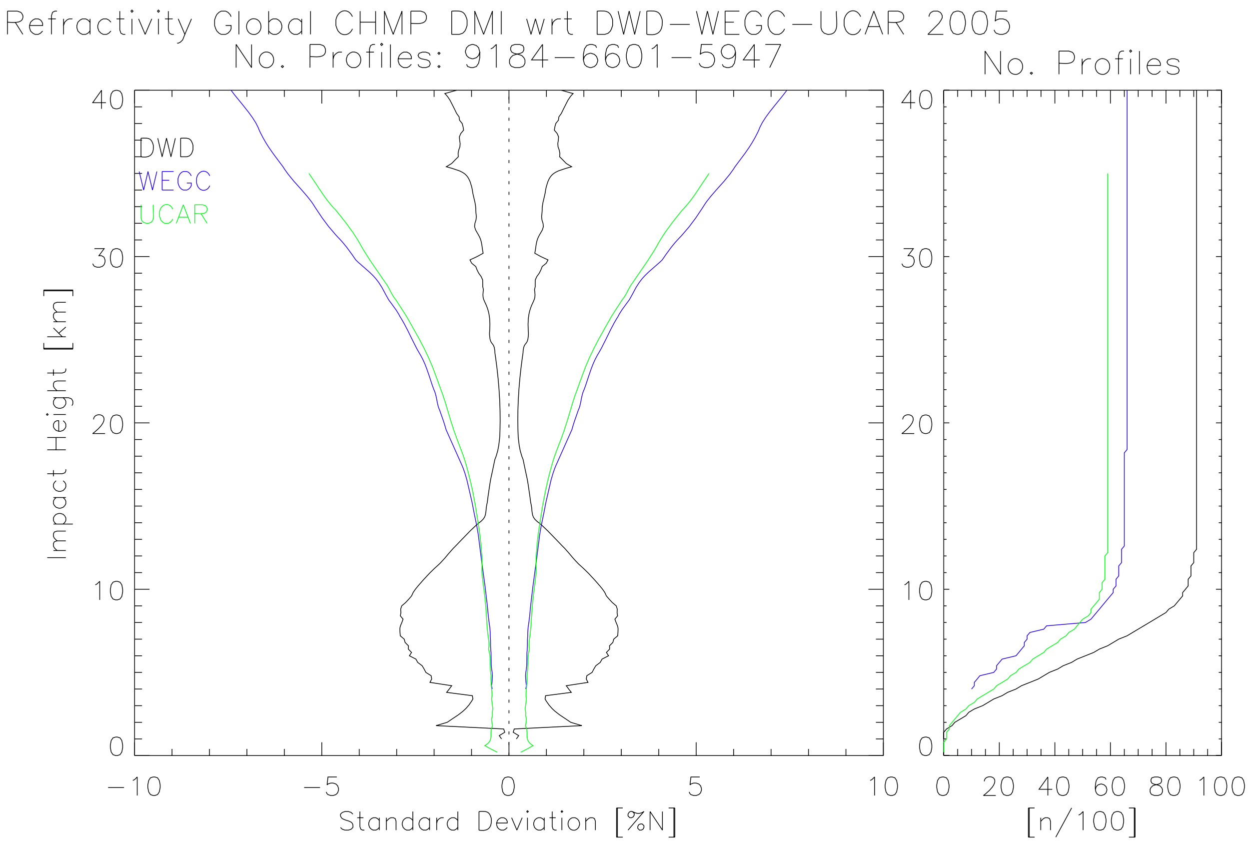

Bending Angle Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9154−6601−2946
No. Profiles
Impact Height [km]
DWD
WEGC
UCAR
Bias [%]
[n/100]

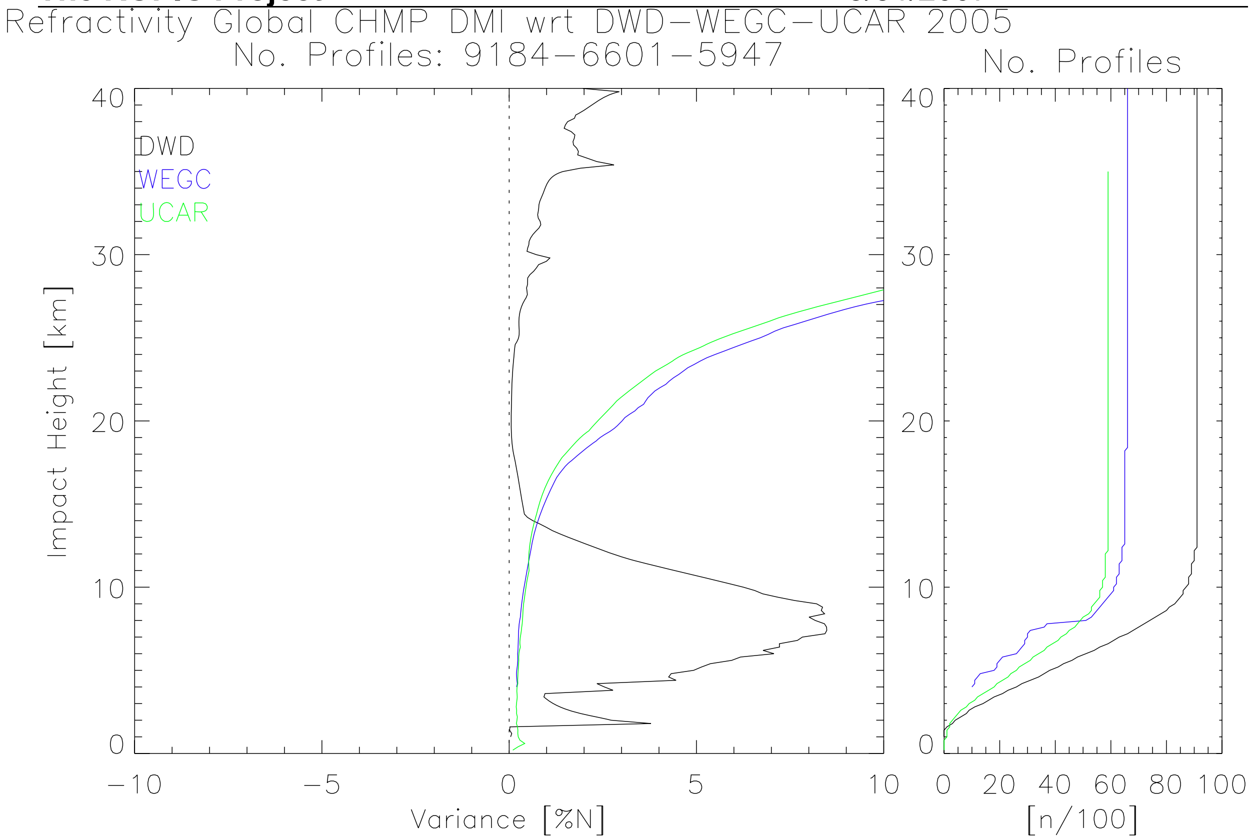

Bending Angle Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9154−6601−2946
No. Profiles
Impact Height [km]
DWD
WEGC
UCAR
Standard Deviation [%]
[n/100]



Refractivity


Refractivity Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Impact Height [km]
Bias [%]
[n/100]
40
30
20
10
0
−2
−1
0
1
2
0
20
40
60
80
100


Refractivity Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Impact Height [km]
Standard Deviation [%N]
[n/100]
40
30
20
10
0
−10
−5
0
5
10
0
20
40
60
80
100


Refractivity Global CHMP DMI wrt DWD−WEGC−UCAR 2005
No. Profiles: 9184−6601−5947
No. Profiles
DWD
WEGC
UCAR
Impact Height [km]
Variance [%N]
[n/100]
40
30
20
10
0
−10
−5
0
5
10
0
20
40
60
80
100

Appendix A: GFZ Data format description

Data Formats are ASCII-Files and nearly identical with data formats of GPS/MET processing results, provided by UCAR (University Corporation for Atmospheric Research) Boulder (http://cosmic.cosmic.ucar.edu/gpsmet/).

In addition to each data file a *.dif File (DIF meta data standard: information can be found at http://gcmo.gsfc.nasa.gov/difguide/whatsadis.html) is provided, containing the meta data information. The file is named identical to the respective *.dat file, but with extension *.dif.

Furthermore an occultation table (TAB) for each file exists.

The data format description for PD, TAB and *.dif files follows.

Since there is no quality flag present in the GFZ files, the quality parameter of the ROPP format for the Level 1a data (`...%Lev1a%phase_qual`) is used to represent the GFZ flywheel flag (0 = no flywheel / 1 = flywheel).

The ROPP NetCDF files are named identically to the respective GFZ files except the end of the filename and the extension (*_ropp.nc).

CH-AI-2-PD (atmospheric excess phase)

Filename

CH-AI-2-PD+2001_238_23_190_sutm_001.dat
CH-AI-2-PD Product type (Path Delay)

2001	Year
238	Day of the year
23	Hour of the day
190	Occultation number
sutm	Name of the GPS ground station for double differencing (sutm .. Sutherland)
001	Product version

Header

```
Example:
#occnr                           000190
#starttime (UTC)                 2001-08-26 23:52:23.00
#endtime (UTC)                   2001-08-26 23:53:23.98
#t|snr_ca|snr_p1|snr_p2|x_leo|y_leo|z_leo|vx_leo|vy_leo|vz_leo|x_gps|y_gps|
z_gps|vx_gps|vy_gps|vz_gps|delay_c|delay_p1|delay_p2|fw_flag
#END OF HEADER
```

Description: 5 lines
(a6,27x,i6.6) occultation number
(a16,17x,i4,a1,i2.2,a1,i2.2,a1,i2.2,a1,i2.2,a1,f5.2) start time occultation UTC (yyyy-mm-dd hh:mm:ss.ss)
(a14,19x,i4,a1,i2.2,a1,i2.2,a1,i2.2,a1,i2.2,a1,f5.2) end time occultation UTC (yyyy-mm-dd hh:mm:ss.ss)
names (abbreviations) of the quantities in the data rows
#END OF HEADER

Data

(f14.6,1x,3(f8.3,1x),3(f14.6,1x),3(f16.8,1x),3(f14.6,1x),3(f16.8,1x),3(f12.4,1x),i2)

1.	TR	Receive time since epoch	seconds	f14.6
2.	CAsnr	Signal/Noise ratio for L1 CA	volts/volt	1x, f8.3
3.	P1snr	Signal/Noise ratio for L1 P code	volts/volt	1x, f8.3
4.	P2snr	Signal/Noise ratio for L2 P code	volts/volt	1x, f8.3
5-7.	xl, yl, zl	CHAMP position	km	3(1x, f14.6)
8-10.	ul, vl, wl	CHAMP velocity	km/s	3(1x, f16.8)
11-13	xg, yg, zg	GPS position	km	3(1x, f14.6)
14-16	ug, vg, wg	GPS velocity	km/s	3(1x, f16.8)
17.	Occ_LC	Atmospheric excess phase LC	m	1x, f12.4
18.	Occ_L1	Atmospheric excess phase L1	m	1x, f12.4
19.	Occ_L2	Atmospheric excess phase L2	m	1x, f12.4
20.	FW_Flag	Flywheel-Flag (on=1, off=0)		2x, i

The satellite positions and velocities are given in the Cartesian True of Date (TOD) inertial reference frame.

Example

-0.500000 393.462 0.000 0.000 4724.009193 4833.806447 -694.817081 0.28958383
0.82137907 7.62276794 -14333.449261 8595.322784 -20656.669517 -2.73686812 -
2.61198049 0.82565176 1.0000 1.0000 1.0000 0

CH-AI-2-TAB (occultation table)

Filename

CH-AI-2-TAB+GFZ_2001_238_00.dat
CH-AI-2-TABProduct type (Occultation Table)

2001	Year
238	Day of the year
00	Product version

Description

Table of occultation events (duration > 20s), derived from CHAMP HR (50 Hz) data.

Data

(i8;2x,i4;1x,i3;4(2x,i2);1x,i3;3x,i1;2(2x,a14),6(1x,f8.3);2x,i2;2(3x,i1);2(f5.2))

1.	Occ_Id	Number of the occultation events	i8
2.	Year	Year of occultation	2x, i4
3.	DOY	Day of the year	1x, i3
4.	Occ_Sat	Occulted GPS satellite (SV) number	2x, i2
5.	Ch_Occ	Channel number for Occ_Sat.	2x, i2
6.	Ref_Sat	Reference GPS satellite (SV) number	2x, i2
7.	Ch_Ref	Channel number for Ref_ Sat.	2x, i2
8.	Fid_Id	Fiducial station identification number	1x, i3
9.	Status	Status of double difference processing	3x, i1
10.	Tstart	Occultation start time (GPS epoch) yyyymmddhhmmss	2x, a14
11.	Tstop	Occultation stop time (GPS epoch) yyyymmddhhmmss	2x, a14
12.	Alt_Min	Minimum altitude of the occultation (km)	1x, f8.3
13.	Lat_Min	Latitude of Occultation at Tstop (deg)	1x, f8.3
14.	Lon_Min	Longitude of Occultation at Tstop (deg)	1x, f8.3
15.	Alt_Max	Maximum altitude of the occultation (km)	1x, f8.3
16.	Lat_Max	Latitude of Occultation at Tstart (deg)	1x, f8.3
17.	Lon_Max	Longitude of Occultation at Tstart (deg)	1x, f8.3
18.	LEO_Id	Number of the LEO (CHAMP=1)	2x, i2
19.	Dir_Id	Direction of the Occultation (backward=1, forward=2)	3x, i1
20.	Set_Id	SetRise Index of the Occultation (setting=1, rising=2)	3x, i1
21.	El_Occ_Gs	Elevation of Occ_Sat at Fid location (deg)	f5.2
22.	El_Ref_Gs	Elevation of Ref_Sat at Fid location (deg)	f5.2

Straight line assumption for calculation of geometric parameters

Example

```
       1  2001  42  21   0   2   0  18   0  20010211190429  20010211190526  -49.500   20.040  171.320
118.120   25.840  171.110   1  1   1 21.61 54.43
```

Appendix B: GFZ Meta data description

In addition to each data file of each product type a *.dif File (DIF meta data standard: information can be found at http://gcmo.gsfc.nasa.gov/difguide/whatisadif.html) is provided, containing the meta data information (additional information characterizing the individual data product). This file is named identical to the respective *.dat file, but with extension *.dif.

CH-AI-2-PD

antispoofing:	Anti spoofing status of GPS
cycle slips in gs data:	No. of detected cycle slips in GPS ground data
data access	access to the data (e.g. public**)**
data rate GPS ground station:	acquisition rate of the GPS ground station (Hz)
doy:	Day of the year
elevation of osat at gs site:	Elevation of GPS occultation satellite at GPS ground station site
elevation of rsat at gs site:	Elevation of GPS reference satellite at GPS ground station site
end latitude:	End latitude of the occultation (estimated from simulation)
end longitude:	End longitude of the occultation (estimated from simulation)
endtime:	End time of occultation (UTC)
generation date:	Date of data product generation
gps anomaly:	GPS anomaly occurred during occultation
GPS differencing modus:	Differencing scheme used for the derivation
method of reconstruction :	Method of excess phase derivation
mission:	GPS occultation mission
occultation number :	Number of the occultation event
occultation satellite:	Occultation GPS satellite (PRN)
occultation satellite channel:	Occultation GPS satellite channel (currently blank)
processing facility:	occultation processing center
quality flag :	Quality flag (tbd)
reference ground station number:	Reference GPS ground station number
reference satellite :	Reference GPS satellite (PRN)
reference satellite channel:	Reference GPS satellite channel (currently 0)
revision :	Revision of the data product
revolution :	Revolution of CHAMP satellite
software package:	Occultation processing software
start latitude :	Start latitude of the occultation (estimated from simulation)
start longitude :	Start longitude of the occultation (estimated from simulation)
starttime:	Start time of occultation (UTC)

Appendix C: ROPP Level 1a vs. GFZ Data description

For details of the ROPP format (Radio Occultation Processing Package) see the ROPP user guide at http://grassaf.dmi.dk. Here a brief introduction to the Level 1a, header data and the equivalent content of the GFZ files is given. No data from the Occultation Tables is used in the ROPP format; several structure elements present in the ROPP format are not available from the GFZ input data and are not listed here, for details on the ROPP format confer to the ROPP user guide. **ATTENTION**, the quality parameter of the ROPP format (`...%Lev1a%phase_qual`) is used to represent the GFZ fly-wheeling flag (0 = no flywheel / 1 = flywheel)! The ROPP NetCDF files are named like the respective GFZ files except the end of the filename and the extension (*_ropp.nc).

Level 1a.

Structure Element	Parameter	Description	GFZ Equivalent
`...%Lev1a%dtime`	Time since start	Time offset from time in header	TR
`...%Lev1a%snr_L1ca`	SNR L1 (ca-code)	Relative signal amplitude for L1 (ca–code)	CAsnr
`...%Lev1a%snr_L1p`	SNR L1 (p–code)	Relative signal amplitude for L1 (p–code)	P1snr
`...%Lev1a%snr_L2p`	SNR L2 (p–code)	Relative signal amplitude for L2 (p–code)	P2snr
`...%Lev1a%phase_L1`	Excess Phase L1	L1 phase corrected for geometry	Occ_L1
`...%Lev1a%phase_L2`	Excess Phase L2	L2 phase corrected for geometry	Occ_L2
`...%Lev1a%r_gns`	Transmitter Position	Earth centered Earth fixed, phase centre (X, Y, Z)	xg, yg, zg
`...%Lev1a%v_gns`	Transmitter Velocity	Earth centered inertial, phase centre (X, Y, Z)	ug, vg, wg
`...%Lev1a%r_leo`	Receiver Position	Earth centered Earth fixed, phase centre (X, Y, Z)	xl, yl, zl
`...%Lev1a%v_leo`	Receiver Velocity	Earth centered inertial, phase centre (X, Y, Z)	ul, vi, wl
`...%Lev1a%phase_qual`	Quality[1] (Flywheel)	Percentage confidence value[1] (Flywheel on=1/off=0)	not existing[1] / (FW_Flag)

1 The ROPP Level 1a quality flag is used to represent the GFZ Flywheel flag (FW_Flag)!

Table 45 Comparison Level 1a ROPP to Level 2 GFZ.

Identifiers.

Structur Element	Parameter	Description	GFZ Equivalent
`...%leo_id`	LEO ID	LEO id code (4 characters)	CH (CHMP in ROPP)
`...%gns_id`	GNSS ID	Letter identification (4 characters) + PRN of the occulting GNSS satellite	Occultation satellite (PRN); (*.dsc)
`...%stn_id`	Station ID	Ground Station id used for differencing [1]	Reference ground station number; (*.dsc)
`...%occ_id`	Occultation ID	Unique occultation ID	occnr

1 For the ROPIC data set the single differencing technique is used, so this parameter is not used.
Table 46 Comparison identifiers Level 1a ROPP to Level 2 GFZ.

Processing

Structur Element	Parameter	Description	GFZ Equivalent
...%FmtVersion	Format Version	Exact text	None
...%processing_center	Processing Center	Text indicating processing center (GFZ)	GFZ Potsdam
...%software_version	Software Version	Processing Software Version	Software package; (*.dsc)
...%pod_methode	POD algorithm	Text String indicating algorithm	Undifferenced dynamical satellite satellite tracking (SST) for LEO
...%phase_methode	Level 1a algorithm	Text String indicating algorithm	Space based single differencing; (*.dsc)

Table 47 Comparison processing Level 1a ROPP to Level 2 GFZ.

Time Stamp

Structur Element	Parameter	Description	GFZ Equivalent
...%DTocc%year	Year	Time stamp at start of occultation (UTC)	Start time (UTC)
...%DTocc%month	Month	-	Start time (UTC)
...%DTocc%day	Day	-	Start time (UTC)
...%DTocc%hour	Hour	-	Start time (UTC)
...%DTocc%minute	Minute	-	Start time (UTC)
...%DTocc%second	Second	-	Start time (UTC)
...%DTocc%msec	Millisecond	-	Start time (UTC)
...%DTpro%year	Year	Time stamp of processing (UTC)	Generation date; (*.dsc)
...%DTpro%hour	Month	-	Start time (UTC) ; (*.dsc)
...%DTpro%day	Day	-	Start time (UTC) ; (*.dsc)
...%DTpro%hour	Hour	-	None
...%DTpro%minute	Minute	-	None
...%DTpro%second	Second	-	None
...%DTpro%msec	Millisecond	-	None
...%DTpro%starttime	Start time of Occultation	Seconds since 2000-01-01 00:00:00	None

Table 48 Comparison time stamp Level 1a ROPP to Level 2 GFZ.

Appendix D: The ROPIC ROPP Format

The ROPP format used for the ROPIC data set had been slightly adapted and supplemented. The following tables (and the tables in Appendix C) contain the ROPP definitions and additions used for ROPIC. The non ROPP structures used are Background Data and Additional Data.

Processing

Parameter	Description	Range	Units
Processing Centre	Text indicating processing centre (40 characters)	[A-Z,0-9]	-
Software Version	String indicating software version	[A-Z,0-9]	-
Level 1 b algorithm	Text strings (40 characters) indicating algorithms used to derive bending angle, refractivity and meteorological data	[A-Z,0-9]	-
Level 2 a algorithm		[A-Z,0-9]	-
Level 2 b algorithm		[A-Z,0-9]	-

Table 49 Processing.

Background Meta Data

Parameter	Description	Range	Units
Background Source	Source of meteorological or atmospheric data used as background (ancillary) data	[A-Z,0-9]	-
Verification Time	Verification time of background data (if applicable)	1999 01 01 00 00 - 2099 12 31 23 59	-

Table 50 Background Meta Data.

Georeferencing

Parameter	Description	Range	Units
Time since start	Time since start of occultation to the time when georeferencing data and radius of curvature are determined	0 – 999.999	s
Latitude	Position of tangent point as used for georeferencing	-90 … 90	deg
Longitude		-180 … 180	deg
Radius of Curvature	Radius of curvature	$6.2 - 6.6 \times 10^6$	m
Centre of Curvature	Centre of curvature coordinates (ECF; X, Y, Z)	± 10000	m
Line of sight	GNSS to LEO azimuth direction w.r.t. North	0 – 360	deg
Geoid Undulation	Difference between ellipsoid (WGS-84) and geoid (EGM-96) heights	± 150	m

Table 51 Georeferencing.

Quality

Parameter	Description	Range	Units
Product Confidence[1]	Product confidence data	Bit flags within a single 32-bit / 4-byte integer	
Data Quality	Overall summary data quality	0 - 100	%

1 only used in the NetCDF ROPP format

Table 52 Quality.

Level 1b

Parameter	Description	Range	Units
Latitude	Longitude and Latitude w.r.t. the WGS 84 ellipsoid of the tangential point of the generic bending angle	-90 … 90	deg
Longitude		-180 … 180	deg
Azimuth	GNSS to LEO azimuth w.r.t. North at tangent point	0 - 360	deg
Impact Parameter L1	Impact parameter derived from L1	$6.2 \times 10^6 – 6.6 \times 10^6$	m
Impact Parameter L2	Impact parameter derived from L2	$6.2 \times 10^6 – 6.6 \times 10^6$	m
Impact Parameter	Impact parameter generic	$6.2 \times 10^6 – 6.6 \times 10^6$	m
Bending Angle L1	Bending angle derived from L1	-10^{-4} – 0.05	rad
Bending Angle L2	Bending angle derived from L2	-10^{-4} – 0.05	rad
Bending Angle	Bending angle generic	-10^{-4} – 0.05	rad
Bending Angle Errors L1	Estimated errors (one σ) of bending angle values L1	0 – 0.02	rad
Bending Angle Errors L2	Estimated errors (one σ) of bending angle values L2	0 – 0.02	rad
Bending Angle Errors	Estimated errors (one σ) of bending angle values generic	0 – 0.02	rad
Bending Angle Quality L1	Percentage confidence value for bending angles L1	0 - 100	%
Bending Angle Quality L2	Percentage confidence values for bending angles L2	0 - 100	%
Bending Angle Quality	Percentage confidence values for bending angles generic	0 - 100	%

Table 53 Level 1b.

Level 2a

Parameter	Description	Range	Units
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm
Refractivity	Derived refractivity	0 - 500	N-units
Refractivity Error	Estimated errors (one σ) of refractivity values	0 - 100	N-units
Refractivity Quality	Percentage confidence value	0 - 100	%

Table 54 Level 2a.

Level 2b

Parameter	Description	Range	Units
Geopotential Height	Geopotential height above geoid (EGM 96)	-1000 - 100000	gpm
Geopotential Height Error	Estimated errors (one σ) of geopotential height values		gpm
Pressure	Retrieved pressure	0.1 - 1100	hPa
Pressure Error	Estimated errors (one σ) of pressure values	0 - 50	hPa
Temperature	Retrieved temperature	150 - 350	K
Temperature Error	Estimated errors (one σ) of temperature values	0 - 50	K
Specific Humidity	Retrieved specific humidity	0 - 50	g/kg
Specific Humidity Error	Estimated errors (one σ) of specific humidity values	0 - 10	g/kg
Quality	Overall percentage confidence value	0 - 100	%

Table 55 Level 2b.

Level 2c

Parameter	Description	Range	Units
Geopotential Height Surface	Geopotential height of surface above geoid (EGM 96)	-1000 - 100000	gpm
Surface Pressure	Retrieved surface (or reference) pressure	900 - 1100	hPa
Surface Pressure Error	Estimated errors (one σ) of surface pressure values	0 - 50	hPa
Quality	Percentage confidence value	0 - 100	%

Table 56 Level 2c.

Level 2d

Parameter	Description	Range	Units
Level Type	ECMWF	-	-
α coefficients	Level coefficients α	900 - 1100	hPa
β coefficients	Level coefficients β	0 - 50	hPa

Table 57 Level 2d.

Background Data

Parameter	Description	Range	Units
Temperature	ECMWF temperature	150 - 350	K
Dry Temperature	ECMWF dry temperature	150 - 350	K
Specific Humidity	ECMWF specific humidity	0 - 50	g/kg
Pressure	ECMWF derived pressure	0.1 - 1100	hPa
Geopotential Height	ECMWF derived geopotential height	-1000 - 100000	gpm
Height	Geometric height above ellipsoid (WGS 84)	-1000 - 100000	m
Refractivity	ECMWF derived refractivity	0 - 500	N-units
Surface Pressure	ECMWF surface pressure	900 - 1100	hPa
Surface Height	ECMWF surface height	-1000 - 100000	m
Surface Geopotential	ECMWF surface geopotential	-1000 - 8000	gpm
Surface Temperature	ECMWF surface temperature	0 - 500	K
Skin Temperature	ECMWF skin temperature	0 - 500	K
Surface Humidity	ECMWF surface humidity	0 – 0.05	g/kg

Table 58 Background Data.

Additional Data

Parameter	Description	Range	Units
Dry Temperature	Retrieved dry temperature	150 – 350	K
Optimized Bending Angle	Retrieved optimized bending angle	-10^{-4} – 0.05	rad
Reference Bending Angle Inverse Able	From background derived (inverse able) bending angle	-10^{-4} – 0.05	rad
Reference Bending Angle Retraced	From background derived (raytraced) bending angle	-10^{-4} – 0.05	rad
Density	Retrieved density	0 - 1100	Kg/m^3

Table 59 Additional Data.

References

The most of the references, listed here, can be downloaded via the online literature data base at the homepage of the German GPS Sounding Project (GASP): *http://www.gfz-potsdam.de/pb1/GASP/GASP2/index_GASP2.html*. A password is required, which is available via jens.wickert@gfz-potsdam.de.

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