EUMETSAT

Metop Orbit and GRAS Occultation Prediction Level 1C Product Format Specification

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1 INTRODUCTION

1.1 Purpose and Scope

This document is the Product Format Specification for the EUMETSAT Polar System (EPS) Radio Occultation (RO) GNSS Receiver for Atmospheric Sounding (GRAS) Level 1C (L1C) products generated centrally by the EPS offline processing at the EUMETSAT Headquarters. These products cover forecasts/predictions of the expected GRAS occultations for all operational Metop satellites; it also includes information on predictions of the Metop sub-satellites positions. Predictions are e.g. done over the next 14 days. The products address e.g. action ACTION 3G-7 of [RD1]. The format of the RO Level 1C products is netCDF-4 [AD1].

1.2 Relation to other documents / Background information

While the presented product format is generic and can be applied for all RO missions, it is used at EUMETSAT to cover its own operational RO instruments.

EPS L1B products are generated and disseminated operationally at the EPS ground segment at EUMETSAT Headquarters. The PFS [RD2] of these products is available on the EUMETSAT website, products are available through the usual operational channels (e.g. Global Telecommunication System (GTS), EUMETSAT's Broadcast System for Environmental Data (EUMETCast)) and through the EUMETSAT archive. The generation of these products requires accurate knowledge of the Precise Orbit Determination (POD) of the 2 involved satellites; Global Positioning System (GPS) ones are provided by an operational service, while the Metop orbits and clocks are derived internally from the GRAS measurements on the zenith pointing antenna and the operational GPS service.

The L1C product covered in the PFS described here builds on these precise orbits and predicts the satellite positions over the next weeks. The processing uses a fit over e.g. the last week of available orbit data to predict future positions of the two satellites. These past orbits are available at EUMETSAT, they are however not included in the L1B products disseminated, they only contain relevant orbit arcs for the occultation provided.

The predicted Metop positions are directly put into the L1C products; for the predicted occultation locations, the predicted Metop and GPS orbits are provided to an occultation prediction tool which determines the possible future occultations.

Note that not every predicted occultation will actually be measured by the GRAS instruments, possible causes for a non-detection of an occultation include outages of GPS satellites, possible manoeuvres of the two satellites. Further information on "best use" of these predictions is provided below.

1.3 Applicable Documents

[AD1] NetCDF data format description, cited 30 November 2016, http://www.unidata.ucar.edu/software/netcdf/docs/.

1.4 Reference Documents

[RD1] WMO WIGOS GRUAN-GSICS-GNSSRO Workshop on Upper-Air Observing System Integration and Application, Geneva, 6-8 May 2014, Final Report.

[RD2] Radio Occultation Level 1 Product Format Specification, EUM/TSS/SPE/16/817861.

[RD3] EPS-SG EPS-SG RO Level 1B Algorithm Theoretical Baseline Document, EUM/LEO-EPSSG/SPE/14/743399.

[RD4] CF Conventions v1.6, 5 December 2011, available at `http://cfconventions.org/cf-conventions/v1.6.0/cf-conventions.pdf`.

1.5 Acronyms

The following table lists abbreviations specific to this document.

CF	Climate and Forecast
EPS	EUMETSAT Polar System
EPS-SG	EUMETSAT Polar System - Second Generation
EUMETCast	EUMETSAT's Broadcast System for Environmental Data
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRAS	GNSS Receiver for Atmospheric Sounding
GTS	Global Telecommunication System
L1	Level 1
L1C	Level 1C
LEO	Low Earth Orbit
NANU	Notice Advisory to Navstar Users
NRT	Near-Real-Time
PFS	Product Format Specification
POD	Precise Orbit Determination
PRN	Pseudo-Random-Noise
RO	Radio Occultation
SLTA	Straight Line Tangent Altitude
SNR	Signal-to-Noise Ratio

1.6 Conventions and Terminology

Generic conventions and terminology incorporated in this document for EPS products are generally following [RD4].

1.7 Document Structure

The document is structured as follows:

Chapter 1: Introduction (this chapter)

Chapter 2:	High-level product overview
Chapter 3:	Product details
Chapter 4:	Product accuracy information

2 EPS RO LEVEL 1C PROCESSING AND DATA FORMAT OVERVIEW

2.1 Introduction

RO observations are measurements of opportunity – they can be taken whenever one of the Global Navigation Satellite System (GNSS) satellites, as seen from the observing spacecraft, sets or rises behind the Earth's horizon. Typically, a single occultation covering the neutral atmosphere lasts less than a few minutes, during which the line of sight between the two satellites moves from high altitudes into the troposphere (for setting occultations; vice versa for rising ones), scanning nearly vertically through the atmosphere.

The location of the occultation depends on the orbit geometry of the satellites being involved in the measurement; it will typically be located about 3000 km away from the sub-satellite point of the RO receiver for a Low Earth Orbit (LEO) satellite like Metop. Individual occultations, when being processed to level 1B, therefore consist of roughly vertical bending angle profiles which are more or less randomly distributed over the globe.

The actual distribution is of course not fully random but can be predicted highly accurate to within a few kilometres and minutes (please refer to Section 4 for more information) for weeks in advance (assuming no manoeuvre is taking place, GNSS satellites are available and are not undergoing maintenance, the RO instrument channels are sufficient (e.g., GRAS can track simultaneously 2 rising and setting occultations), etc), based on available POD data and making use of an occultation prediction tool.

2.2 Processing Setup

The RO L1C products are generated daily (processing starts at 05:00 UTC), once all orbit data of the previous days has been collected. Thus new products are available on a particular day shortly after this time, covering predictions for this day plus the prediction period of e.g. 2 weeks.

The following sub-sections 2.2.1 and 2.2.2 provide more information on the POD and Occultation Prediction tools used.

2.2.1 POD Processing

While a complete description of the POD processing at EUMETSAT goes beyond the scope of the PFS, a short description is provided below. For full details, please refer to [RD2] and reference therein.

The processing of occultation data requires very accurate knowledge of the positions and clocks of the two involved satellites. For the operational EPS processing of GRAS data, the GNSS satellite positions and clocks are provided by an operational service, assuring high accuracy and availability for the Near-Real-Time (NRT) processing of the occultations (note that in the case of GRAS the GNSS satellites are restricted to GPS).

With information on the GNSS satellites orbits and clocks available, EUMETSAT's LEO (i.e. Metop) POD is based on a batch processing, i.e. the orbit for the centre-of-mass and the clock estimates for the spacecraft's GNSS receiver are obtained by fitting the orbit and clock solution to zenith antenna carrier phase and pseudorange measurements over a long (typically between several hours up to a full day) period. The nominal length of this estimation arc is configurable, although certain operational conditions such as manoeuvres or gaps in the level 0 or auxiliary data may cause shorter estimation arcs. In general, orbit and clock estimates will become more accurate with longer estimation arcs.

Once the LEO orbit is determined, level L1B occultations products for the orbit arc can be processed and disseminated. This operational processing, as well as the GRAS L1B data disseminated does however not cover orbit arcs of several days into the past that can be used for fitting and predicting the future satellite and occultation positions. The data is thus collected, concatenated and processed in the EUMETSAT offline environment.

The collected, longer orbit arcs are used in the EUMETSAT POD tool to estimate future GNSS and LEO positions. The predicted Metop positions are directly put into the L1C products, while this orbit and the GNSS predicted orbits are made available to the occultation prediction tool. Note that the fitting of the LEO and GNSS actual data, collected over several days, does not allow for data gaps; thus a missing GNSS satellite on any of these collected days will not be predicted, a gap in the LEO orbit will also lead to no predictions available. GNSS orbit gaps are more frequent than LEO ones, at least for the EUMETSAT processing.

2.2.2 Occultation Prediction Processing

With longer GNSS and Metop GRAS orbit and clock information available, the occultation prediction tool can determine where future occultations are expected (temporal and geographical). Relevant input parameters to the tool are the availability of setting and rising antennas, the viewing directions of these antennas, the azimuth angle coverage, and the vertical range over which the occultation shall be tracked by the antenna (expressed in Straight Line Tangent Altitude (SLTA), the altitude above or below the reference Earth's ellipsoid of a straight line connecting transmitter and receiver).

The SLTA = 0 altitude is often used as the nominal location of the occultation – thus neglecting the bending of the signal's ray path – valid for the moment in time when the transmitter-receiver straight line touches the Earth's ellipsoid. This nominal georeferencing is useful when the occultation is interpreted as a vertical profile, it is also a reference location provided in the operational processing of L1B data. It neither represents the impact of bending on the location of the true tangential point nor its actual motion during the occultation. The SLTA = 0 altitude corresponds to a tangent point of the actual ray at about 12 km geometrical altitude.

The motion of the tangent point (excluding again the impact of the bending angle) is also provided by the occultation prediction tool, namely the start and end of the occultation latitude, longitude and time for the configured upper and lower SLTA limit (vertical range) of the occultations. Generally, the upper limit information in this approximation is more accurate since the impact of the bending is small.

2.3 RO Level 1C File Names

File names generally follow the EPS and EPS-SG file name conventions for auxiliary files (<> entries indicate variable fields, other fields are hard coded to indicate this is a L1C occultation prediction file, generated within the offline environment, using the Yaros processor):

```
<inst>_OCP_1C_<sat>_<start_time>Z_<stop_time>Z_<create_time>Z_YARx_OCCORBPRED.nc
```

where:

`<inst>`	4-character instrument ID (e.g., `GRAS` for the GRAS instrument)
`<sat>`	3-character satellite ID (e.g., `M02` for Metop-A but for 1C data generally XXX since several Metop satellites are included)
`<start_time>`	14-digit sensing start time (e.g., `20170101000000` for 00:00:00 UTC on 01 January 2017)
`<end_time>`	14-digit timestamp characterising sensing end time
`<create_time>`	14-digit timestamp characterising product creation time

A nominal GRAS level 1C file, providing predictions for more than one Metop satellite, with predictions starting at 00:00:00 UTC on 01 January 2017 and ending on 00:00:00 UTC on 15 January 2017, generated on 10:00:00 UTC on 01 January 2017, would have the following file name:

```
GRAS_OCP_1C_XXX_20170101000000Z_20170115000000Z_20170101100000Z_YARx_OCCORBPRED.nc
```

Each RO level 1C product exploits netCDF's data group feature in order to structure its data contents as shown in Fig. 2.1. In particular, it consists of a root (`/`) group, holding global attributes as well as `status` and `data` sub-groups. The detailed contents and structure of each data group are described in more detail in chapter 3.

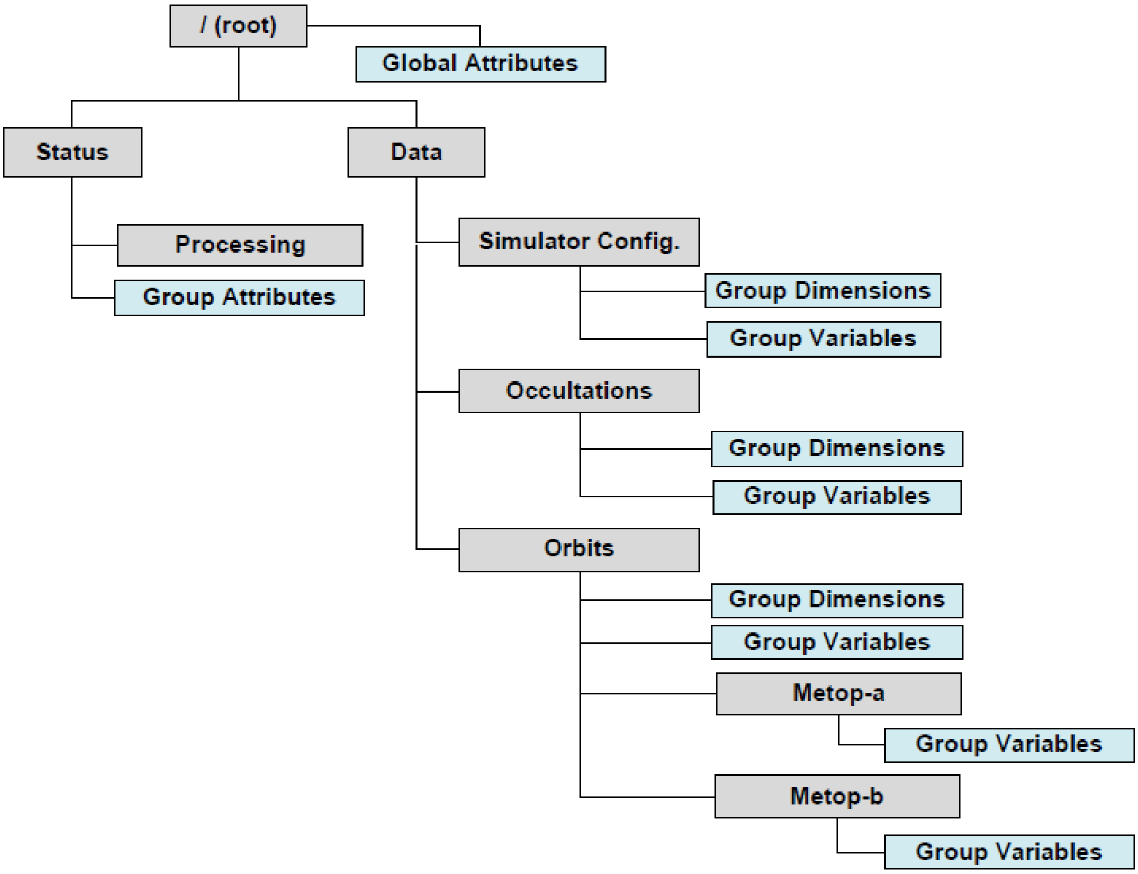

Fig. 2.1: Overall netCDF data group structure of EPS Level 1C file example, assuming Metop-A and -B orbits are covered.

3 EPS L1C PRODUCT DETAILS

The L1C netCDF-4 product entries are described in more detail below, after some general information on the product structure and details, as well as an introduction of conventions used. The general structure was already introduced in Figure 2.1.

3.1 Overall Structure of L1C Products

All EPS L1C product types generated by the EPS offline processing are NetCDF-4 files. Their high-level structure consists of a root group holding global attributes and two netCDF sub-groups: `/status` and `/data`.

In the following sections, further information on the product, the use of dimensions, attributes, missing values, and the physical composition of each product type is specified.

3.2 Product Summary Sheet

The filename entry in the table below is for illustrative purpose only, it assumes a certain prediction period, as outlined in Section 2.3. For further information on the product file name entries, please also refer to that section.

Filename	GRAS_OCP_1C_XXX_20170101000000Z_20170115000000Z_20170101100000Z_YARx_OCCORBPRED.nc
Product ID	OCP
Product Description	Occultation/Orbit predictions for LEO satellites
Format	netCDF-4
Size	8 MB (e.g., for a Metop-A and Metop-B, 14 day predictions, orbits with 1 minute resolution)
Duration	as indicated in file name, here 14 days

3.3 Overall Group Structure

The overall group structure of the NetCDF-4 files is shown in Figure 2.1. The high-level structure consists of a `root` group, holding global attributes, and the following sub-groups: `status`, `data`.

3.4 Overall Conventions

The RO level 1C data format is implemented using the netCDF-4 standard. In contrast to the older netCDF-3 data format specification, netCDF-4 provides hierarchical group structures for organising sets of variables, adds a number of additional native data types (64-bit wide and unsigned integer data types, along with a string data type), and provides transparent variable-wise data compression. Some of these new features of netCDF-4 are used in this RO data format, while other improvements like compound and variable length arrays are not exploited.

Name	Description	Length
`scalar`	Scalar variables	1
`dim`	Occultations predicted	variable
`t`	Time coordinates	variable

Tab. 3.2: Standard dimension names and their meaning.

The structure of RO Level 1C data in terms of groups and subgroups follows from the characteristics of the various data subsets. In particular, individual subgroups contain data which have common time stamps, share one dimension.

Meta data handling is mostly based on the Climate and Forecast (CF) conventions [RD4]. As this mainly provides guidance on netCDF-3 formatted data files, the original CF conventions are applied at the level of individual groups and subgroups, with the repetition of meta data being avoided as far as possible. The resulting use of variable attributes, and conventions on representing times and missing data are described in sections 3.4.2, 3.4.3 and 3.4.4, respectively. In some cases, this and other adaptations of the CF conventions are required due to EUMETSAT needs, and lead to deviations from the original CF text which are described in section 3.4.5.

3.4.1 Dimensions

Only dimension type of unlimited, 1-dimensional and of scalar are present. These are not constant between different L1C files since the number of occultations predicted varies. The number of elements provided for the respective Metop orbit / sub-satellite predictions are fairly constant between different product files if the same prediction period and temporal resolution is used.

As the number of dimension types is limited, the RO data format uses standard dimension names in all groups; they are listed in Table 3.2. In the tables describing the contents of the various data groups in the following sections, the shape of array variables is given in terms of these dimension names. For example, a variable with a shape of `(t)` denotes a 1d variable dependent on time, with a length defined by the dimension `t` of the data group in which this variable is contained. Scalar variables are represented by `scalar`, and consist of single values.

3.4.2 Attributes

Recommendations of the CF conventions regarding global attributes are generally applied for individual data groups as far as possible. In the RO L1C data format, every netCDF variable where it makes senses comes with standard attributes describing the meaning of the variable (`long_name`), its physical units (`units`), and a missing data indicator value (`missing_value`). Variables do not carry any other attributes.

In order to simplify the listing of data units in the tables of the following sections, abbreviations are used to represent long unit strings for angle, longitude, latitude, and time variables. These are consistent with the CF convention guidelines for these units, and listed in Tab. 3.3. See section 3.4.3 for details on time representation.

Unit	Abbr.	Comments
`degrees`	`<deg>`	angles if not expressed in `rad`
`degrees_east`	`<degE>`	geographical longitudes
`degrees_west`	`<degW>`	
`degrees_north`	`<degN>`	geographical latitudes
`degrees_south`	`<degS>`	
`days since 2000-01-01`†	`<days>`	compound times; see section 3.4.3
`seconds since 00:00:00.00`	`<time>`	

† actual reference date might differ depending on context

Tab. 3.3: Abbreviations for unit strings used in the Tables 3.7 – 3.11.

3.4.3 Time

Low level GNSS data requires precise time stamping, with accuracy in the order of a few picoseconds or less. In order not to have numerical round-off errors affecting the precise storage of observation times, times are stored as a logical compound which is made up of an `integer` variable carrying the days since a reference date, and a `double` variable carrying the seconds elapsed since midnight, i.e. since the start of the day. The two components of the logical time compound are named `utc_absdate` (for the number of days since the reference date) and `utc_abstime` (for the number of seconds since the beginning of the day) for the orbit prediction data. These names are extended at the beginning with either `start_`, `end_`, `ref_` for the occultation prediction data, referring to the start, end, and reference time respectively. This high precision storage of time is actually not required for the L1C products covered here, but is kept for consistency with the EPS and EPS-SG conventions.

The RO L1C data format provides times in addition as a simple string for easy human readability (indicated by a `_utc_time_str` ending), using e.g., the string format "2017-01-01 01:02:03.004" to indicate 01 January 2017, at 01:02:03 and 4 milliseconds UTC.

3.4.4 Missing Data

"Missing data" is data not present in a data set or measurement. Missing data indicator values are identical across all variables in the RO data format, and only depend on the data type of the variable. Their values are shown in Table 3.4, note though (1) missing data would only occur if there was a problem in the processing; and (2) that not all data types are used in the L1C products covered here.

3.4.5 Deviations from the CF Conventions

The RO level 1b data format is not consistent with the CF convention in the following points:

- Precision time variables are stored in a (logical) compound data types consisting on an integer number of days since a reference days, and a (double) number of seconds since midnight; see section 3.4.3.

Type	Missing value	Comments
single	NaN	IEEE 954 Not-a-Number (float)
double	NaN	IEEE 954 Not-a-Number (double)
byte	-128	Minimum representable value
short	-2^{15}	Minimum representable value
int	-2^{31}	Minimum representable value
int64	-2^{63}	Minimum representable value
ubyte	255	Maximum representable value
ushort	$2^{16}-1$	Maximum representable value
uint	$2^{32}-1$	Maximum representable value
uint64	$2^{64}-1$	Maximum representable value
string	”	Empty string
char	”	Empty string

Tab. 3.4: Standard missing value indicators.

3.5 `/` (Root) Group

The `/` (root) group of the RO L1C data format contains no variables, but several global attributes as listed in Table 3.5. These attributes provide high level information on the measurement type and processing.

These entries are generic for most EUMETSAT products and are not necessarily meaningful in the context of L1C product. E.g., the `orbit_start` and `orbit_end` are just empty, `receive_start` and `receive_end` are set to ""unknown"".

Name	Description	Shape	Type	Units
Attributes				
`Conventions`	Name of the conventions followed by the dataset	–	string	–
`metadata_conventions`	Name of the meta data conventions followed by the dataset	–	string	–
`title`	Short description of the data set or group contents	–	string	–
`summary`	Short description of the data set or group contents	–	string	–
`keywords`	The RO Level 1 data format currently does not set any keywords	–	string	–
`history`	One of “original generated product”, “aggregated product”, or “sub-setted product”	–	string	–
`institution`	Name of the institution where the data was produced	–	string	–
`spacecraft`	Satellite identifier	–	string	–
`instrument`	Instrument or product identifier and flight model number	–	string	–
`product_level`	Product processing level	–	string	–
`type`	Type of product	–	string	–
`mission_type`	One of “Global” or “Regional”	–	string	–
`disposition_mode`	One of “Test”, “Commissioning”, “Operational”, or “Validation”	–	string	–
`sensing_start`	UTC time of the start of sensing data	–	string	–

Tab. 3.5: Attributes in the `/` group.

Name	Description	Shape	Type	Units
`sensing_end`	UTC time of the end of sensing data	–	string	–
`environment`	One of “Operational”, “Validation”, “Integration & Verification”, “Development”, “Engineering”, and “Offline”	–	string	–
`references`	URL of the data provider	–	string	–
`orbit_start`	Orbit number at sensing_start	–	int	–
`orbit_end`	Orbit number at sensing_end	–	int	–
`receive_start`	UTC time of the start of data reception	–	string	–
`receive_end`	UTC time of the end of data reception	–	string	–
`subsetting`	Subsetting applied to the data	–	string	–
`receiving_ground_station`	Receiving ground station identifier	–	string	–

Tab. 3.5: Attributes in the `/` group.

3.6 Status / Processing Group

The `processing` group within the `status` group contains attributes on the processing, further described in Table 3.6. This contains information on the facility used (e.g., the `YAR` offline environment), the processor name (a combination of the Yaros and Occultation Prediction tool names, e.g. `YAROS/RO Pred tool`), the corresponding processor versions and the mode it was running in. The selection of `processing_mode` is limited to "NRT" and "Reprocessing" and is set here to "NRT", although the data is not strictly running in "NRT" mode. Some attributes are common and are here just empty (e.g. the `baseline` one) or are set to not applicable (such as the `idb_info` one).

Name	Description	Shape	Type	Units
Attributes				
`generating_facility`	Name of the originating / generating facility	–	string	–
`processor_name`	Name of the product processor	–	string	–
`processor_version`	Processor version number	–	string	–
`processing_mode`	One of “NRT” or ”Reprocessing”	–	string	–
`format_version`	Format version number	–	string	–
`source`	The method of production of the original data	–	string	–
`creation_time`	UTC time of the creation of the product	–	string	–
`idb_info`	Information characterising which Instrument Data Base version was used	–	string	–
`baseline`	Reprocessing baseline version number	–	string	–
`processing_centre`	Processing centre identifier	–	string	–

Tab. 3.6: Attributes in the `/status/processing` group.

3.7 Simulator Configuration

The simulator configuration is covered in the group `/data/simulator_config`, shown in Table 3.7, providing information on e.g., over what altitude range occultations can be observed (in the `slta_lower_bound` and `slta_upper_bound`), the occultation antenna pointing and azimuth coverage (in the variables `ant_pointing_*`, `ant_azimuth_range_*`), as well as information on the SLTA where the reference information is provided.

Name	Description	Shape	Type	Units
Variables				
slta_lower_bound	Lower SLTA altitude of the occultation simulation	(scalar)	double	m
slta_upper_bound	Upper SLTA altitude of the occultation simulation	(scalar)	double	m
slta_reference	Reference SLTA altitude of the occultation simulation	(scalar)	double	m
ant_azimuth_range_set	Azimuth angle coverage around the setting antenna pointing	(scalar)	double	<deg>
ant_pointing_set	Azimuth angle of the setting antenna pointing	(scalar)	double	<deg>
ant_azimuth_range_ris	Azimuth angle coverage around the rising antenna pointing	(scalar)	double	<deg>
ant_pointing_ris	Azimuth angle of the rising antenna pointing	(scalar)	double	<deg>

Tab. 3.7: Variables in the `/data/simulator_config` group.

3.8 Occultation Predictions

The predicted occultations are provided in the group `/data/occultations`, for all LEO and GNSS satellites included. The available variables are shown in Table 3.8, the involved satellites are covered in the variables `gns_id` and `leo_id`; whether this is a setting or rising occultation is provided by a flag; time of the occultation, latitude, longitude are provided at the reference and the start and end points of the occultation (Note that occultations are only provided if the simulation shows they are observed over the complete vertical extend, not if they actually move in and out of the coverage of the antenna patter).

The involved satellite positions (altitude, longitude, latitude at sub-satellite point) are also provided in this group, but only at the reference location, the full LEO orbit is provided in another group (see Section 3.9). In addition, angles are provided that provide further information on the observation direction at the reference location and at what angle it is observed on the antenna.

The group also provides a quality indicator, which at the moment primarily uses this `ant_azimuth` information for some rough estimation of the likelihood for this occultation to be observed, since occultations on the edge of the antenna are more likely to be not observed by an RO instrument (this is due to lower Signal-to-Noise Ratio (SNR) values for occultations on the antenna edge). For more information on this please refer to Section 4.

Name	Description	Shape	Type	Units
Variables				
id	Occultation ID	(dim)	string	–
gns_id	Occulting GNSS satellite ID	(dim)	string	–
leo_id	LEO satellite ID	(dim)	string	–
setting	Setting (1) or Rising (0) flag	(dim)	byte	–
start_utc_time_str	Time for the start of the occultation	(dim)	string	–
start_utc_absdate	Time for the start of the occultation (full days) in UTC	(dim)	int	<days>

Tab. 3.8: Variables in the `/data/occultations` group.

Name	Description	Shape	Type	Units
`start_utc_abstime`	Time for the start of the occultation (seconds since last midnight) in UTC	`(dim)`	double	<time>
`end_utc_time_str`	Time for the end of the occultation	`(dim)`	string	–
`end_utc_absdate`	Time for the end of the occultation (full days) in UTC	`(dim)`	int	<days>
`end_utc_abstime`	Time for the end of the occultation (seconds since last midnight) in UTC	`(dim)`	double	<time>
`ref_utc_time_str`	Time for the reference point of the occultation	`(dim)`	string	–
`ref_utc_absdate`	Time for the reference point of the occultation (full days) in UTC	`(dim)`	int	<days>
`ref_utc_abstime`	Time for the reference point of the occultation (seconds since last midnight) in UTC	`(dim)`	double	<time>
`start_lat`	Latitude of the start of the occultation	`(dim)`	float	<degN>
`end_lat`	Latitude of the end of the occultation	`(dim)`	float	<degN>
`ref_lat`	Latitude of the reference point of the occultation	`(dim)`	float	<degN>
`start_lon`	Longitude of the start of the occultation	`(dim)`	float	<degE>
`end_lon`	Longitude of the end of the occultation	`(dim)`	float	<degE>
`ref_lon`	Longitude of the reference point of the occultation	`(dim)`	float	<degE>
`quality`	Quality of the occultation prediction	`(dim)`	float	percent
`azimuth`	GNSS->LEO line of sight angle (from True North) for the reference coordinate	`(dim)`	float	<deg>
`ant_azimuth`	Incoming GNSS ray on antenna (0 Degrees is flight direction)	`(dim)`	float	<deg>
`leo_lat`	Latitude of the LEO for the reference point of the occultation	`(dim)`	float	<degN>
`leo_lon`	Longitude of the LEO for the reference point of the occultation	`(dim)`	float	<degE>
`leo_alt`	Altitude of the LEO for the reference point of the occultation	`(dim)`	float	m
`gnss_lat`	Latitude of the GNSS for the reference point of the occultation	`(dim)`	float	<degN>
`gnss_lon`	Longitude of the GNSS for the reference point of the occultation	`(dim)`	float	<degE>
`gnss_alt`	Altitude of the GNSS for the reference point of the occultation	`(dim)`	float	m

Tab. 3.8: Variables in the `/data/occultations` group.

3.9 Orbit Predictions

All covered LEO satellite orbits are also included with high temporal resolution in the product, not just the orbit position when an occultation is made. The group `/data/orbits` (see Table 3.9) holds general information, applicable for all predicted LEO satellites and includes information on orbit parameters (ellipsoid values) plus the times of the observations in the already introduced two time formats (see Section 3.4.3).

The actual orbits (provided as altitude, latitude and longitude of the sub-satellite point) of each LEO satellite are provided in sub-groups (below as an example for the Metop-A and -B satellites in sub-groups `/data/orbits/metop-a` and `/data/orbits/metop-b`, Tables 3.10 and 3.11).

Name	Description	Shape	Type	Units
Variables				
`ellipsoid_axis`	Ellipsoid Semi-major axis	`(scalar)`	double	m
`ellipsoid_flattening`	Flattening factor of the Earth	`(scalar)`	double	N/A
`utc_absdate`	Epochs (full days) in UTC	`(t)`	int	<days>
`utc_abstime`	Epochs (seconds since last midnight) in UTC	`(t)`	double	<time>
`utc_time_str`	Epochs in string format	`(t)`	string	–

Tab. 3.9: Variables in the `/data/orbits` group.

Name	Description	Shape	Type	Units
Variables				
`latitude`	Latitude of the LEO at epoch	`(t)`	float	<degN>
`longitude`	Longitude of the LEO at epoch	`(t)`	float	<degE>
`altitude`	Altitude of the LEO at epoch	`(t)`	float	m

Tab. 3.10: Variables in the `/data/orbits/metop-a` group.

Name	Description	Shape	Type	Units
Variables				
`latitude`	Latitude of the LEO at epoch	`(t)`	float	<degN>
`longitude`	Longitude of the LEO at epoch	`(t)`	float	<degE>
`altitude`	Altitude of the LEO at epoch	`(t)`	float	m

Tab. 3.11: Variables in the `/data/orbits/metop-b` group.

4 EPS L1C ACCURACY INFORMATION

The following sections provide some information on the expected accuracy of the orbit and occultation predictions. They also briefly discuss the impact of manoeuvres, look at the information provided in the quality indicator for occultations, and list possible future improvements to the product accuracy.

4.1 Orbit Predictions

Assuming a fitting interval of 7 days and a 14 day prediction, for nominal conditions (no manoeuvre), results for the 3D maximum error for the LEO satellite are shown in Figure 4.1.

These have negligible impact on the predicted occultation positions. The situation is more complicated for In-Plane or Out-of-Plane manoeuvres and depends on whether prior information on the manoeuvre was available.

4.2 Occultation Predictions

Under nominal LEO conditions, predicted occultation position and time can be very accurate. There are however more occultations predicted than actually observed (currently roughly 15%).

Results for a few test periods are presented in Table 4.1. The table includes includes the number of occultations predicted, actually observed, predicted but not observed and observed but not predicted. The latter are due to occultations actually taking place on the edge of the antenna, where the occultation prediction tool was discarding observations. Note that the provided number of real observations are also not further cleaned for high quality ones, thus these also include incomplete occultations.

Period	Occs Pred.	Occs Obs.	Not Obs.	Not Pred.	Matches [%]
2016/12/06 00:00.24 to 2016/12/19 23:56.36	10411	9047	1429	51	87
2016/11/30 00:00.24 to 2016/12/13 23:58.07	10634	8987	1713	52	84
2016/11/29 00:01.06 to 2016/12/12 23:54.59	10660	9006	1720	54	84
2016/11/24 00:00.30 to 2016/12/07 23:58.26	10771	9141	1700	55	84

Tab. 4.1: Number of predicted and actually observed occultations for Metop-A GRAS in the indicated observation period.

Generally, rising occultations are more often predicted and not observed, since they require tracking at very low altitudes where SNR values are low. The percentage of occultations actually predicted and measured depends also on unavailability of certain GPS satellites. The GRAS instrument relies for its observation on real-time information provided in the GPS ephemeris data, but the prediction tool does not have this information, it currently assumes all GPS satellites are healthy/available.

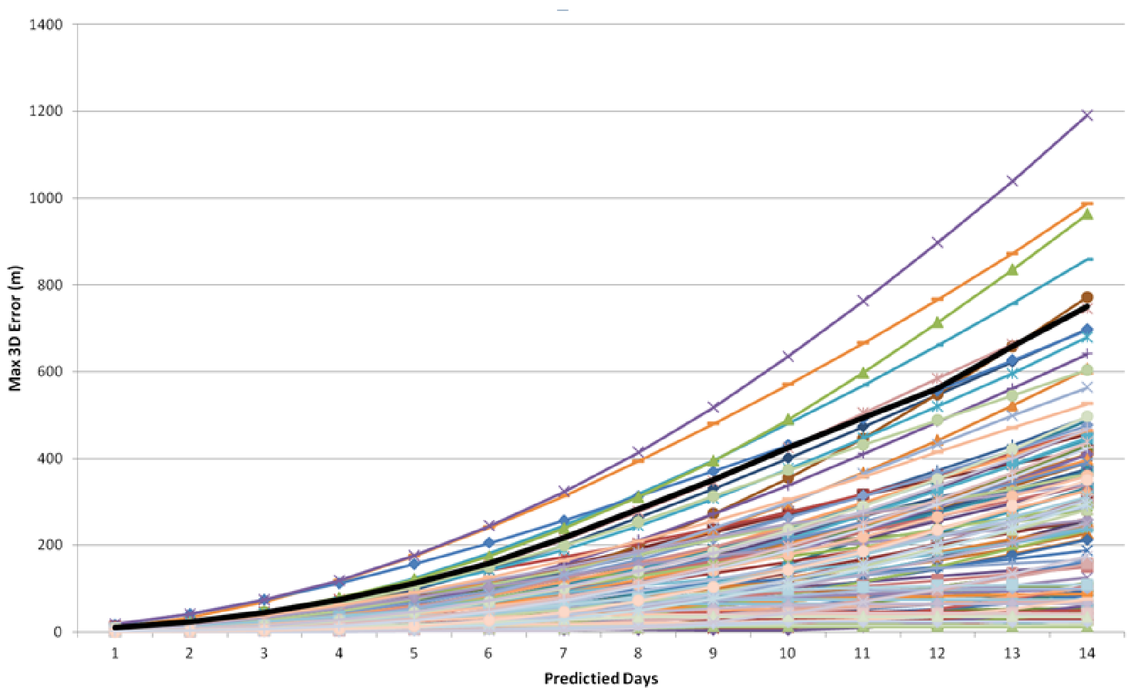

Fig. 4.1: 3D maximum errors over predicted days, for nominal conditions. Each line represents one run.

The following figures 4.2 to 4.5 show further details of one of the periods analysed.

Figure 4.2 shows the accuracy of the horizontal position of the prediction vs. the actual occultation position (both at SLTA = 0 km). Generally, the prediction is accurate to less than 1 km, however there is one GPS satellite that underwent a manoeuvre over this period (7th GPS satellite on x-axis), and here the location can be inaccurate to more than 100 km. Others show some individual occultations differing by more than 100 km, this is due to occultations not fully captured by the GRAS instrument over the full vertical extend; in these cases the operational processing does not provide the reference location at SLTA = 0 km, but at the lowest available SLTA values. And the horizontal movement of the occultation point can be > 300 km over an occultation.

Figure 4.3 shows the accuracy of the temporal matching; generally the time of the occultation can be predicted within a seconds. There is an irrelevant offset of a few seconds visible (likely due to leap seconds being accounted in one data set and not the other); otherwise the GPS satellite undergoing a manoeuvre shows also time accuracy decreasing towards the end of the prediction interval. The scatter of time differences for other GPS occultations is likely caused again by occultations not covering the full vertical range, investigations are however ongoing.

Figure 4.4 shows the different GPS satellites and whether they were observed by GRAS (red cross indicates no match). Not all GPS satellites were available in this period, e.g. the one with Pseudo-Random-Noise (PRN) number 04 was unavailable in the prediction and the observation. Others are available in the prediction for certain periods, but not observed, here the GPS satellite with PRN 08 around 8 to 9 days into the prediction (which is also the one that shows larger temporal and geographical mismatching in the figure above since it had a manoeuvre). The figure also shows a period where GRAS was not providing measurements, right before the 10th prediction day (Note this might be due to an outage of the data flow, the instrument, the satellite, etc. In this case, the whole Metop-A satellite data was unavailable for a short period).

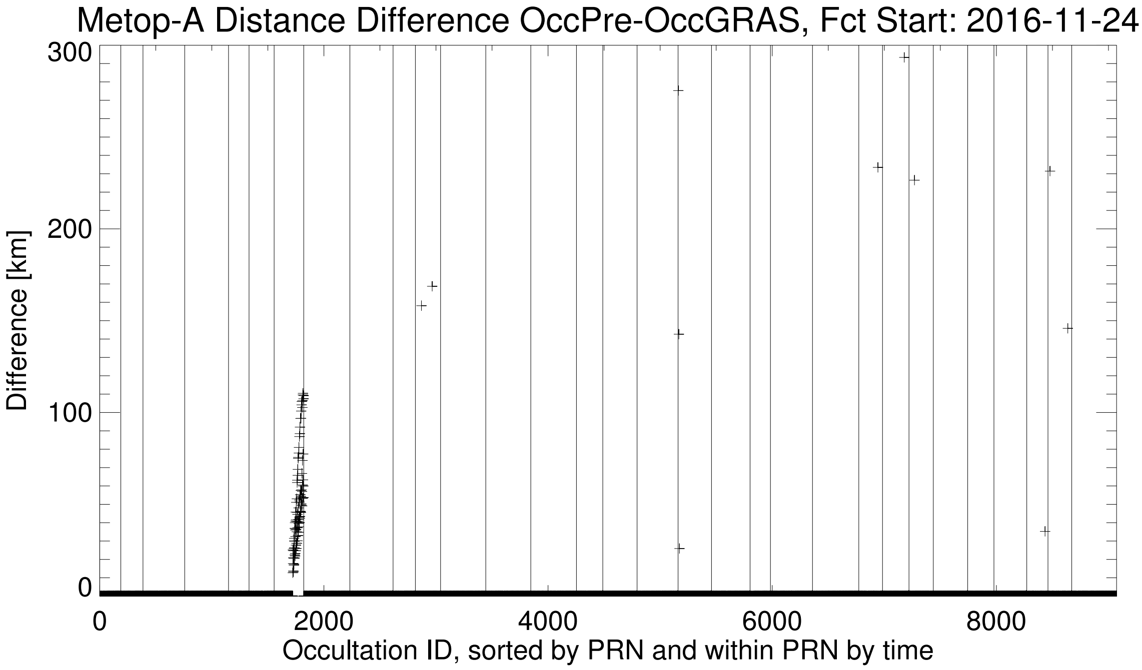

Fig. 4.2: Example of location prediction accuracy for all occultations; x-axis sorted by GPS PRN number and within each PRN by time, PRNs separated by vertical lines.

Figure 4.5 shows the daily averaged information provided in the quality indicator of the occultation data, separated for matching and not matching data as well as for rising and setting. Evidently, the quality forecast is only partly useful. It mostly reflects a general degradation of the quality over the time of the prediction period (we assume a 30% degradation over 2 weeks), plus the already mentioned information on where the occultation is situated on the antenna. Otherwise, it also shows the already mentioned better matching statistics for setting observations (87.3%) vs. those for rising ones (81.1%) and the outage of GRAS data around the 10th day of the prediction (where the red lines with the no match is close to the ones that were matched).

The reason for flagging particular occultations near the edge of the antenna is illustrated in Figure 4.6, showing results for a different period where there was no outage of GRAS data. It shows the percentage of failures over the occultation antenna azimuth, where angles around zero are the rising antenna (pointing in flight direction) and the ones around 180 Degree are covering the setting antenna.

The black line shows the relative failures. Generally, the relative number of unmatched data is high on the edge of the antenna (so $\pm$ 55 Degrees around the flight and anti-flight direction). There are however not a lot of occultations made here, see the blue line. The figure also clearly shows the problem when the GRAS receiver tries to track rising occultations near the antenna edge, where SNR values are low. Failures here are more than 10% higher than for corresponding setting observations.

The figure in addition includes the improvement if GPS outages as provided by the operators in Notice Advisory to Navstar Users (NANU) are used. This removes parts of PRN 11 and 17 from the statistics and generally improves the failure occurrence slightly. There are however also areas where the failure rate is higher after accounting for NANU – due to the fact that the NANU affected data is removed for all times $\geq$ the manoeuvre time. And, as was visible in e.g.,

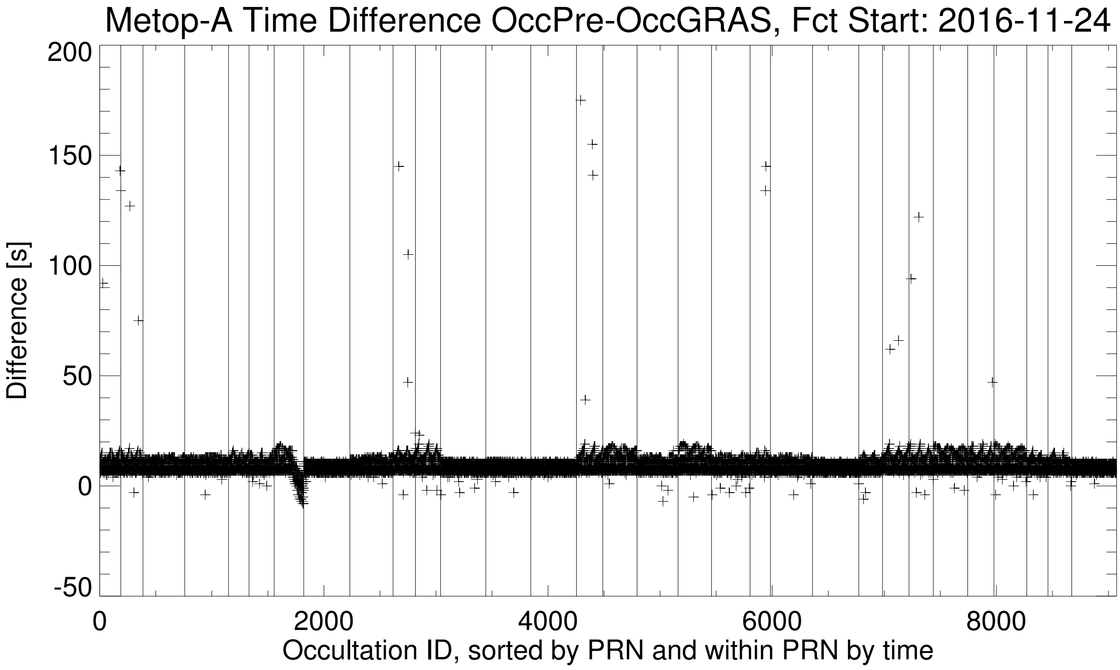

Fig. 4.3: Example of time prediction accuracy, otherwise as Figure 4.2.

Figure 4.2, even after a GPS manoeuvre, matches are still found but the errors in the time and location predictions increase.

Manoeuvres do not explain all unmatched data. There are still unmatched occultations at all antenna angles, these should ideally be covered by the GRAS instrument. Potential causes of these are under investigation.

The improvement to the quality information if NANU are available is shown in Figure 4.7 for one of the investigated periods (one that did not have a GRAS data outage). Only small improvements are obtained on the quality information, primarily since occultations that are found in the prediction are not available during GPS manoeuvres are removed. And note again that this quality information does not reflect the errors in the time and location predictions (as shown in Figure 4.2 and 4.3).

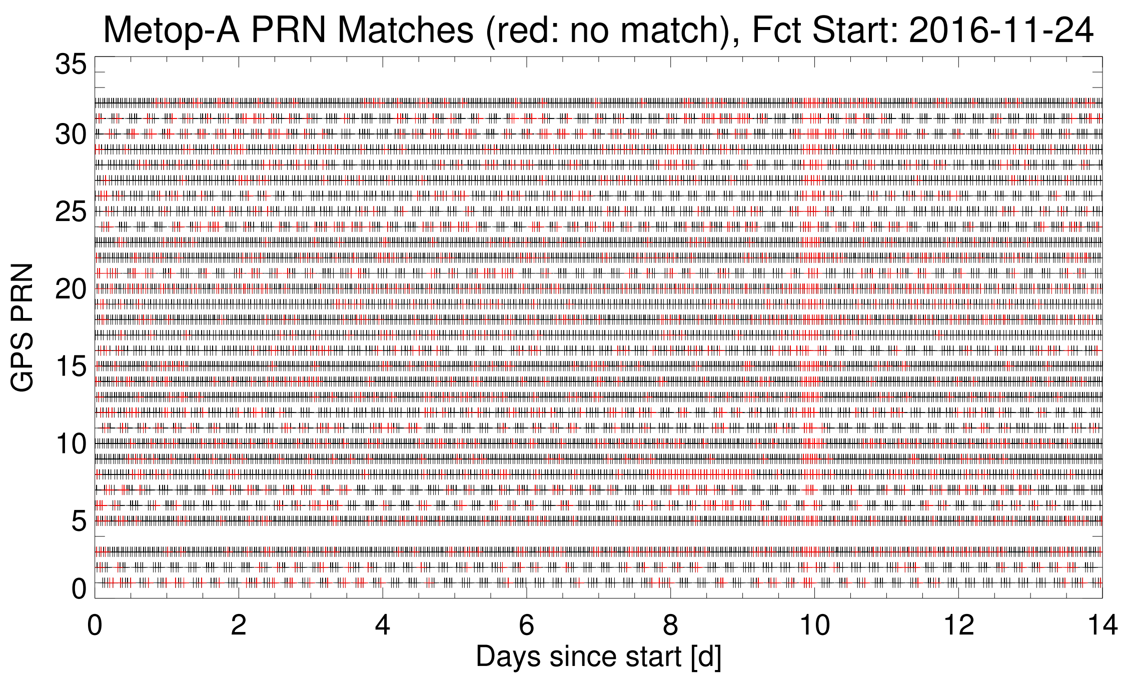

Fig. 4.4: Example of GPS prediction matches over the prediction period, showing an outage of GRAS data around day 10 and an unavailability of GPS PRN 08 starting near day 8.

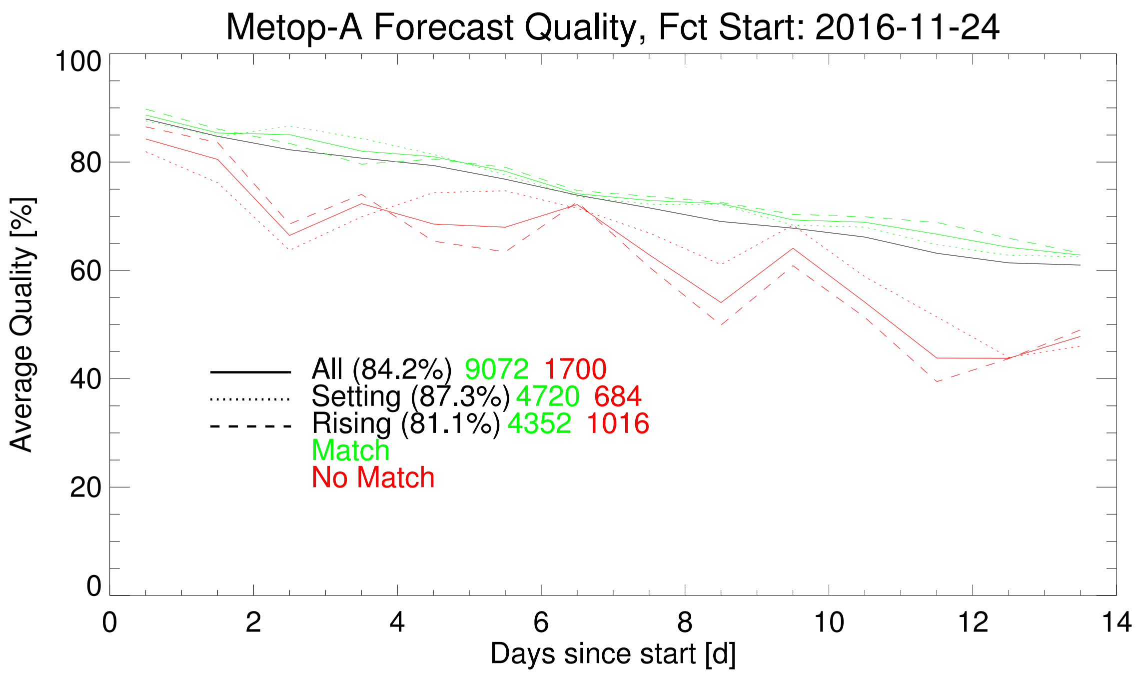

Fig. 4.5: Example of prediction quality information averaged daily over the prediction period, further separated for data that was matched (green), not matched (red), setting (dotted) and rising (dashed). Numbers in () indicate the mean quality over all corresponding occultations. The total number of occultations matched and not matched is also given.

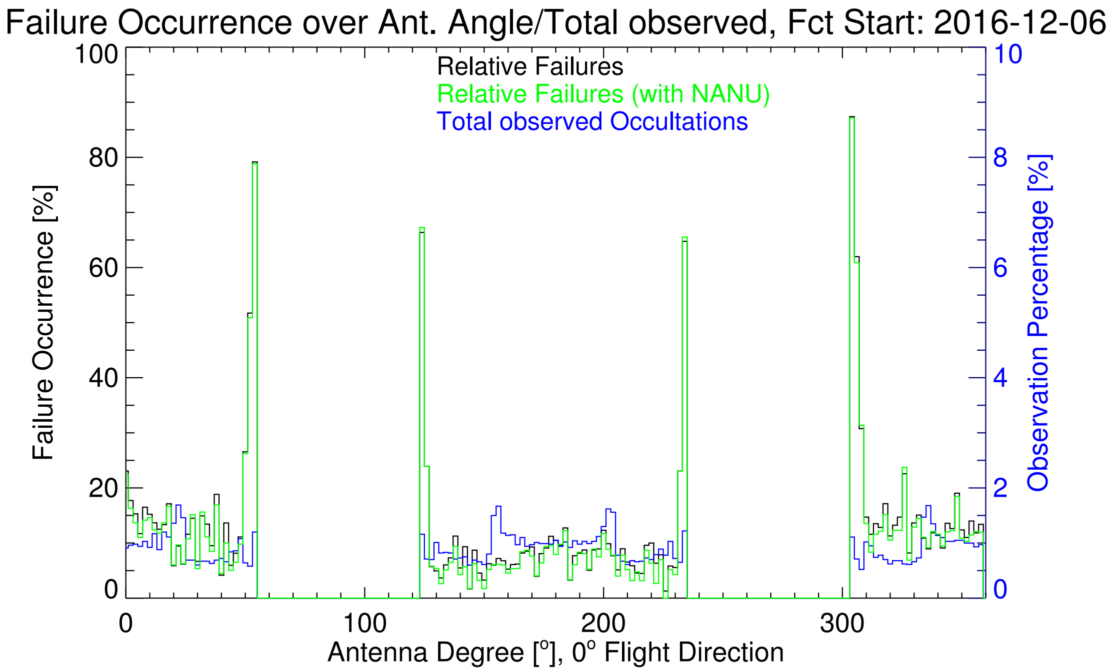

Fig. 4.6: Normalized occultation prediction failures over antenna azimuth, 0 Degrees is flight direction (rising occultations). Bin-size for all histograms is 2 Degrees, failures are shown without NANU (black) and with NANU information (green) taken into account; also shown in blue (right y-axis) is the normalized number of occultations per bin-size.

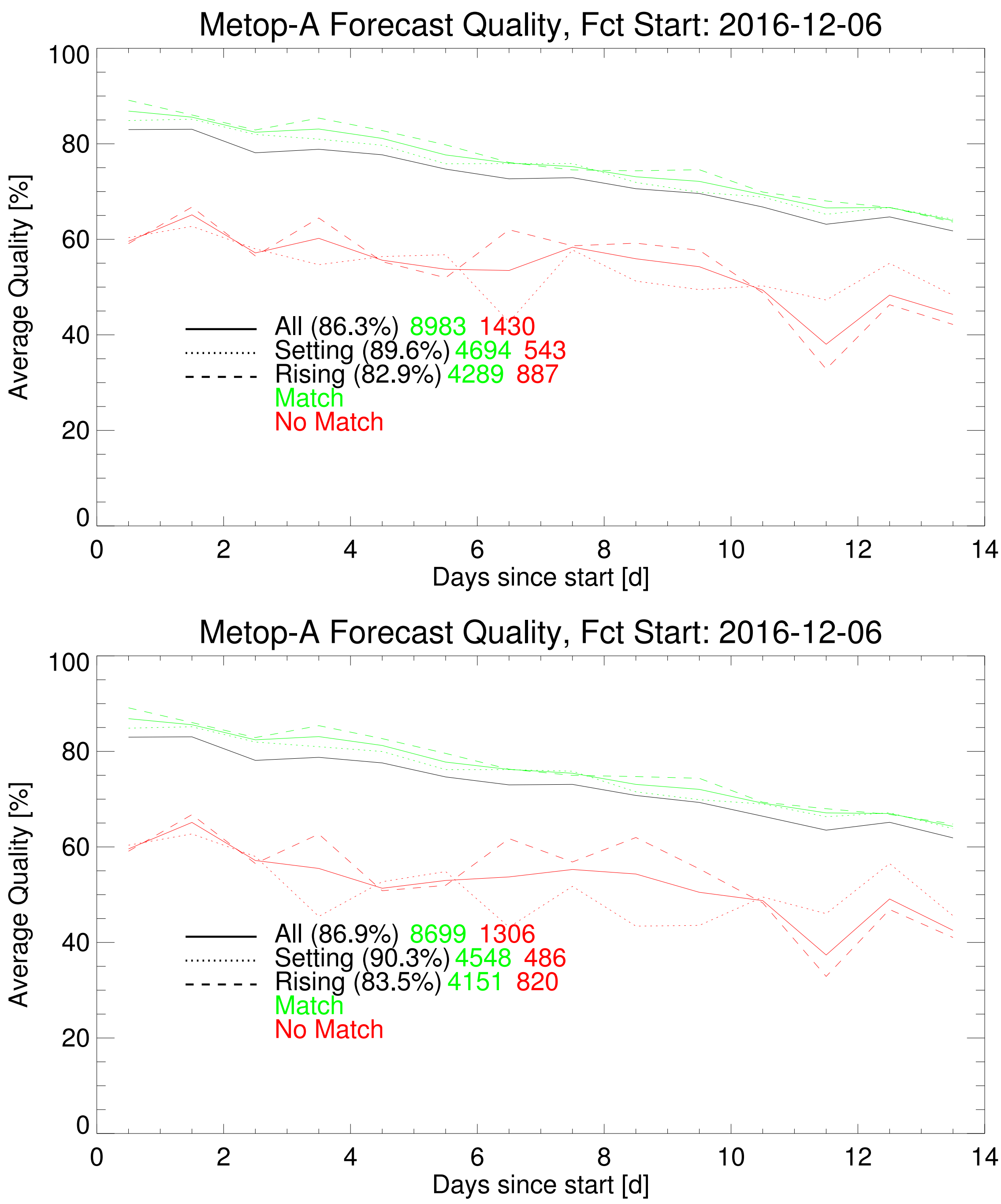

Fig. 4.7: Example of prediction quality information averaged daily over the prediction period, without (top) and with (bottom) NANU use, otherwise as Figure 4.5.