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DOCUMENT

Accuracy of EOCFI Software functions in the Pointing library

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CHANGE RECORD

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Sentinel-1B transponder data used. Minor improvements and clarifications.	13/2/2017	All	All

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1 INTRODUCTION

This note presents the accuracy of computations performed using the Earth Observation Mission CFI Software functions (or shortly EOCFI, see [RD01] and [RD02] for more details) in the Pointing (see [RD03]) library.
All Pointing functions are listed in Table 18 (see Annex A). For several of them (highlighted in grey), accuracy determination is not relevant. Functions for which accuracy determination is required are highlighted in green when they are presented in this version of this document.

With reference to Table 18, for each function the following details are provided:

- Name, Description and Outputs;
- Algorithm Type, that can be:
  - Model: the computation is based on a model;
  - Iterative: the computation is done iteratively;
  - Analytical: the computation is done using closed form expressions;
  - EOCFI specific: the method used has been specifically developed for the EOCFI SW;
  - N/A: Not Applicable (e.g. it is an initialisation function).
- Accuracy Determination, that can be:
  - N/A: Not Applicable (when algorithm type is N/A);
  - Not Required: when the algorithm is analytical, no accuracy determination is required. The correctness of analytical computations is verified at Software testing level, e.g. validating the reversibility of conversions;
  - Required: accuracy determination is required when the algorithm is CFI specific, iterative or model based.
- Document Reference: the document in which the accuracy determination is presented.

All computations described in this document have been performed using a MacBook Pro Computer (2.8 GHz Intel Core i7 Processor, 16 GB 1600 MHz DDR3 Memory).

References

Id	Title
[RD01]	EOCFI documentation main page, http://eop-cfi.esa.int/index.php/mission-cfi-software/eocfi-software/branch-4-x/eocfi-v4x-documentation
[RD02]	"Earth Observation Mission CFI Software - General Software User Manual", v4.12, http://eop-cfi.esa.int/Repo/PUBLIC/DOCUMENTATION/CFI/EOCFI/BRANCH_4X/4.12/C-Docs/SUMs/GeneralSUM_v4_12.pdf
[RD03]	"Earth Observation Mission CFI Software - Pointing Software User Manual", v4.12, http://eop-cfi.esa.int/Repo/PUBLIC/DOCUMENTATION/CFI/EOCFI/BRANCH_4X/4.12/C-Docs/SUMs/PointingSUM_v4_12.pdf
[RD04]	SLERP algorithm, https://en.wikipedia.org/wiki/Slerp
[RD05]	"Accuracy of EOCFI Software functions in the Lib and Orbit libraries", doc. PE-TN-ESA-GS-404

2 POINTING LIBRARY

2.1 Attitude Computation

2.1.1 xp_attitude_compute

The **xp_attitude_compute** function calculates the satellite attitude frame with an algorithm that depends on the method used to initialise the various attitude frames involved in the calculation. Most of the algorithms implement an ideal attitude model, e.g. ideal Yaw Steering Model Law (YSM), for which accuracy determination is not applicable. The only exception is the attitude computed using a list of quaternions (e.g. an attitude file containing a list of quaternions and corresponding epochs). In this case the EOCFI SW uses an interpolation algorithm (SLERP, see [RD04]) that can introduce some differences w.r.t to the actual attitude. The difference is due by the linear angular rate implemented by the SLERP interpolator, while the angular rates in real attitude evolution follows a more complex profile.
Table 1 shows the maximum difference, along one orbit and in terms of Roll-Pitch-Yaw, between the attitude frame computed with the ideal YSM law and the one computed using quaternions interpolation. The quaternions have been computed using the same YSM law. The calculation has been repeated using different time steps in the quaternion set (resp. 1, 5, 10, 20, 30 sec.) and it can be observed that the difference gets bigger with a longer time step.
This test scenario only shows the limitations of the SLERP interpolation and that this limitation can be reduced using a suitable time step (i.e. reducing the time step has the effect of reducing the difference). The selection of the time step should take into account all requirements related to attitude determination (e.g. dynamics of the satellite like oscillations a certain frequencies).

Time Step [s]	Roll-Pitch-Yaw Components		
	Roll	Pitch	Yaw
1	0.000001	< 0.000001	0.000001
5	0.000013	0.000002	0.000013
10	0.000053	0.000009	0.000053
20	0.000213	0.000034	0.000212
30	0.000479	0.000077	0.000476

Table 1 – Roll-Pitch-Yaw difference – maximum values in degrees

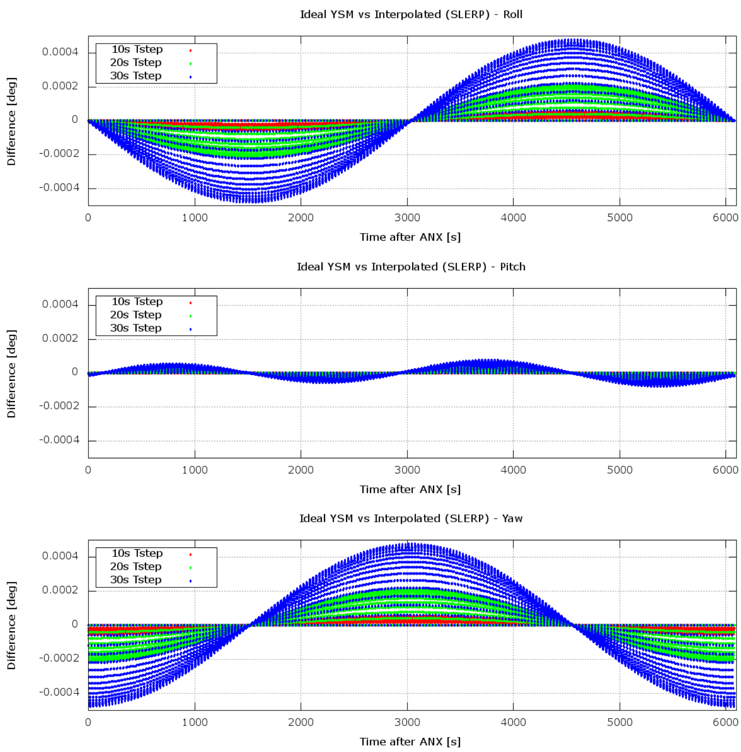

Figure 1 - Ideal YSM vs. interpolated attitude – one full orbit as function of ANX time

Figure 1 shows the difference along one orbit as function of time after ANX (only for 10, 20, 30 sec.). Figure 2 (detail on a shorter time interval) shows that the difference is zero at the quaternions epochs and reaches the maximum in the middle of the time interval between one quaternion and the next. Figure 3 (difference as function of latitude) shows that he amplitude of the difference changes along the orbit and depends on the latitude.

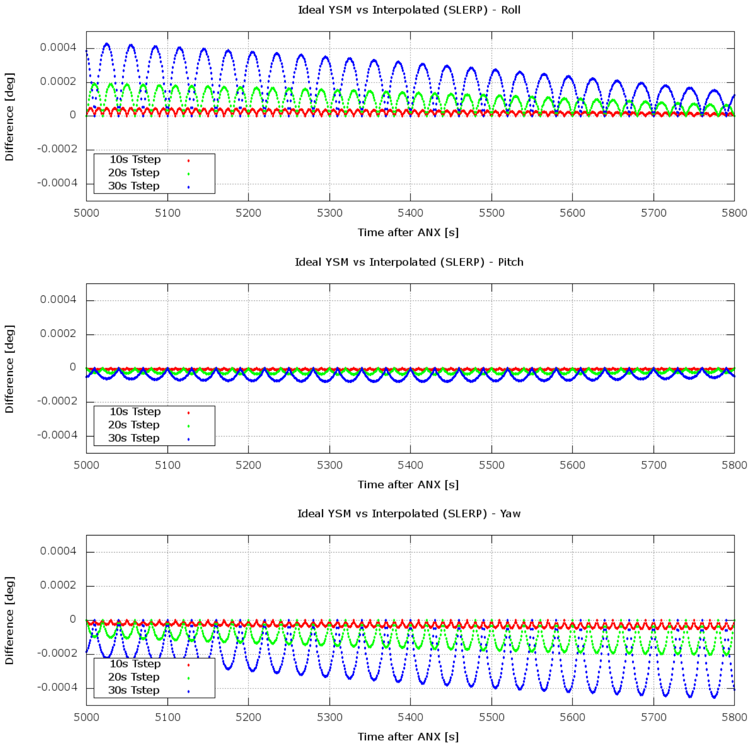

Figure 2 - Ideal YSM vs. interpolated attitude – short time interval

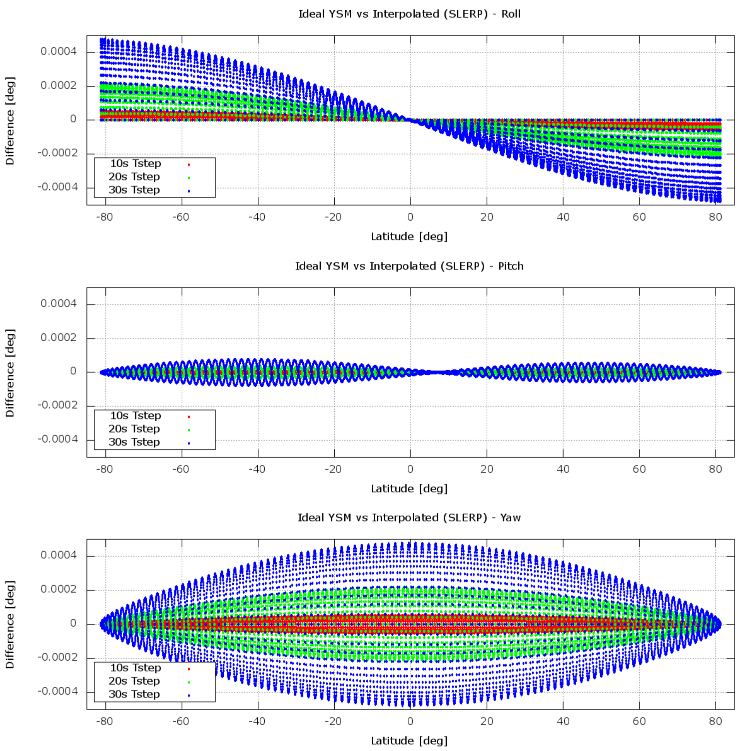

Figure 3 – Ideal YSM vs. interpolated attitude – one full orbit as function of latitude

2.1.2 xp_change_frame

This function converts a vector to a different reference / attitude frame. Its accuracy is equivalent to the one of the xl_change_cart_cs function (function in the Lib library computing co-ordinate system transformations). The accuracy of this function is presented in section 2.3 of [RD05].

2.2 Target Computations

The EOCFI SW provides several functions for target computation; the accuracy of such functions is described in the following sections. The accuracy is estimated using one or more of the following methods:

- **evaluating the effect of attitude computation accuracy:** as described in section 2.1, using quaternion interpolation can introduce a difference between attitude computed by the EOCFI and real attitude. This difference has an impacts to the target computation;
- **comparing the output of the target function to data acquired by instruments during mission campaigns (e.g. Sentinel-1B):** this comparison gives an indication of the inaccuracy due to un-modelled features or other inaccuracy sources. ***This inaccuracy is not fully originated by the EOCFI Software, however it gives an indication of residual error that needs to be compensated (e.g. by calibration / processing)***;
- **comparing some geometric properties of the computed target points with the expected ones.** This method is also used for Software validation.

2.2.1 xp_target_inter

It calculates the intersection point(s) of the line of sight defined by an elevation and an azimuth angle (or a set of them) expressed in the input Attitude frame, with a surface(s) located at a certain geodetic altitude(s) over the Earth.

2.2.1.1 Effect of the attitude computation accuracy

Figure 4 shows (only for the 10, 20, 30 sec. cases) the distance, as function of latitude, between the two target points calculated (at altitude 0m over the ellipsoid) using, for the attitude computation, respectively the ideal YSM law and a quaternion file (see also section 2.1). The computation has been repeated with different quaternions time steps (resp. 1, 5, 10, 20 and 30s) and line of sights (resp. nadir, 27.5deg off-nadir, 55deg off-nadir). A summary of maximum differences depending on time step and LOS is given in Table 2. The difference remains **below 5m** with the time step set to 10s or less and **1.1m or less** with the time step set to less than 5s.

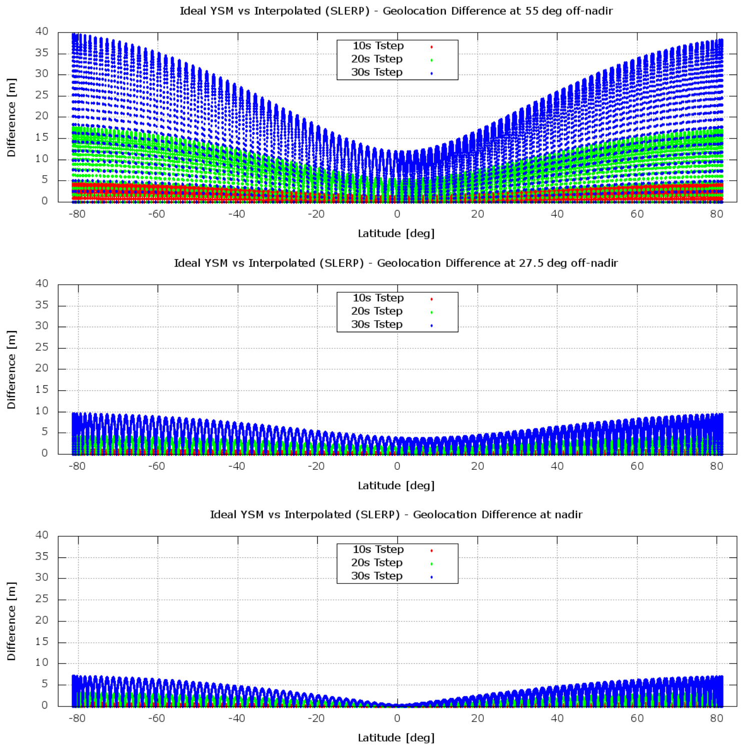

Figure 4 – xp_target_inter - Geo-location difference as function of latitude

Time Step [s]	LOS off-nadir angle		
	55 deg	27.5 deg	0.0 deg
1	0.049	0.012	0.009
5	1.103	0.266	0.197
10	4.398	1.059	0.786
20	17.589	4.235	3.143
30	39.569	9.528	7.071

Table 2 – xp_target_inter - Geo-location difference – maximum values in meters

2.2.1.2 Comparison with Sentinel-1B transponder acquisition data

Transponders are reference targets used for calibration of the SAR instrument on-board Sentinel-1B. The SAR sends an impulse and after a so called "RangeTime" receives the echo coming from the transponder. Given also the artificial delay added by the transponder, it is possible to compute the range (i.e. distance) between satellite and target via the following formula:

$$Range = c \cdot \frac{RangeTime - TransponderDelay}{2} \quad (1)$$

The following quantities are therefore known:

- **Transponder position:** in terms of lon,lat,alt and therefore as a vector in the Earth Fixed reference system;
- **Time of Acquisition:** (UTC);
- **Satellite position and velocity**: from an orbit file provided by the Precise Orbit Determination (POD) service;
- **The LOS azimuth:** it is also known that, at the acquisition time, the transponder lies in the Zero-Doppler plane, i.e. the plane perpendicular to the satellite velocity and passing through the satellite position. Using the EOCFI conventions, this means that the azimuth of the LOS from satellite to transponder is, in the zero-doppler attitude frame, either 90 or 270 depending on the flying direction;
- **The LOS elevation:** in zero-doppler attitude frame is the angle between the LOS and the X axis of the zero-doppler frame, that is the vector belonging to the zero-doppler plane and perpendicular to the nadir direction. It can be calculated as follows:

$$\begin{aligned} Nadir &= SatPos - Ssp \\ Los &= \frac{TransponderPos - SatPos}{\left|TransponderPos - SatPos\right|} \\ ZeroDopplerX &= \frac{SatVel \times Nadir}{\left|SatVel \times Nadir\right|} \\ LosElevation &= \arccos(ZeroDopplerX \cdot Los) \end{aligned} \quad (2)$$

- **The range:** (computed as per (1));
- **The range rate:** it is zero as both satellite and transponder lie on the zero-doppler plane;

Details related to a given transponder acquisition are summarized in Table 3.
These values have been used to estimate the accuracy of the xp_target_inter function as summarized in Table 4. The difference between the calculated target position and the real one is **below 2 m**.
This difference is due to the accumulation of small inaccuracies in the inputs that cannot be removed, for example:

- Satellite and transponder position/velocity determination;
- Range Time determination;
- Offset between SAR and GPS instruments;
- Atmosphere modelling (e.g. signal delay)

Transponder Acquisition Details		
Transponder Position	Geodetic co-ordinates: Longitude [deg], Latitude [deg], Altitude [m]	5.176526, 52.099344, 45.613
	EF co-ordinates: X, Y, Z [m]	3910258.571, 354246.181, 5009637.179
Satellite Position	EF co-ordinates: X, Y, Z [m]	4362525.861, 687101.351, 5518993.362
Satellite Velocity	EF Velocity components: VX, VY, VZ [m/s]	5961.389, -1119.482, -4561.646
Line of Sight	Azimuth, Elevation [deg]	90.0, 69.252170
Range	Calculated as per (1), [m]	758144.398
Range Rate	[m/s]	0.0
Acquisition Time	UTC	2016-06-27T06:05:39.680806

Table 3 – Transponder Acquisition Details

Inputs		
Time	UTC	2016-06-27T06:05:39.680806
Satellite Position	EF co-ordinates: X, Y, Z [m]	4362525.861, 687101.351, 5518993.362
Satellite Velocity	EF Velocity components: VX, VY, VZ [m/s]	5961.389, -1119.482, -4561.646
Attitude	Zero-doppler	-
Line of Sight	Azimuth, Elevation [deg]	90.0, 69.252170
Altitude	Geodetic Altitude [m]	45.613
Outputs		
Target Position	Calculated, EF co-ordinates: X, Y, Z [m]	3910259.948, 354245.925, 5009636.129
	Expected (Transponder position), EF co-ordinates: X, Y, Z [m]	3910258.571, 354246.181, 5009637.179
	Difference (magnitude of Calculated minus Expected) [m]	1.750

Table 4 – xp_target_inter: inputs/outputs

2.2.2 *xp_target_range*

It calculates the location of a point that is placed on a surface at a certain geodetic altitude over the Earth, that is seen from the Spacecraft on a line of sight that forms a certain azimuth angle in the input Attitude frame, and that is at a certain range or slant-range from the Spacecraft.

2.2.2.1 Effect of the attitude computation accuracy

Figure 5 shows (only for the 10, 20, 30 sec. cases) the distance, as function of latitude, between the two target points calculated (at altitude 0m over the ellipsoid) using, for the attitude computation, respectively the ideal YSM law and a quaternion file (see also section 2.1). The computation has been repeated with different quaternions time steps (resp. 1, 5, 10, 20 and 30s) and input ranges (resp. 850, 1250, 1650 km). A summary of maximum differences depending on time step and input range is given in Table 5. The difference remains **below 0.4m** with the time step set to less than 5s and **below 1.3m** with the time step set to 10s or less.

Time Step [s]	Input Range		
	850 km	1250 km	1650 km
1	0.003	0.010	0.015
5	0.063	0.218	0.324
10	0.251	0.871	1.289
20	1.003	3.481	5.154
30	2.256	7.830	11.598

Table 5 – xp_target_range - Geo-location difference – maximum values in meters

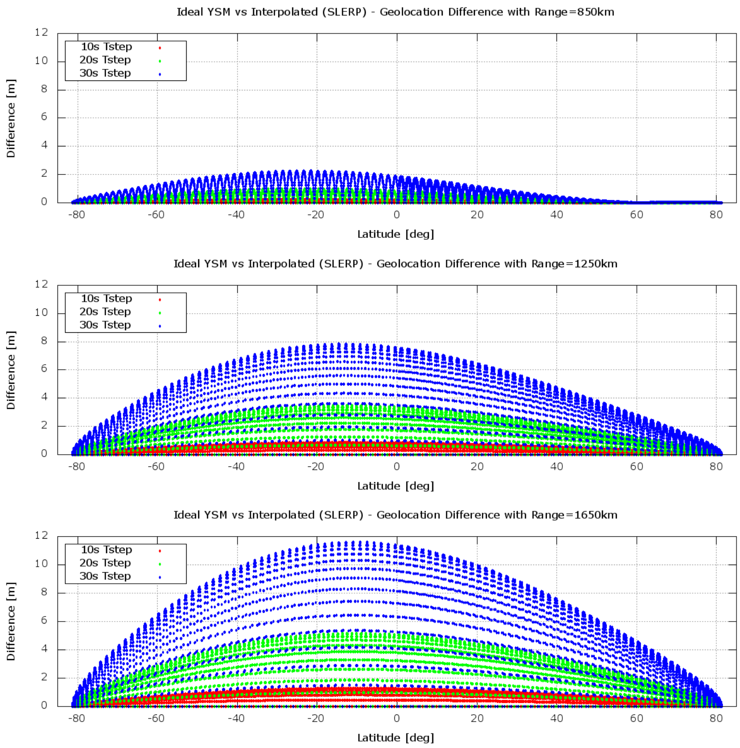

Figure 5 – xp_target_range - Geo-location difference

2.2.2.2 Comparison with Sentinel-1B transponder acquisition data

An approach similar to the one described in section 2.2.1.2 can be followed; the results are given in Table 6. The difference is **less than 2.5m**. This difference is due to the accumulation of inaccuracies in the inputs, see also 2.2.1.2.

Inputs		
Time	UTC	2016-06-27T06:05:39.680806
Satellite Position	EF co-ordinates: X, Y, Z [m]	3910258.571, 354246.181, 5009637.179
Satellite Velocity	EF Velocity components: VX, VY, VZ [m/s]	5961.389, -1119.482, -4561.646
Attitude	Zero-Doppler	-
Line of Sight	Azimuth [deg]	90.0
Range	Distance Satellite Target [m]	758144.398
Altitude	Geodetic Altitude [m]	45.613
Outputs		
Target Position	Calculated, EF co-ordinates: X, Y, Z [m]	3910259.817, 354244.357, 5009636.342
	Expected (Transponder position), EF co-ordinates: X, Y, Z [m]	3910258.571, 354246.181, 5009637.179
	Difference (magnitude of Calculated minus Expected) [m]	2.361

Table 6 – xp_target_range: inputs/outputs

2.2.2.3 Comparison between calculated and expected range

The calculated distance satellite to target (i.e. the distance between the computed target position and the satellite position) shall be equal to the expected distance (i.e. the input range). The difference between calculated and expected distance gives therefore an indication of the accuracy computation: the smaller the difference, the better the accuracy.

The target has been calculated for several positions along one orbit and with three different input ranges (resp. 850, 1250, 1650 km), the difference between expected and calculated distance is always below **1e-6 m**.

2.2.3 *xp_target_generic*

It calculates the LOS from satellite to a given target whose position / velocity / acceleration is given as input.
For this function, the target position is an input. The output is the line of sight expressed as azimuth and elevation.

2.2.3.1 Effect of the attitude computation accuracy

Figure 6 shows (only for the 10, 20, 30 sec. cases) the difference angle, as function of latitude, between the two line of sight vectors calculated using, for the attitude computation, respectively the ideal YSM law and a quaternion file (see also section 2.1). The computation has been repeated with different quaternions time steps (resp. 1, 5, 10, 20 and 30s) and input targets (resp. 60, 40, 20 deg off-nadir). A summary of maximum differences depending on time step and target position is given in Table 7. The difference remains **below 0.00006deg** with the time step set to 10s or less and **0.00002deg or less** with the time step set to less than 5s.

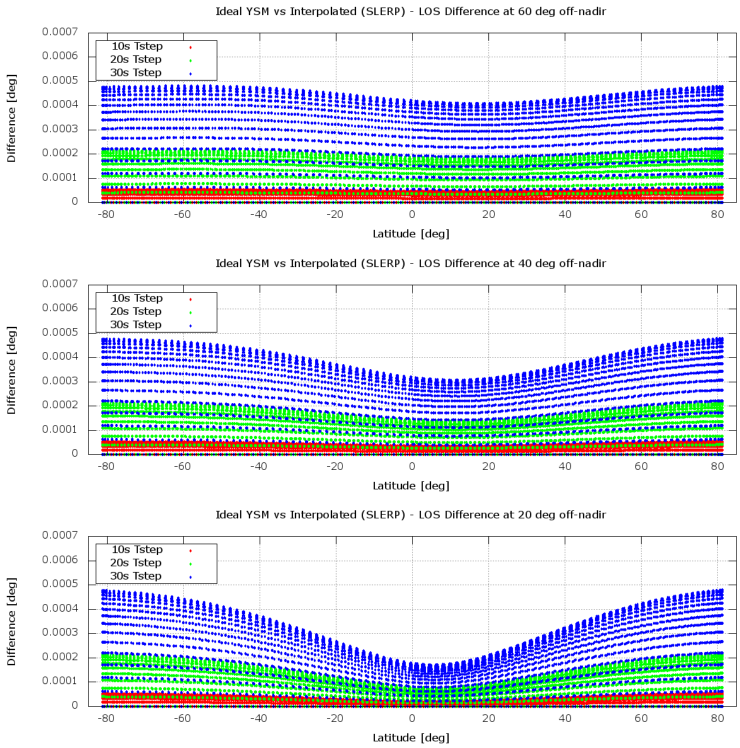

Figure 6 – xp_target_generic – difference between LOS calculated using YSM vs. Interpolation

Time Step [s]	LOS off-nadir angle		
	60 deg	40 deg	20 deg
1	0.000001	0.000001	< 0.000001
5	0.000013	0.000013	0.000013
10	0.000053	0.000053	0.000053
20	0.000214	0.000213	0.000213
30	0.000481	0.000479	0.000479

Table 7 – xp_target_generic – difference between LOS calculated using YSM vs. Interpolation – maximum values in degrees

2.2.3.2 Comparison with Sentinel-1B transponder acquisition data

An approach similar to the one described in section 2.2.1.2 can be followed; the results are given in Table 8. The input for the function is the target (transponder) position and the output is the Line of Sight in terms of azimuth and elevation. The calculated azimuth and elevation can be compared with the expected ones, see Table 8. The results of the comparison can be seen in Table 8: the difference in azimuth is less than **0.0004 deg** and the difference in elevation is < **0.000001 deg.**

Inputs		
Time	UTC	2016-06-27T06:05:39.680806
Satellite Position	EF co-ordinates: X, Y, Z [m]	3910258.571, 354246.181, 5009637.179
Satellite Velocity	EF Velocity components: VX, VY, VZ [m/s]	5961.389, -1119.482, -4561.646
Attitude	Zero-doppler	-
Transponder Position	Geodetic co-ordinates: Longitude [deg], Latitude [deg], Altitude [m]	5.176526, 52.099344, 45.613
	EF co-ordinates: X, Y, Z [m]	3910258.571, 354246.181, 5009637.179
Outputs		
Line of sight	Azimuth [deg]	90.000373
	Elevation [deg]	69.252170
	Difference (magnitude of Calculated minus Expected) [m]	Azimuth=0.000373 Elevation= < 0.000001

Table 8 – xp_target_generic: inputs/outputs

2.2.4 *xp_target_travel_time*

It calculates the point of the line or sight from the satellite (defined by an elevation and an azimuth angle expressed in the selected Attitude Frame) at a given travel time(s) along the (curved) line of sight.

To Be Written.

2.2.5 *xp_target_ground_range*

It calculates the location of a point that is placed on a surface at a certain geodetic altitude over the Earth, that lays on the plane defined by the S/C position, the nadir and a reference point, and that is at a certain distance or ground range measured along that surface from that reference point.
This reference point is calculated being the intersection of the previous surface with the line of sight defined by an elevation and azimuth angle in the input Attitude coordinate system.

To Be Written.

2.2.6 *xp_target_incidence_angle*

It calculates the location of a point that is placed on a surface at a certain geodetic altitude over the Earth and that is seen from the S/C on a line of sight that forms a certain azimuth angle in the input Attitude frame and that intersects that surface with a certain incidence angle.

To Be Written.

2.2.7 *xp_target_range_rate*

It calculates the location of a point that is placed on a surface at a certain geodetic altitude over the Earth, that is at a certain range from S/C, and whose associated Earth-fixed target has a certain range-rate value.

2.2.7.1 Comparison with Sentinel-1B transponder acquisition data

An approach similar to the one described in section 2.2.1.2 can be followed; the results are given in Table 9. The difference is **less than 2.5m**. This difference is due to the accumulation of inaccuracies in the inputs, see also 2.2.1.2.

Inputs		
Time	UTC	2016-06-27T06:05:39.680806
Satellite Position	EF co-ordinates: X, Y, Z [m]	3910258.571, 354246.181, 5009637.179
Satellite Velocity	EF Velocity components: VX, VY, VZ [m/s]	5961.389, -1119.482, -4561.646
Attitude	Zero-Doppler	-
Range	[m]	758144.398
Range Rate	[m/s]	0.0
Altitude	Geodetic Altitude [m]	45.613
Outputs		
Target Position	Calculated, EF co-ordinates: X, Y, Z [m]	3910259.817, 354244.357, 5009636.342
	Expected (Transponder position), EF co-ordinates: X, Y, Z [m]	3910258.571, 354246.181, 5009637.179
	Difference (magnitude of Calculated minus Expected) [m]	2.361

Table 9 – xp_target_range_rate: inputs/outputs

2.2.7.2 Comparison between calculated and expected range and range rate

The calculated distance satellite to target (i.e. the distance between the computed target position and the satellite position) shall be equal to the expected distance (i.e. the input range).
The calculated range-rate (i.e. the component of the satellite velocity vector along the satellite to target direction) shall be equal to the expected range-rate (i.e. the input range-rate).

The difference between calculated and expected distance / range-rate gives therefore an indication of the accuracy computation: the smaller the difference, the better the accuracy.

The target has been calculated for several positions along one orbit and with three different input ranges (resp. 850, 1250, 1650 km), the difference between expected and calculated distance / range-rate is always below **1e-6 m**.

2.2.8 *xp_target_tangent*

It calculates the location of the tangent point over the Earth that is located on the line of sight defined by an elevation and azimuth angles expressed in the input Attitude frame.

2.2.8.1 Effect of the attitude computation accuracy

Figure 7 shows (only for the 10, 20, 30 sec. cases) the distance, as function of latitude, between the two target points calculated using, for the attitude computation, respectively the ideal YSM law and a quaternion file (see also section 2.1). The computation has been repeated with different quaternions time steps (resp. 1, 5, 10, 20, and 30s) and line of sights (resp. elevation = 5deg, azimuth = 0, 45, 90 deg). A summary of maximum differences depending on time step and LOS is given in Table 10. The difference remains **below 7m** with the time step set to 10s or less and **1.7m or less** with the time step set to less than 5s.

Time Step [s]	LOS azimuth		
	0.0 deg	45.0 deg	90.0 deg
1	0.020	0.056	0.074
5	0.296	1.241	1.685
10	1.177	4.950	6.725
20	4.701	19.774	26.886
30	10.577	44.488	60.498

Table 10 – xp_target_tangent - Geo-location difference – maximum values in meters

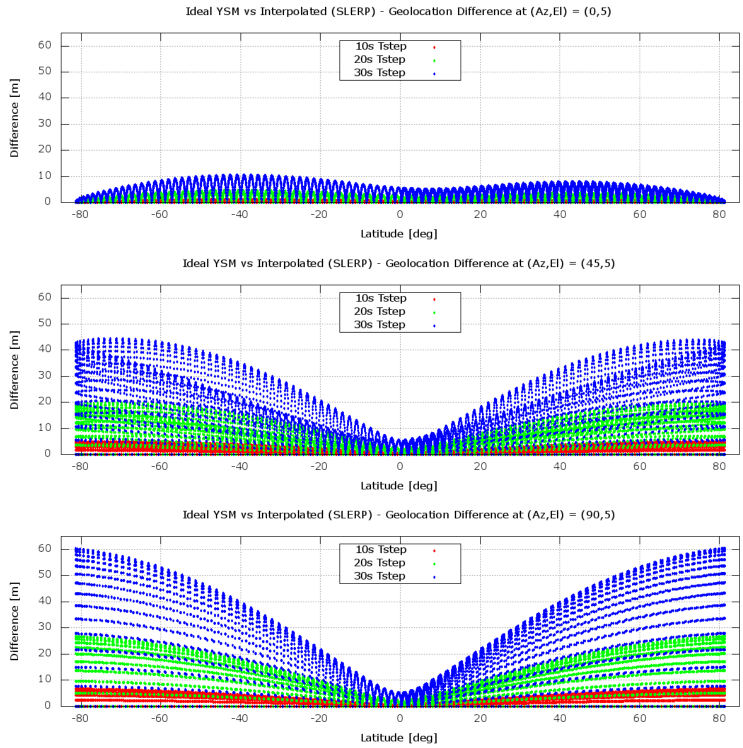

Figure 7 – xp_target_tangent - Geo-location difference as function of latitude

2.2.8.2 Comparison between calculated and expected tangent point

In the target point, the line of sight vector (i.e. the normalised vector from satellite to target) is perpendicular to the vector normal to the ellipsoid (calculated with equation 3). The angle between these two vectors is expected to be 90deg. Therefore the difference between 90deg and such angle is an indication of the computation accuracy: the smaller the difference, the better the accuracy.

Figure 8 shows the difference calculated along one orbit for different line of sight directions (defined by azimuth and elevation). The maximum difference is always below **0.00002 deg**.

Considering a constant Earth radius of ~6380 km and an altitude of the target point of max. 800km, this corresponds to a maximum difference of **~2.5m** in the target position computation.

$$Norm = \begin{bmatrix} \cos(lat)\cos(lon) \\ \cos(lat)\sin(lon) \\ \sin(lat) \end{bmatrix} \quad (3)$$

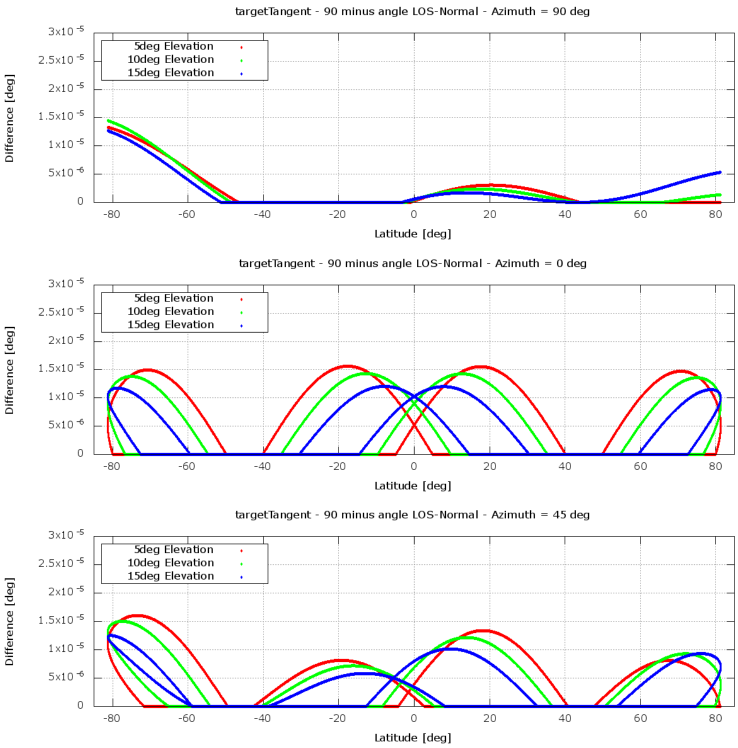

Figure 8 – xp_target_tangent – difference between 90deg and angle LOS-normal

2.2.9 xp_target_altitude

It calculates the location of the tangent point over the Earth that is located on a surface at a certain geodetic altitude over the Earth and that is on a line of sight that forms a certain azimuth angle in the input Attitude frame.

To Be Written.

2.2.10 xp_target_star

It calculates the location of the tangent point over the Earth that is located on the line of sight that points to a star defined by its right ascension and declination coordinates.

To Be Written.

2.2.11 xp_target_tangent_sun

It calculates the location of the tangent point over the Earth that is located on the line of sight that points to the Sun

To Be Written.

2.2.12 xp_target_tangent_moon

It calculates the location of the tangent point over the Earth that is located on the line of sight that points to the Moon

To Be Written.

2.2.13 xp_target_station

It calculates the most relevant observation parameters of the link between the satellite and a ground station.

This function is equivalent to the function xp_target_generic at it receives as input the position of the target (in this case, a ground station position). The output is the line of sight expressed as azimuth and elevation.

The used algorithm (and consequently the accuracy) is the same as the one in xp_target_generic (see section 2.2.3).

2.2.14 xp_target_reflected

It computes, from S/C position and attitude, and emitting source position, the point of reflection from the source towards the SC at a certain geodetic altitude.

To Be Written.

2.2.15 xp_target_sc

It calculates the most relevant observation parameters of the link between one satellite and another Satellite.

This function is equivalent to the function xp_target_generic at it receives as input the position of the target (in this case, another satellite). The output is the line of sight expressed as azimuth and elevation.

The used algorithm (and consequently the accuracy) is the same as the one in xp_target_generic (see section 2.2.3).

2.2.16 xp_target_extra_vector

This function extracts target computation results / computes auxiliary target data.
The list of outputs is given in Table 11. If applicable, the accuracy estimation is given for each output.

Id	Output Description	Accuracy Estimation
1	Target position (EF)	The accuracy depends on the function that has been used to compute the target. Refer to the accuracy determination done for the specific function. For example, for xp_target_inter, see section 2.2.1.
2	Target velocity (EF)	TBW
3	Target acceleration (EF)	TBW
4	LOS direction (expressed as vector in EF)	The LOS direction is the vector from the satellite to the target. Therefore the accuracy for the LOS direction is the same as the accuracy of the Target position.
5	LOS direction rate (expressed as vector in EF)	TBW
6	LOS direction rate-rate (expressed as vector in EF)	TBW
7	Range to Attitude Frame Origin	The Range to Attitude Frame Origin is the distance between the satellite and the target. Therefore the accuracy for the range is the same as the accuracy of the Target position.
8	Travel Time to Attitude Frame Origin	The Travel Time to Attitude Frame Origin is the range divided by the speed of light. Therefore the accuracy for the travel time is the same as the accuracy of the Range divided by the speed of light.

Table 11 - xp_target_extra_vector: list of outputs

2.2.17 xp_target_extra_main

This function extracts target computation results / computes auxiliary target data.
The list of outputs is given in Table 12. If applicable, the accuracy estimation is given for each output.

Id	Output Description	Accuracy Estimation
1	Target geocentric / geodetic co-ordinates	The accuracy of this computation is equivalent to the one of function xl_cart_to_geod (Cartesian to Geodetic Co-ordinates, see [RD05], section 2.2.
2	Satellite to Target Azimuth / Elevation in topocentric frame	The accuracy of this computation is the angle between the vectors satellite->true target and satellite->calculated target. It depends on: - the accuracy of the target computation (therefore on the specific target function used to compute the target); - the distance satellite target. For example, for xp_target_inter (section 2.2.1) the target accuracy computation is < 5m, the distance is < 832km, the angle is: ~ (180 * 5) / (pi * 832000) = ~ 0.00034 deg
3	Satellite to Target Azimuth / Elevation in attitude frame	The accuracy of this computation is the angle between the vectors satellite->true target and satellite->calculated target. It depends on: - the accuracy of the target computation (therefore on the specific target function used to compute the target); - the accuracy of the attitude computation; - the distance satellite target. For example, for xp_target_inter (section 2.2.1) the target accuracy computation is < 5m, the distance is < 832km, the angle is: ~ (180 * 5) / (pi * 832000) = ~ 0.00034 deg This value has to be increased adding the attitude computation accuracy, see section 2.1.1.
4	Target to satellite azimuth / elevation in topocentric frame	Same as item 2, Satellite to Target Azimuth / Elevation in topocentric frame.
5	only for xp_target_sc: target to source satellite aziumth / elevation in attitude frame	TBW
6	Target geocentric / geodetic co-ordinates rate	TBW
7	Satellite to Target Azimuth / Elevation rate in topocentric frame	TBW
8	Satellite to Target Azimuth / Elevation rate in attitude frame	TBW
9	Target to satellite azimuth / elevation in topocentric frame	TBW
10	only for xp_target_sc: target to source satellite aziumth / elevation rate in attitude frame	TBW
11	Target geocentric / geodetic co-ordinates rate-rate	TBW
12	Satellite to Target Azimuth / Elevation rate-rate in topocentric frame	TBW
13	Satellite to Target Azimuth / Elevation rate-rate in attitude frame	TBW
14	Target to satellite azimuth / elevation rate-rate in topocentric frame	TBW
15	only for xp_target_sc: target to source satellite aziumth / elevation rate-rate rate in attitude frame	TBW

Table 12 - xp_target_extra_main: list of outputs

2.2.18 xp_target_extra_aux

This function extracts target computation results / computes auxiliary target data.
The list of outputs is given in Table 13. If applicable, the accuracy estimation is given for each output.

Id	Output Description	Accuracy Estimation
1	Radius of curvature in the look direction at the nadir of the target (Earth fixed CS)	TBW
2	Distance from the nadir of the target to the satellite nadir. (Earth fixed CS)	TBW
3	Minimum distance from the nadir of the target to the ground track (Earth Fixed CS).	TBW
4	Distance from the SSP to the point located on the ground track that is at a minimum distance from the nadir of the target (Earth fixed CS)	TBW
5	Mean Local Solar Time at target.	TBW
6	True Local Solar Time at target.	TBW
7	Right ascension at which the look direction from the satellite to the target points at target point. (True of Date CS)	TBW
8	Declination at which the look direction from the satellite to the target points at target point. (True of Date CS)	TBW
9	Radius of curvature-rate in the look direction at the nadir of the target (Earth fixed CS)	TBW
10	Distance-rate from the nadir of the target to the satellite nadir. (Earth fixed CS)	TBW
11	Distance-rate from the nadir of the target to the ground track (Earth fixed CS)	TBW
12	Distance-rate from the SSP to the point located on the ground track that is at a minimum distance from the nadir of the target (Earth fixed CS)	TBW
13	Northward component of the velocity relative to the Earth of the nadir of the target (Topocentric CS)	TBW
14	Eastward component of the velocity relative to the Earth of the nadir of the target (Topocentric CS)	TBW
15	Azimuth of the velocity relative to the Earth of the nadir of the target. (Topocentric CS)	TBW
16	Magnitude of the velocity relative to the Earth of the nadir of the target. (Topocentric CS)	TBW
17	Radius of curvature-rate-rate in the look direction at the nadir of the target (Earth fixed CS)	TBW
18	Distance-rate-rate from the nadir of the tar get to the satellite nadir.	TBW
19	Distance-rate-rate from the nadir of the tar get to the ground track (Earth fixed CS)	TBW
20	Distance-rate-rate from the SSP to the point located on the ground track that is at a minimum distance from the nadir of the target (Earth fixed CS)	TBW

Table 13 - xp_target_extra_aux: list of outputs

2.2.19 *xp_target_extra_ef_target*

This function extracts target computation results / computes auxiliary target data.
The list of outputs is given in Table 14. If applicable, the accuracy estimation is given for each output.

Id	Output Description	Accuracy Estimation
1	2-way Doppler shift of the signal (Earth Fixed CS)	The formula used to compute the doppler shift is: -2 * freq * range_rate / c Therefore the accuracy of Doppler shift computation depends on the input frequency, the speed of light and the range rate computation accuracy (see item 2).
2	Earth fixed target to satellite range-rate. (Earth Fixed CS)	The range rate is the projection of the satellite velocity along the LOS direction. Therefore, assuming a=angle between LOS and satellite velocity: Range_rate = sat_vel * cos(a) The accuracy of the range rate computation is the difference between the range_rate computed with the true target and the computed target. Being d the angle seen from the satellite between computed and true target (calculated as max. ~ 0.00034 deg for x_target_inter, see section 2.2.17): Accuracy = sat_vel * (cos(a) – cos(a-d)) Assuming sat_vel ~ 7 km/s, This function has a maximum < 0.05 m/s. Therefore the accuracy of the range_rate computation is < 0.05 m/s
3	Earth fixed target to satellite azimuth-rate. (Topocentric CS)	TBW
4	Earth fixed target to satellite elevation-rate. (Topocentric CS)	TBW
5	Satellite to earth fixed target azimuth-rate. (Topocentric CS)	TBW
6	Satellite to earth fixed target elevation-rate. (Topocentric CS)	TBW
7	Satellite to earth fixed target azimuth-rate. (Attitude Frame)	TBW
8	Satellite to earth fixed target elevation-rate. (Attitude Frame)	TBW
9	Earth fixed target to satellite range-rate-rate. (Earth Fixed CS)	TBW
10	Earth fixed target to satellite azimuth-rate-rate. (Topocentric CS)	TBW
11	Earth fixed target to satellite elevation-rate-rate. (Topocentric CS)	TBW
12	Satellite to earth fixed target azimuth-rate-rate. (Topocentric CS)	TBW
13	Satellite to earth fixed target elevation-rate-rate. (Topocentric CS)	TBW
14	Satellite to earth fixed target azimuth-rate-rate. (Attitude Frame)	TBW
15	Satellite to earth fixed target elevation-rate-rate. (Attitude Frame)	TBW

Table 14 - xp_target_extra_ef_target: list of outputs

2.2.20 xp_target_extra_target_to_sun

This function extracts target computation results / computes auxiliary target data.
The list of outputs is given in Table 15. If applicable, the accuracy estimation is given for each output.

Id	Output Description	Accuracy Estimation
1	Target to Sun (centre) azimuth (Topocentric CS)	TBW
2	Target to Sun (centre) elevation (Topocentric CS)	TBW
3	Tangent altitude over the Earth in the target to Sun (centre) look direction (Earth fixed CS)	TBW
4	Target to Sun visibility flag	TBW
5	Target to Sun (centre) azimuth-rate (Topocentric CS)	TBW
6	Target to Sun (centre) elevation-rate. (Topocentric CS)	TBW
7	Target to Sun (centre) azimuth-rate-rate. (Topocentric CS)	TBW
8	Target to Sun (centre) elevation- rate-rate. (Topocentric CS)	TBW

Table 15 - xp_target_extra_target_to_sun: list of outputs

2.2.21 xp_target_extra_target_to_moon

This function extracts target computation results / computes auxiliary target data.
The list of outputs is given in Table 16. If applicable, the accuracy estimation is given for each output.

Id	Output Description	Accuracy Estimation
1	Target to Moon (centre) azimuth (Topocentric CS)	TBW
2	Target to Moon (centre) elevation (Topocentric CS)	TBW
3	Tangent altitude over the Earth in the target to Moon (centre) look direction (Earth fixed CS)	TBW
4	Target to Moon visibility flag	TBW
5	Target to Moon (centre) azimuth-rate (Topocentric CS)	TBW
6	Target to Moon (centre) elevation-rate. (Topocentric CS)	TBW
7	Target to Moon (centre) azimuth-rate-rate. (Topocentric CS)	TBW
8	Target to Moon (centre) elevation- rate-rate. (Topocentric CS)	TBW

Table 16 - xp_target_extra_target_to_moon: list of outputs

2.2.22 xp_target_extra_specular_reflection

This function extracts target computation results / computes auxiliary target data.
The list of outputs is given in Table 17. If applicable, the accuracy estimation is given for each output.

Id	Output Description	Accuracy Estimation
1	coordinates of reflected pointing direction. (EF CS)	TBW
2	Azimuth of the reflected pointing direction. (Topocentric CS)	TBW
3	Elevation of the reflected pointing direction. (Topocentric CS)	TBW
4	Right ascension at which the reflected pointing direction points at target point. (True of Date CS)	TBW
5	Declination at which the reflected pointing direction points at target point. (True of Date CS)	TBW
6	velocity of reflected pointing direction. (EF CS)	TBW
7	Azimuth rate of the reflected pointing direction (Topocentric CS)	TBW
8	Elevation rate of the reflected pointing direction (Topocentric CS)	TBW
9	Right ascension rate at which the reflected pointing direction points at target point. (True of Date CS)	TBW
10	Declination rate at which the reflected pointing direction points at target point. (True of Date CS)	TBW
11	acceleration of reflected pointing direction. (EF CS)	TBW
12	Azimuth rate rate of the reflected pointing direction (Topocentric CS)	TBW
13	Elevation rate rate of the reflected pointing direction (Topocentric CS)	TBW
14	Right ascension rate rate at which the reflected pointing direction points at target point. (True of Date CS)	TBW
15	Declination rate rate at which the reflected pointing direction points at target point. (True of Date CS)	TBW

Table 17 - xp_target_extra_specular_reflection: list of outputs

ANNEX A: LIST OF POINTING FUNCTIONS

POINTING library Function(s)	Description	Outputs	Algorithm Type	Accuracy Determination	Document Reference
xp_sat_nominal_att_init xp_sat_nominal_att_init_model xp_sat_nominal_att_init_harmonic xp_sat_nominal_att_init_file xp_sat_nominal_att_close xp_sat_nominal_att_init_status xp_sat_nominal_att_get_sat_id xp_sat_nominal_att_get_mode xp_sat_nominal_att_get_aocs xp_sat_nominal_att_set_aocs xp_sat_nominal_att_get_param xp_sat_nominal_att_set_param xp_sat_nominal_att_get_harmonic xp_sat_nominal_att_set_harmonic xp_sat_nominal_att_get_file xp_sat_nominal_att_set_file	functions for nominal attitude id initialisation and manipulation	Nominal attitude id and/or its internal data	N/A	N/A	N/A
xp_sat_att_angle_init xp_sat_att_matrix_init xp_sat_att_init_harmonic xp_sat_att_init_file xp_sat_att_quat_plus_matrix_init xp_sat_att_quat_plus_angle_init xp_sat_att_close xp_sat_att_init_status xp_sat_att_get_sat_id xp_sat_att_get_mode xp_sat_att_get_angles xp_sat_att_set_angles xp_sat_att_get_matrix xp_sat_att_set_matrix xp_sat_att_get_harmonic xp_sat_att_set_harmonic xp_sat_att_get_file xp_sat_att_set_file xp_sat_att_get_quat_plus_matrix xp_sat_att_set_quat_plus_matrix xp_sat_att_get_quat_plus_angle xp_sat_att_set_quat_plus_angle	functions for satellite attitude id initialisation and manipulation	Satellite attitude id and/or its internal data	N/A	N/A	N/A
xp_instr_att_angle_init xp_instr_att_matrix_init xp_instr_att_init_harmonic xp_instr_att_init_file xp_instr_att_close xp_instr_att_init_status xp_instr_att_get_sat_id xp_instr_att_get_mode xp_instr_att_get_angles xp_instr_att_set_angles xp_instr_att_get_matrix xp_instr_att_set_matrix	functions for instrument attitude id initialisation and manipulation	Intrument attitude id and/or its internal data	N/A	N/A	N/A

POINTING library Function(s)	Description	Outputs	Algorithm Type	Accuracy Determination	Document Reference
xp_instr_att_get_harmonic xp_instr_att_set_harmonic xp_instr_att_get_file xp_instr_att_set_file xp_instr_att_get_offset xp_instr_att_set_offset					
xp_attitude_init xp_attitude_user_set xp_attitude_close xp_attitude_init_status xp_attitude_get_sat_id xp_attitude_get_mode xp_attitude_get_id_data xp_attitude_set_id_data	functions for instrument attitude id initialisation and manipulation	attitude id and/or its internal data	N/A	N/A	N/A
xp_target_close xp_target_status xp_target_get_sat_id xp_target_get_mode xp_target_get_id_data	functions for target id initialisation and manipulation	Target id and its internal data	N/A	N/A	N/A
xp_atmos_init xp_atmos_close xp_atmos_init_status xp_atmos_get_sat_id xp_atmos_get_mode xp_atmos_get_id_data	functions for atmosphere id initialisation and manipulation	Atmosphere id and its internal data	N/A	N/A	N/A
xp_dem_init xp_dem_compute xp_dem_close xp_dem_init_status xp_dem_get_sat_id xp_dem_get_mode xp_dem_get_id_data xp_dem_get_info xp_dem_id_configure xp_gen_dem_max_altitude_file xp_gen_dem_altitudes_from_ellipsoid	functions for DEM id initialisation and manipulation	DEM id and its internal data	N/A	N/A	N/A
xp_set_az_el_definition	Configuration function	N/A	N/A	N/A	N/A
xp_target_drs	Obsolete	N/A	N/A	N/A	N/A
xp_attitude_user_set xp_attitude_close xp_attitude_init_status xp_attitude_get_sat_id xp_attitude_get_mode xp_attitude_get_id_data xp_attitude_set_id_data xp_attitude_define	Attitude Id initialisation / mnaipulation / accessors	N/A	N/A	N/A	N/A
xp_change_frame	Converts a vector to a different reference / attitude frame	Converted vector	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.1.2
xp_ attitude_compute	Attitude computation	Rotation matrix from reference frame to	CFI specific	Required	PE-TN-ESA-GS-

POINTING library Function(s)	Description	Outputs	Algorithm Type	Accuracy Determination	Document Reference
		attitude frame			470 Section 2.1.1
xp_target_inter	It calculates the intersection point(s) of the line of sight defined by an elevation and an azimuth angle (or a set of them) expressed in the input Attitude frame, with a surface(s) located at a certain geodetic altitude(s) over the Earth.	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.1
xp_multi_target_inter	Same as xp_target_inter but the user can supply as input several altitudes, the function computes the interesction of the LOS with those altitudes	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Not Required (equivalent to xp_target_inter)	N/A
xp_target_travel_time	It calculates the point of the line or sight from the satellite (defined by an elevation and an azimuth angle expressed in the selected Attitude Frame) at a given travel time(s) along the (curved) line of sight.	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.4
xp_multi_target_travel_time	Same as xp_target_travel_time but the user can supply as input several altitudes, the function computes the interesction of the LOS at those travel times	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Not Required (equivalent to xp_target_travel_time)	N/A
xp_target_ground_range	It calculates the location of a point that is placed on a surface at a certain geodetic altitude over the Earth, that lays on the plane defined by theS/C position, the nadir and a reference point, and that is at a certain distance or ground range measured along that surface from that reference point. This reference point is calculated being the intersection of the previous surface with the line of sight defined by an elevation and azimuth angle in the input Attitude coordinate system.	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.5
xp_target_incidence_angle	It calculates the location of a point that is placed on a surface at a certain geodetic altitude over the Earth and that is seen from the S/C on a line of sight that forms a certain azimuth angle in the	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.6

POINTING library Function(s)	Description	Outputs	Algorithm Type	Accuracy Determination	Document Reference
	input Attitude frame and that intersects that surface with a certain incidence angle.				
xp_target_range	It calculates the location of a point that is placed on a surface at a certain geodetic altitude over the Earth, that is seen from the S/C on a line of sight that forms a certain azimuth angle in the input Attitude frame, and that is at a certain range or slant-range from the S/C.	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.2
xp_target_range_rate	It calculates the location of a point that is placed on a surface at a certain geodetic altitude over the Earth, that is at a certain range from S/C, and whose associated Earth-fixed target has a certain range-rate value.	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.7
xp_target_tangent	It calculates the location of the tangent point over the Earth that is located on the line of sight defined by an elevation and azimuth angles expressed in the input Attitude frame.	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.8
xp_target_altitude	It calculates the location of the tangent point over the Earth that is located on a surface at a certain geodetic altitude over the Earth and that is on a line of sight that forms a certain azimuth angle in the input Attitude frame.	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.9
xp_target_star	It calculates the location of the tangent point over the Earth that is located on the line of sight that points to a star defined by its right ascension and declination coordinates.	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.10
xp_target_tangent_sun	It calculates the location of the tangent point over the Earth that is located on the line of sight that points to the Sun	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.11
xp_target_tangent_moon	It calculates the location of the tangent point over the Earth that is located on the line of sight that points to the Moon	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.12

POINTING library Function(s)	Description	Outputs	Algorithm Type	Accuracy Determination	Document Reference
xp_target_station	It calculates the most relevant observation parameters of the link between the satellite and a ground station	LOS defined in terms of azimuth / elevation / range	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.13
xp_target_generic	It calculates the LOS from satellite to a given target whose position / velocity / acceleration is given as input.	LOS defined in terms of azimuth / elevation / range	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.3
xp_target_reflected	compute, from S/C position and attitude, and emitting source position, the point of reflection from the source towards the SC at a certain geodetic altitude.	pos, vel, acc of target point (as computed by xp_target_extra_vector)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.14
xp_target_sc	It calculates the most relevant observation parameters of the link between one satellite and another Satellite.	LOS defined in terms of azimuth / elevation / range	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.15
xp_target_inter_run xp_target_travel_time_run xp_target_ground_range_run xp_target_incidence_angle_run xp_target_range_run xp_target_range_rate_run xp_target_tangent_run xp_target_altitude_run xp_target_star_run xp_target_tangent_sun xp_target_tangent_sun_run xp_target_tangent_moon_run xp_target_station_run xp_target_drs_run xp_target_generic_run xp_target_reflected_run xp_multi_target_inter_run xp_multi_target_travel_time_run xp_change_frame_run xp_attitude_compute_run xp_attitude_user_set_run xp_run_init	Run functions (equivalent to the corresponding "non-run" functions)	See the corresponding "non-run" functions	CFI specific	Not Required (already determined in "non-run" functions)	N/A
xp_target_list_extra_vector xp_target_list_extra_main xp_target_list_extra_aux xp_target_list_extra_ef_target xp_target_list_extra_specular_reflection xp_target_list_extra_target_to_moon xp_target_list_extra_target_to_sun	Multi-threading versions of target functions	See the corresponding "single-thread" functions	CFI specific	Not Required (already determined in "single-thread" functions)	N/A

POINTING library Function(s)	Description	Outputs	Algorithm Type	Accuracy Determination	Document Reference
xp_target_extra_vector	extracts target computation results / computes auxiliary target data	Various (see Document Reference)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.16 (only a subset of outputs)
xp_target_extra_main	extracts target computation results / computes auxiliary target data	Various (see Document Reference)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.17 (only a subset of outputs)
xp_target_extra_aux	extracts target computation results / computes auxiliary target data	Various (see Document Reference)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.18
xp_target_extra_ef_target	extracts target computation results / computes auxiliary target data	Various (see Document Reference)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.19 (only a subset of outputs)
xp_target_extra_target_to_sun	extracts target computation results / computes auxiliary target data	Various (see Document Reference)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.20
xp_target_extra_target_to_moon	extracts target computation results / computes auxiliary target data	Various (see Document Reference)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.21
xp_target_extra_specular_reflection	extracts target computation results / computes auxiliary target data	Various (see Document Reference)	CFI specific	Required	PE-TN-ESA-GS-470 Section 2.2.22

Table 18 – List of functions in the POINTING library