BepiColombo MCAM Channels Spice Kernels Optimization

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Approvation

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Document Change Record

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1 Introduction

1.1 Scope

The aim of this document is to define the correction to be implemented on the Spice Kernels (SK) of the BepiColombo Monitoring-CAMera (MCAM) to improve the geometric definition of the pinhole models (intrinsic parameters of the cameras) and their pointing (extrinsic parameters) with respect to the BepiColombo Space Craft reference frame.

1.2 References

[RD. 1] bc_mtm_mcam_v03.ti - MTM_CAM Instrument Kernel (Delivery: April 6, 2020)

1.3 Acronyms

FoV	Field of View
FK	Frame Kernel
IK	Instrument Kernel
MCAM	Monitoring CAMera
SK	Spice Kernels
TC	Telecommand

1.4 Document organization

This document is organized as follows:

- Section 2 will describe the considered assumptions for the reported analysis in terms of image benches exploited for the analysis, the current geometrical model for the cameras and the pin-hole model definition.
- Section 3 will describe firstly the misalignment between current camera models definition and the data reduction; later the result which can be obtained thanks to Instrument Kernel (IK), and Frame Kernels (FK) optimization.
- Section 4 will describe briefly the heuristics adopted for the detection and image reduction.

2 Assumptions

The reported data analysis considers the images data benches of the three MCAMs on board the BepiColombo mission covering the time window between the launch and first Mercury flyby (1 October 2021) and in particular the ones in which the Earth, Venus and Mercury planets felt into the MCAM Field of View (FoV). In this manner it is possible to compare the position of different features (the center of the targets defined by image detection or well known craters coordinates on the Mercury surface) and the one supplied by current or optimized Spice Kernels.

2.1 Image dataset

The considered image datasets correspond to the different events reported in Table 1. For each event the Table indicates the Naif IDs of the MCAM unit and the references to the suitable image to be analyzed.

Phase	Time Window	Suitable Images		
		MTM_MCAM1	MTM_MCAM2	MTM_MCAM3
Instrument Naif ID		-652950	-652960	-652970
Near_earth_commissioning	2018-10/12			
Earth_flyby	2020-04	45 (11-04-2020)		26 (09-04-2020)
Venus_flyby_1	2020-10			Only image of 14-10-2021
Venus_flyby_2	2021-08			89
Mercury_flyby_1	2021-10-01		12	16

Table 1 BepiColombo events in which the MCAM instruments were planned to command the acquisition of a known target.

2.2 Pinhole model

2.2.1 Intrinsic Parameters

As reported in current Spice Kernels it is assumed that all MCAM cameras can be geometrically modelled as a pinhole defined historically by following intrinsic parameters

$$K_i = \begin{bmatrix} f_x & \omega & x_0 \\ 0 & f_y & y_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1$$

Where $x_0$and y_0 are the coordinates of the principal point, $f_x$and f_y are the horizontal and vertical focal lengths (in pixels) and ω is the skew factor.
Under the hypothesis:

- all the camera systems are not affected by astigmatism or other anamorphism,
- they have not an off-axis configuration (as reported in documentation),
- the boresight definition is at the center of the CCD

Equation 1 can be simplified in Equation 2:

$$K_i = \begin{bmatrix} f & 0 & W/2 \\ 0 & f & H/2 \\ 0 & 0 & 1 \end{bmatrix} \quad (2$$

Where H, W represent the height and width of the CCD while f is the focal length of the camera in pixels (unique intrinsic free parameter).
Current IK (see [RD. 1]) defines main intrinsic parameters for the three cameras:

Name Parameter	Value	Unit
Focal Length	12.385	[mm]
Pitch (pixel dimention)	14e-3	[mm]
H,W	1024	[px]

Table 2 Intrinsic parameters reported in current version of the IK Spice Kernels (for details see [RD. 1]).

2.2.2 Extrinsic Parameters

The definition of the MCAM orientation is reported in Table 3.
The column, $R_{sc\rightarrow MCAM-i}$, supplies the rotational matrix between the MPO_SPACECRAFT frame and the i-camera one.
This rotation matrix can be evaluated by NAIF code:

```
R_SC_MCAM=cspice_pxform('MPO_SC',cam_frame, et ))
```

This means that last versor of the rotational matrix defines the boresight camera in S/C frame as reported in [RD. 1].

	FoV (diag) [°]	FoV (side) [°]	V/H FOV Start/STOP [°]	IFOV [mrad/px]	$R_{sc\rightarrow MCAM-i}$
MCAM1	70	49.5	± 24.75	1.2	-0.087199203 -0.99619089 0 -0.17299729 0.015142906 0.98480589 **-0.98105466 0.085874288 -0.17365877**
MCAM2	70	49.5	± 24.75	1.2	0.42260624 -0.90631339 0 -0.69427327 -0.32373374 0.64279164 **-0.58257067 -0.27164776 -0.76604106**
MCAM3	70	49.5	± 24.75	1.2	0.70710678 0.70710678 0 0.54168114 -0.54168114 0.64277763 **0.45451242 -0.45451242 -0.76605282**

Table 3 Angular parameters deducible by current version of the IK and FK Spice Kernels (for details see [RD. 1]).

2.2.3 Projection definition

Considering the definition assumed in Equation (2) for a target (planet center or feature) whose position is known in the reference system of the camera (with z -axis representative of the boresight) it is possible to evaluate the projection on the image plane as:

$$\bar{j} \propto K\, x_{Target} \qquad (3$$

Where:

- $\bar{j} = [j\ i\ 1]^T$ is the vector of the homogeneous coordinates of the projection on the sensor;
- "$\propto$" is the equivalence of homogeneous projection
- $x_{Target} \in R^3$ are the coordinates of the target in the camera reference system.

As an example, we report here a simple code in MATLAB® for the evaluation of the data starting from the current SK

```
%% Input parameters
observer= 'MPO';                          % satellite observer
et=cspice_str2et('2020-04-10 17:11:06');% epoch
cam_frame= 'MTM_MCAM1';                   % camera reference frame
abcorr= 'LT+S';                           % absolute correction
target_planet= 'Earth';                   % target
D=H/2;                                    % boresight coordinates (H=W=D)
f_mm=12.385;                              % focal length in mm
pitch_mm=14e-3;                           % pixel dimension in mm
f=f_mm/pitch_mm;                          % focal length in pixel
K=[f 0 D ; 0 f D ; 0 0 1];                 % intrinsic matrix

%% Eval target position in camera reference frame
[ x_Target, ltime ] = cspice_spkpos(observer, et,. . .
                     cam_frame, abcorr, target_planet);

%% Project in image reference system
J=K*x_Target; J=J/J(3);
```

Residual of targets projections

2.3 Current SK analysis

All the images (see Table 1) that allow a complete target definition were analyzed with two heuristics:

- in the case of MCAM1 and MCAM3 it was possible to define on one side the pixel center of the target (see Section 3.1) on the other the projection foreseen by SK (at their current version [RD. 1]).
- In the case of MCAM2 and MCAM3 the images of the Mercury flyby were used defining (for the most visible craters) the rim center associated to the latitude and longitude coordinates and comparing this data with the projection foreseen by SK (at their current version [RD. 1]).

The resulting data bench includes 25 images for MCAM1 (based on the planet positions), 12 images for MCAM2 (based on the Mercury crater positions) and 139 for MCAM3 (including both the strategies).

The comparison between the expected and measured data are shown in Figure 1 where, for all the three cameras, we show the position of each target acquisition considered.

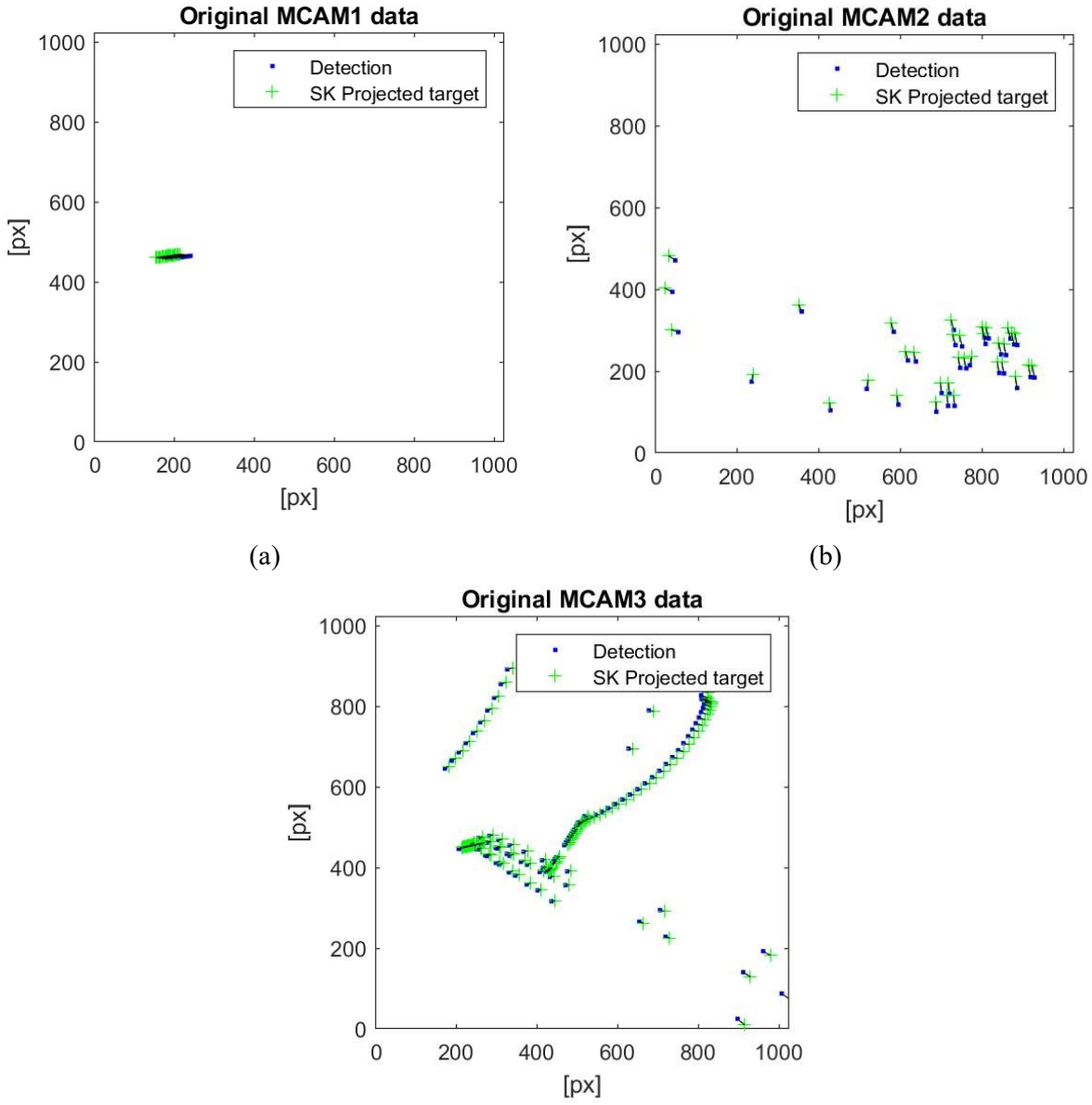


Figure 1 The figure shows the comparison for MCAM1 (a), MCAM2(b) and MCAM3 (c) between the expected (green) and measured (blu) positions of the features

A better visualization of the effect of the misalignment between SK and measured projection can be found in Figure 2 and Figure 3 where all the results are summarized.
In the first two cases the misalignment is, on average, greater than 20 pixels and is limited to 10 pixel for the MCAM3.

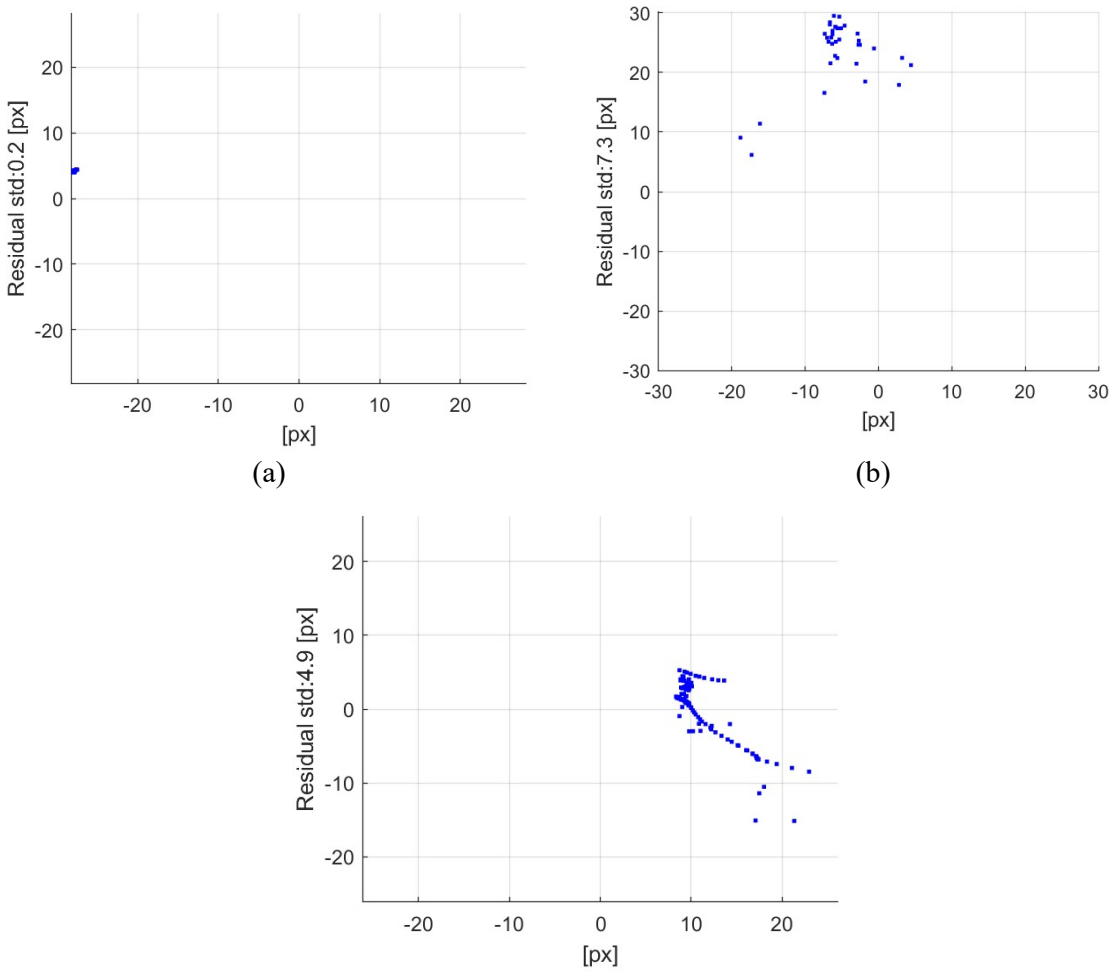


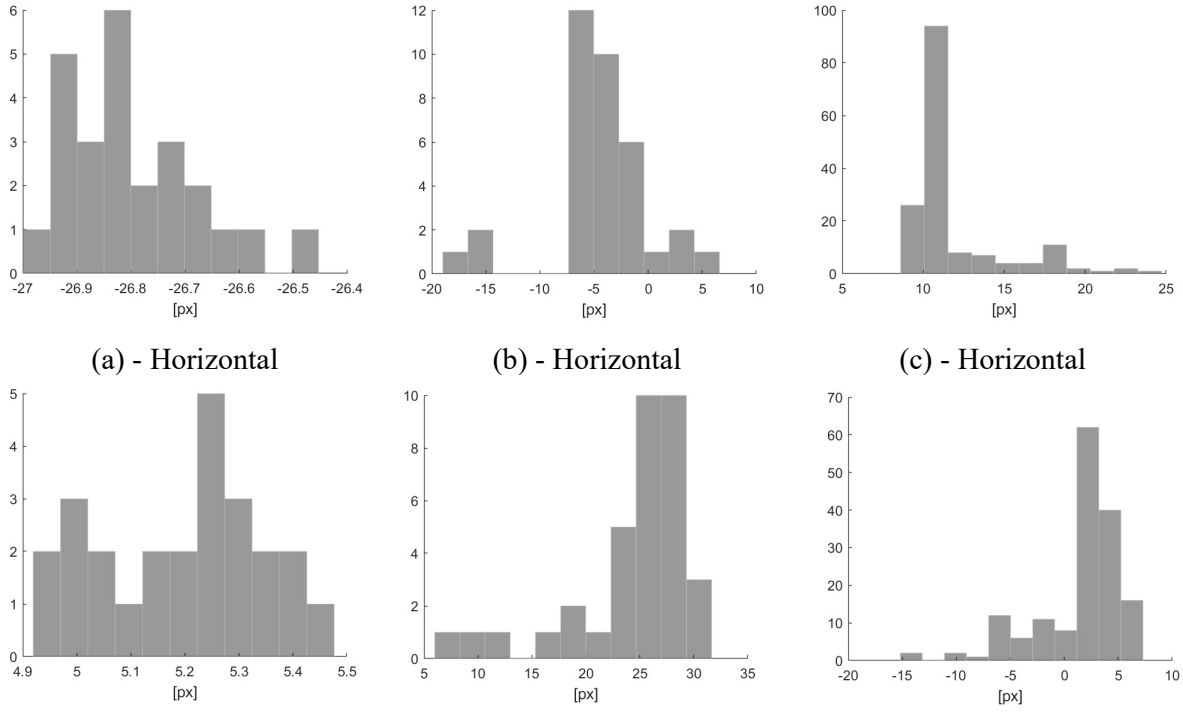
Figure 2 The image shows the Residuals for MCAM1 (a), MCAM2(b) and MCAM3(c) between the expected (green) and measured (blu) positions of the features reported in previous figure.

The obtained residuals, both for horizontal and vertical coordinates, are reported in Table 4.

		Current SK Residual Mean [px]	Residual StD [px]
MCAM1	Horizontal	-26.8	0.126
	Vertical	5.19	0.152
MCAM2	Horizontal	-4.52	4.75
	Vertical	24.5	5.53
MCAM3	Horizonal	11.9	3
	Vertical	1.47	3.93

Table 4 Resulting residual with current SK for the different cameras in mean and std

The same data are shown as histograms in Figure 3.



(a) - Horizontal (b) - Horizontal (c) - Horizontal

(a) – Vertical (b) - Vertical (b) - Vertical

Figure 3 The image shows the Residuals statistics (horizontal and vertical) for MCAM1 (a), MCAM2(b) and MCAM3 (c). Residuals are evaluated as the difference between the expected (green) and measured (blu) positions of the features reported in Figure 1.

2.4 Optimization

2.4.1 Correction model

SK can be corrected by the optimization of the residual as non-linear least squares problem (in MATLAB®: LSQNONLIN) based on Levenberg-Marquardt algorithm.
We assume to optimize the focal length correction and reference frame (and boresight direction) correction.
Equation 3 can be corrected in

$$\bar{J} \propto K_{(f)} R_{(\omega_i, \phi_i, \kappa_i)}\, x \qquad (3$$

Where f is the MCAM focal length (**we assume focal lengths are equal in the three cases**), $\omega_i, \phi_i, \kappa_i$ are the Rotation matrix angles between the current frame and the optimized one (R=Rodrigues ($[\omega_i, \phi_i, \kappa_i]$)).
Considering the assumption defined by Equation 2 and 3, we expect, after optimization, to reduce the residuals. Remining sources of error should be limited to:

- Pinhole model definition not considering possible optical distortion
- The optimization assumes the cameras are similar (in terms of intrinsic parameters)
- The errors depending by the detection are not optimized

2.4.2 Parameters Results

The obtained optimized parameters are reported in Table 5 where are defined the focal lengths, Euler angles or rotational matrices defined in Equation 3 .

	Focal Length [mm]	Angles vector $\omega_i, \phi_i, \kappa_i$ [deg]	R_i
MCAM1	12.326	0.52428 1.4814 -0.39938	0.999641 0.00708781 0.0258208 -0.00685123 0.999934 -0.00923927 -0.0258846 0.00905906 0.999624
MCAM2	12.326	1.286 0.57586 -1.2073	0.999728 0.02118 0.00981253 -0.0209544 0.999526 -0.0225471 -0.0102854 0.0223353 0.999698
MCAM3	12.326	0.042131 -0.72228 0.87123	0.999805 -0.0152095 -0.0125998 0.0152003 0.999884 -0.000831125 0.012611 0.000639442 0.99992

Table 5 Parameters following single camera optimization

The traces of the Rotation matrices indicates that in the three cases the optimization is reached adding a rotation respectively of 1.6214°, 1.8555° and 1.1325° while focal lengths needs a correction of 0.5%.

Frame Kernel data (reported at current version of SK in Table 3) should be updated by the ones reported in Table 6. The $R_{sc \to MCAM-i}$ column is the rotational matrix between the MPO_SCACECRAFT frame and each MCAM unit one (result of NAIF code pxform described in Section 2.2.2). This means that last versor of the rotational matrix defines the boresight camera in S/C frame. It can be evaluated as the product $R_i * R_{sc \to MCAM-i}$.

	Focal Length [mm]	Field of view (side) [°]	V/H FOV Start/STOP [°]	IFOV [mrad/px]	$R_{sc \to MCAM-i}$
MCAM1	12.325	60.36	± 30.18	1.0288	-0.11372575 -0.99350904 0.0024961 -0.16332419 0.02117362 0.98634522 **-0.97999575 0.11176518 -0.16467204**
MCAM2	12.325	60.36	± 30.18	1.0288	0.40206989 -0.91558868 0.006097533 -0.68966452 -0.29846419 0.65975903 **-0.602248 -0.26947449 -0.75145249**
MCAM3	12.325	60.36	± 30.18	1.0288	0.69300337 0.72093433 -0.00012424122 0.55198883 -0.53049241 0.64333983 **0.46373986 -0.44590525 -0.76558073**

Table 6 Angular parameters reported in current version of the IK and FK Spice Kernels (for details see [RD. 1]).

2.4.3 Resulting optimized errors

Figure 4 shows the comparison between the detected features, the original SK based projections and the optimized ones.

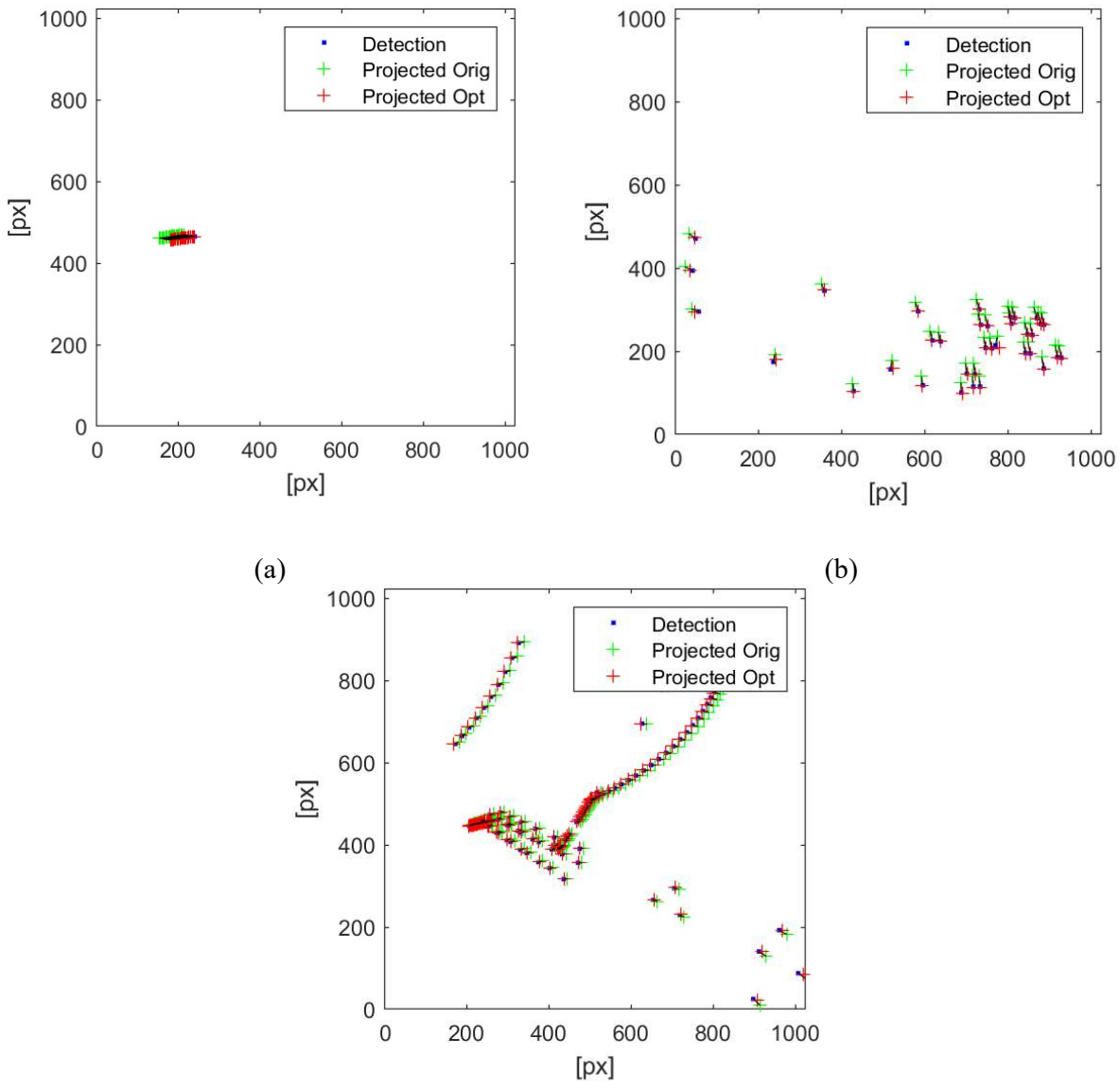


Figure 4 The image shows the comparison for MCAM1 (a),MCAM2 (b) and MCAM3(c) between detected features (blu), the current SK based projections (green) and the optimized ones expected (red)

The visualization only of the residual can be found in Figure 5.
The plots indicate, for the optimized SK, a null misalignment, on average, for each camera with a standard deviation limited to 0.3, 3 and 2 px for MCAM1,MCAM2 and MCAM3 respectively.

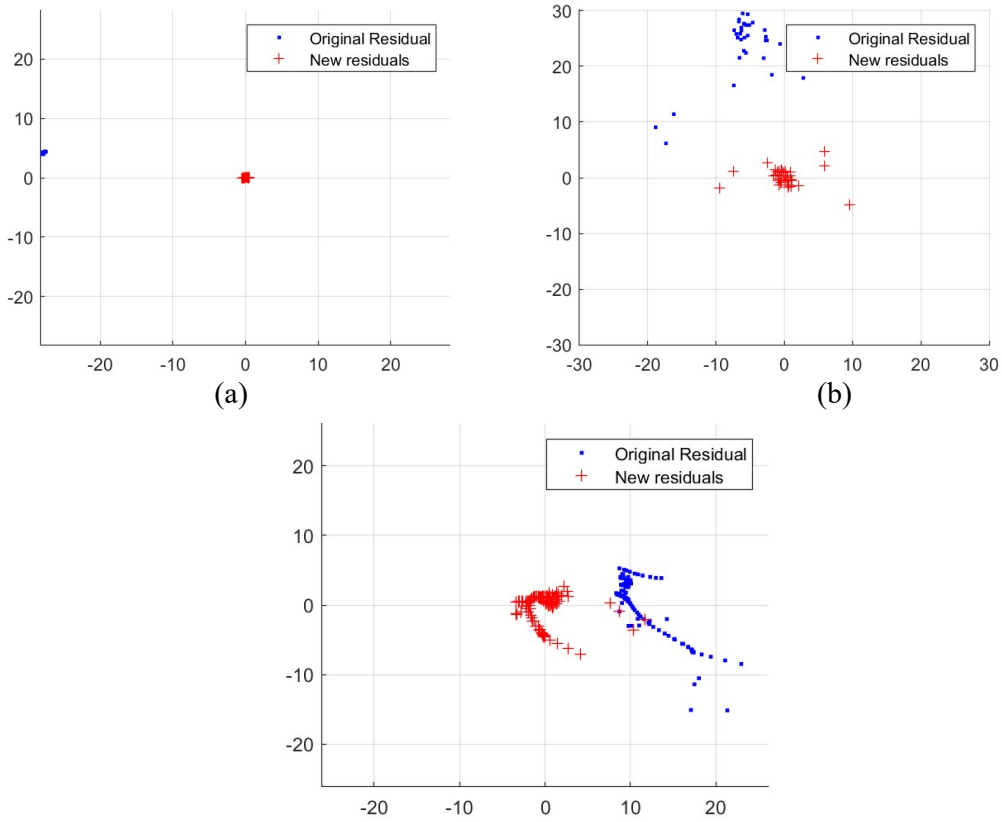


Figure 5 The image shows the Residuals for MCAM1 (a) ,MCAM2 (b) and MCAM3(c) between expected and detected data (reported in previous figure) comparing the results at current version of SK (blu) and the optimized one (red).

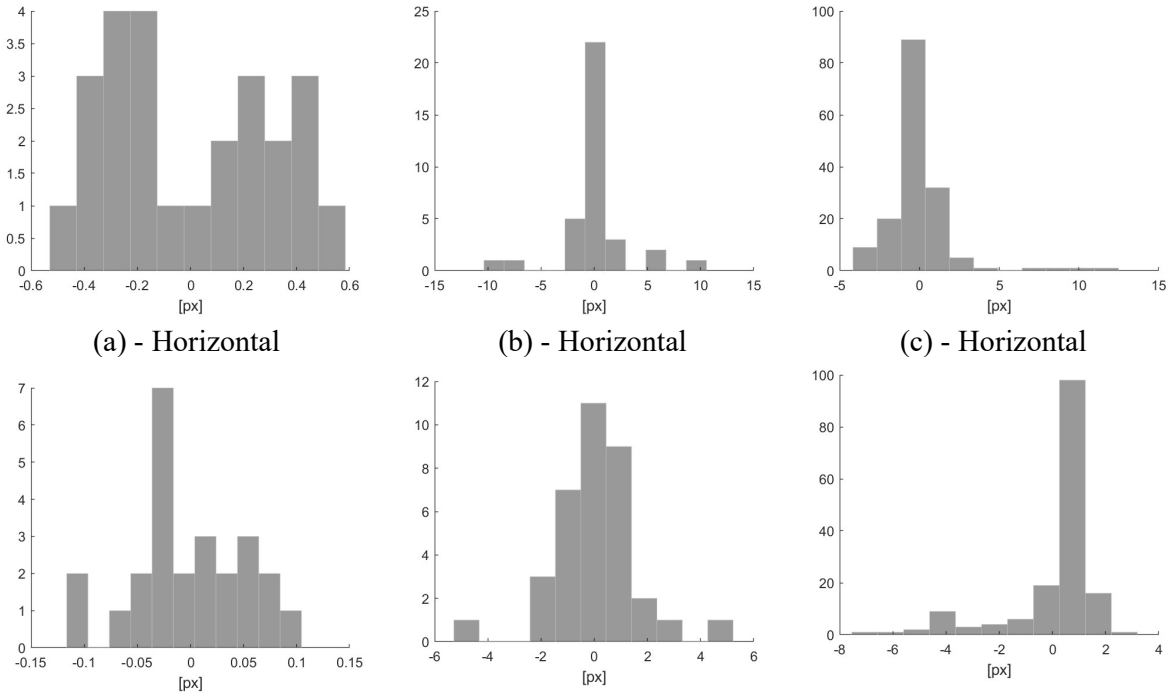
The statistical description of the residuals error (before and after optimization) is reported in Table 7 while the errors histograms for each optimized models of the cameras are show in *Figure 6*.

		Current		Optimized	
		Residual Mean [px]	Residual StD [px]	Residual Mean [px]	Residual StD [px]
MCAM1	Horizontal	-26.8	0.126	-0.00341	0.29
	Vertical	5.19	0.152	-0.000513	0.0518
MCAM2	Horizontal	-4.52	4.75	0.0569	3.18
	Vertical	24.5	5.53	0.109	1.61
MCAM3	Horizonal	11.9	3	0.00264	2
	Vertical	1.47	3.93	0.116	1.78

Table 7 Resulting residual for the different cameras in mean and std

As described 2.4.1 focal length and pointing changes as optimized in mean all the residuals avoiding the old misalignment (greater than 30 px for one of the camera) to subpixel level. To limit standard deviations it is possible (as future work):

- to increase the number of features (in particular for MCAM2 and MCAM3)
- to introduce a simple distortion model (here not considered)
- to consider a possible difference between the camera coal lengths
-



(a) - Horizontal (b) - Horizontal (c) - Horizontal

(a) – Vertical (b) - Vertical (c) - Vertical

Figure 6 The image shows the Residuals statistics (horizontal and vertical) for MCAM1 (a) and MCAM2(b). Residuals are evaluated as the difference between the expected (green) and measured (blu) positions of the target reported in Figure 4.

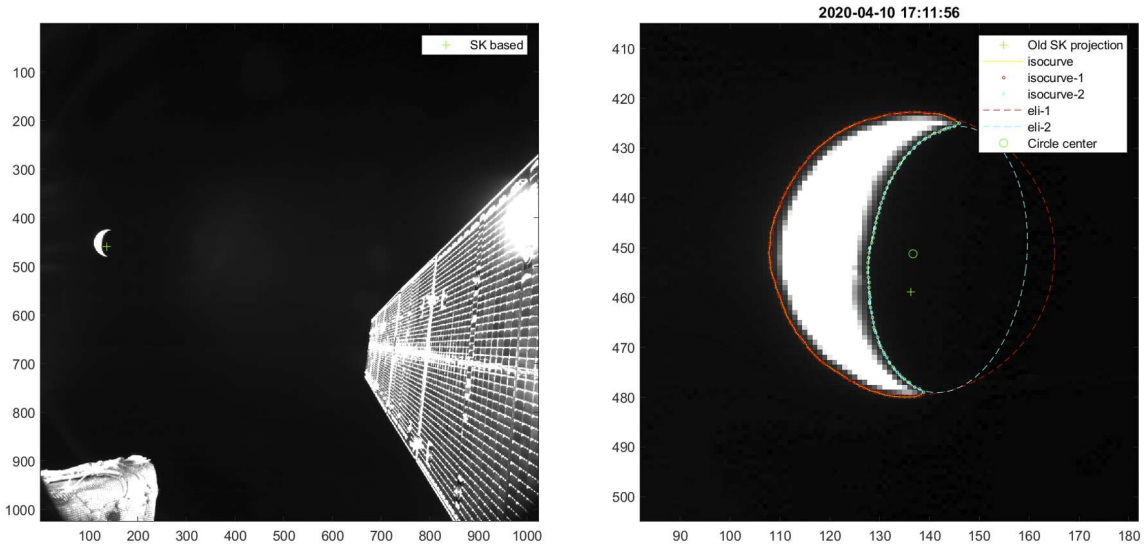
3 Annexes

3.1 Detection in case of entire planets

The detection of the target center is based on following hypothesis:

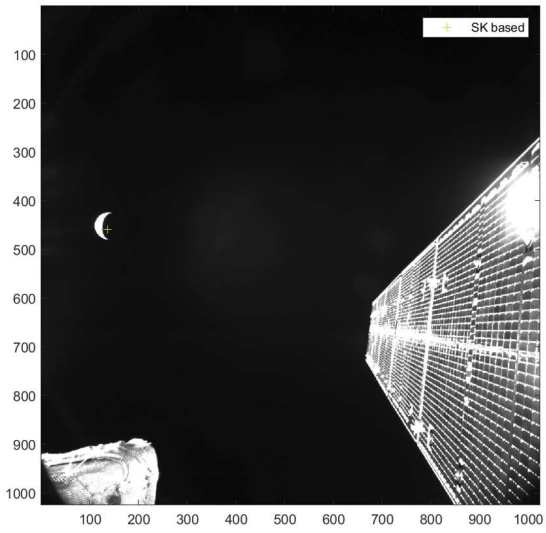
- considering a template window around the target, we assume as a background the mean value of the image on the borders of the template. On the base of the background assumption it is possible to define an isocurve at the 10% of the maximum value reach by the image in this region
- this isocurve can be divided in two main arcs defined by local curvature peak
- these two main arcs can be modelled as an ellipse (on the terminator) and a circle (the intersection between the image plane and the target sphere).

As shown in Figure 7b, an acquisition of first Earth flyby on April 2020, the isocurve (yellow) defines automatically the borders of the target. In the image the target is divided in a first sub arc (in red) defining the limits of the target and a latter sub-arc (green) defining the terminator. Both the arches can be fitted as ellipses with different eccentricity. The ellipse having the lower eccentricity can be assumed as the target and it can be modelled as a circle. Figure 7b shows even the old SK base projection (+) of the center of the planet and the new one defined by the circle detection (o).

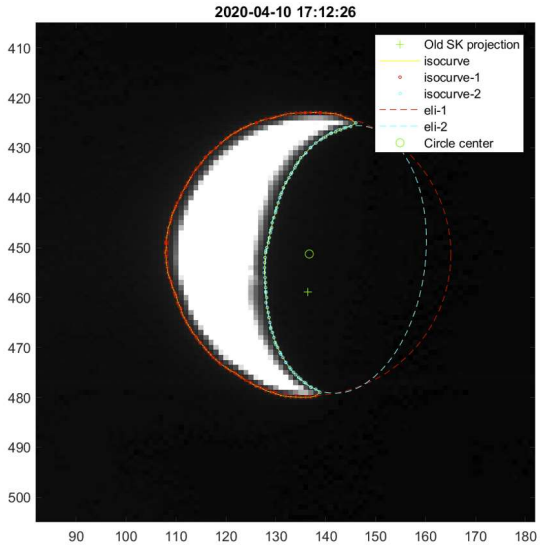


(a) *(b)*

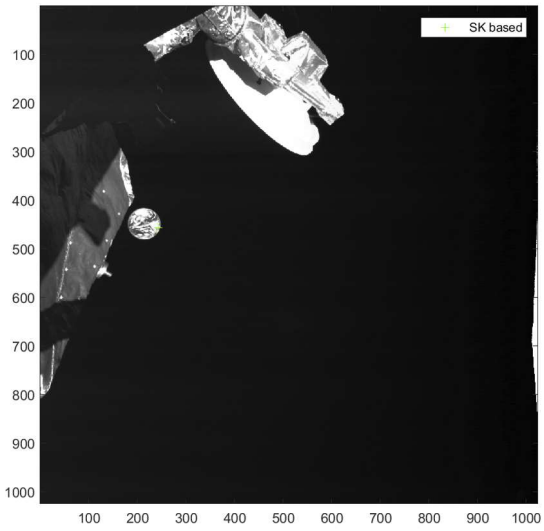
Figure 7 In (a) an MCAM1 complete image during the first earth flyby. In (b) a crop of the same image showing the current SK base projection (cross green), the isocurve definition, the two arcs divided by the isocurve, the two resulted fitted ellipses. Red one (the less eccentric) is assumed as image plane / target intersection for the definition of the actual target center projection.


SK based

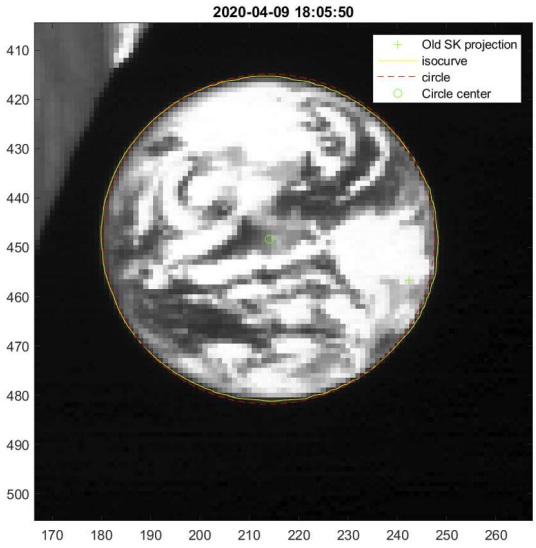
a.1


2020-04-10 17:12:26
Old SK projection
isocurve
isocurve-1
isocurve-2
eli-1
eli-2
Circle center

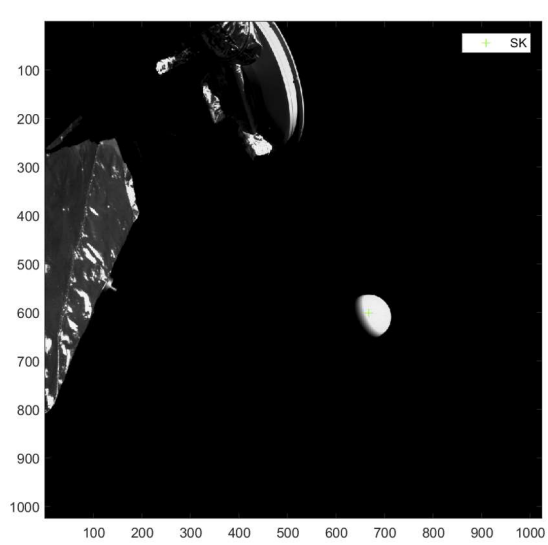
a.2


SK based

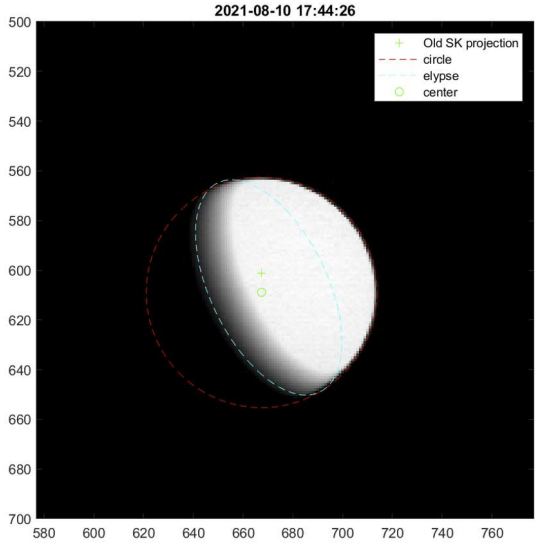
b.1


2020-04-09 18:05:50
Old SK projection
isocurve
circle
Circle center

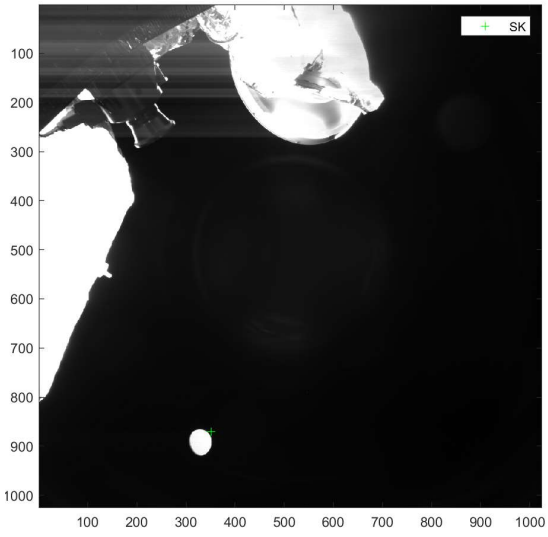
b.2



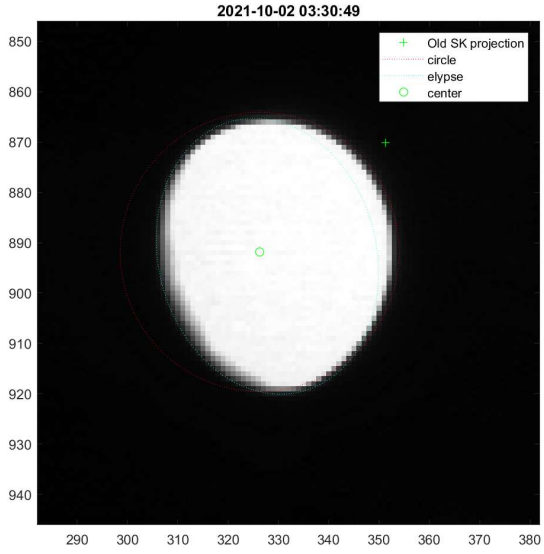
c.1



c.2



d.1



d.2

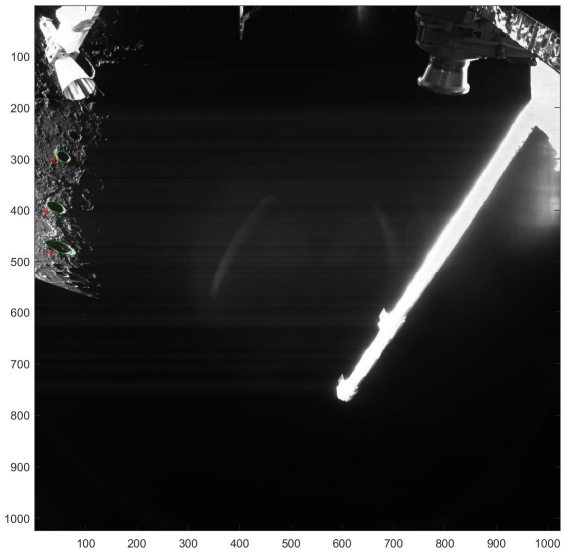
Figure 8 (a) and (b) show the results of the detection for two sample images of the first Earth flyby performed respectively by MACAM1 and MCAM3. (c) images show an example of the first Venus flyby (acquisition of MCAM3) while (d) images show an example of the first Mercury Flyby (same instrument)

3.2 Craters features

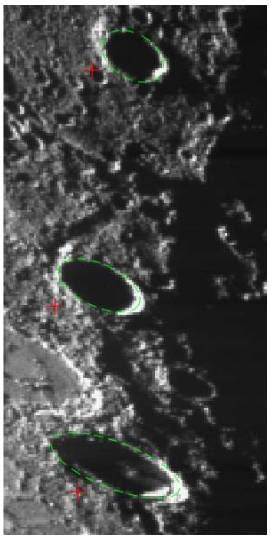
Crater features are defined fitting an ellipse on 8 points defined on the rim of the feature. Knowing the latitude and longitude coordinates of the feature it is possible to define the 3d coordinates in the reference frame of the considered camera as described in the Example:

```
%% Define x3d feature coordinate in cam frame
    [ x_p, ltime ] = cspice_spkpos('MERCURY', et, cam_frame, 'MPO');
     R_IAU2CAM = cspice_pxform( 'IAU_MERCURY', cam_frame, et );
     [lat long]=get_coordMCAM3(ncrater);
     rectan = cspice_latrec( radius, long*pi/180, lat*pi/180);
%% X 3d feature coordinate in cam frame
     X = x_p +R_IAU2CAM*rectan;
```

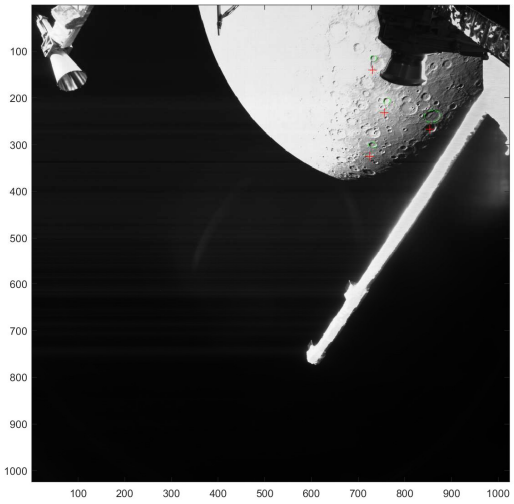
Figure 9 and Figure 10 show an example of the considered images respectively for MCAM2 and MCAM3



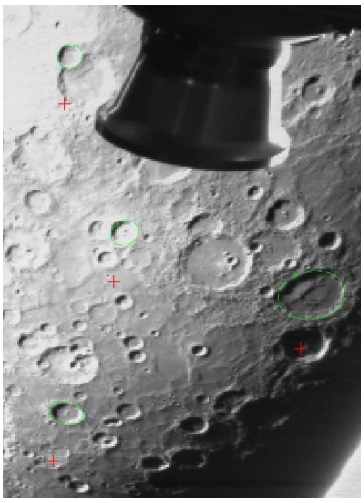
(a.1)



(b.1)

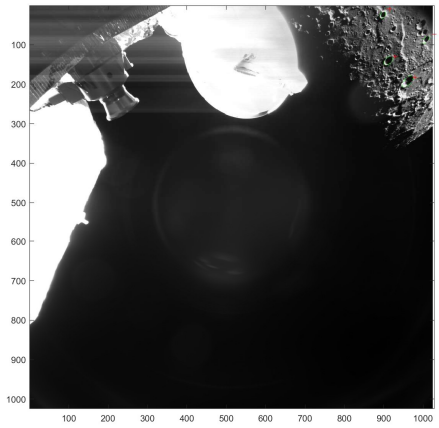


(a.2)

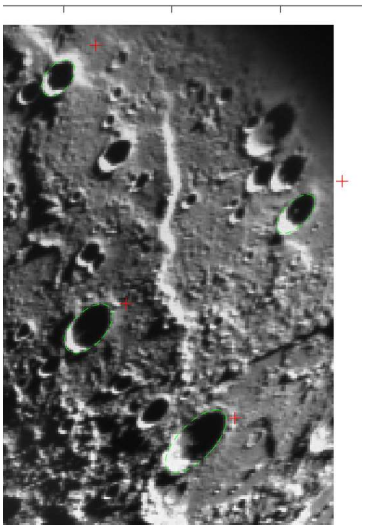


(b.2)

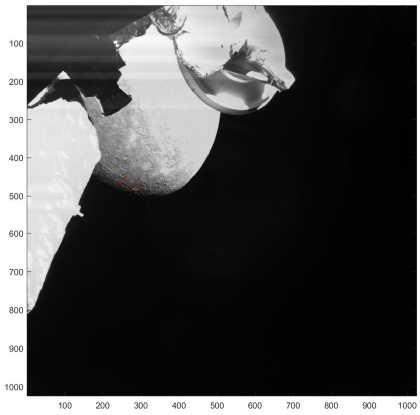
Figure 9 Image shows two examples of MCAM2 images (respectively cam2_browse_20211001t233944_00_f__t0040 and cam_raw_sc_cam2_browse_20211001t234557_11_f__t0020.jpeg). On the left (a) the complete image and on the right (b) a zoom on the features. The plot shows in green the feature defined by an ellipse and in red the projection of the same feature following the current spice kernels.



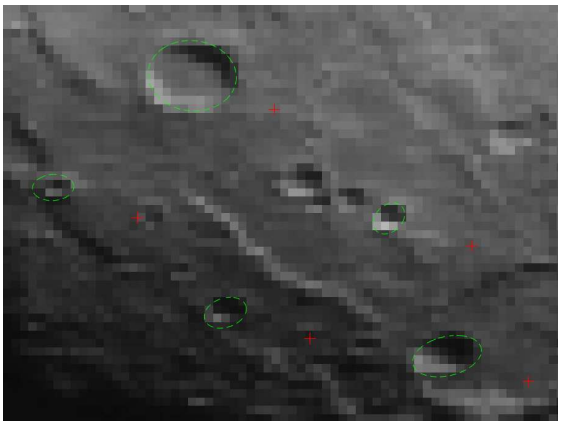
(a.1)



(b.1)



(a.2)



(b.2)

Figure 10 shows two examples of MCAM3 images (respectively cam3_browse_20211001t234029_01_f_t0040 and cam_raw_sc_cam3_browse_20211001t235229_28_f__t0010). On the left (a) the complete image and on the right (b) a zoom on the features. The plot shows in green the feature defined by an ellipse and in red the projection of the same feature following the current spice kernels.

3.3 Dataset

Image ID	Feature coordinate X [px]	Feature coordinate Y [px]	3d Coord CAM frame [km] x	3d Coord CAM frame [km] y	3d Coord CAM frame [km] z	Lat [deg]	Long [dg]
cam1_browse_20200411t032635_27_f__t0020	240.8384	465.3257	174420.1	24675.04	-516501		
cam1_browse_20200411t040615_31_f__t0020	236.5981	464.7719	168136.5	23785.87	-491088		
cam1_browse_20200411t044555_35_f__t0020	234.6578	464.4078	165133.3	23360.9	-479030		
cam1_browse_20200411t050545_37_f__t0020	229.8288	463.7969	158468	22417.73	-452466		
cam1_browse_20200411t052535_39_f__t0020	227.1522	463.4275	154911.3	21914.44	-438402		
cam1_browse_20200411t060515_43_f__t0020	223.0735	462.906	149979.6	21216.58	-419027		
cam1_browse_20200411t062505_45_f__t0020	225.0846	463.2087	152451.1	21566.31	-428718		
cam1_browse_20200411t064455_47_f__t0020	219.3025	462.4274	145626.5	20600.61	-402045		
cam1_browse_20200411t070445_49_f__t0020	216.6096	462.0202	142494.8	20157.48	-389897		
cam1_browse_20200411t074425_53_f__t0020	214.7338	461.776	140606.7	19890.31	-382601		
cam1_browse_20200411t080415_55_f__t0020	215.3224	461.8706	141236.8	19979.48	-385034		
cam1_browse_20200411t082405_57_f__t0020	211.5642	461.3673	137444.3	19442.83	-370428		
cam1_browse_20200411t084355_59_f__t0020	209.7211	460.9948	135537.3	19172.99	-363116		
cam1_browse_20200411t090345_61_f__t0020	207.5365	460.7617	133622.9	18902.11	-355796		
cam1_browse_20200411t095130_16_f__t0020	204.7232	460.4306	131060	18539.45	-346031		
cam1_browse_20200411t101120_18_f__t0020	201.0495	459.9444	127835.7	18083.23	-333800		
cam1_browse_20200411t111050_24_f__t0020	197.1916	459.3835	124709.9	17640.93	-322000		
cam1_browse_20200411t115030_28_f__t0020	192.2235	458.7132	120785	17085.57	-307266		

cam1_browse_20200411t121020_30_f__t0020	193.8578	459.001	122097.1	17271.22	-312181		
cam1_browse_20200411t123010_32_f__t0020	191.2378	458.6767	120127.6	16992.54	-304806		
cam1_browse_20200411t125000_34_f__t0020	188.5275	458.255	118149.4	16712.63	-297421		
cam1_browse_20200411t130950_36_f__t0020	187.4949	458.2007	117488	16619.04	-294958		
cam1_browse_20200411t142402_15_f__t0020	184.605	457.766	115497.7	16337.42	-287559		
cam1_browse_20200411t142422_17_f__t0020	183.5004	457.6133	114832.2	16243.26	-285090		
cam1_browse_20200411t142442_19_f__t0020	181.5451	457.3595	113498.1	16054.48	-280150		
cam3_browse_20200409t171616_36_f__t0010	205.7236	446.5231	62563.31	12845.65	-186205		
cam3_browse_20200409t172611_37_f__t0010	207.2736	446.8653	61438.79	12614.73	-183828		
cam3_browse_20200409t173606_38_f__t0010	208.8855	447.2205	60310.66	12383.07	-181448		
cam3_browse_20200409t174600_39_f__t0010	210.5335	447.5799	59180.78	12151.04	-179071		
cam3_browse_20200409t175555_40_f__t0010	212.2638	447.9533	58045.29	11917.87	-176687		
cam3_browse_20200409t180550_41_f__t0010	214.0672	448.3309	56906.04	11683.93	-174300		
cam3_browse_20200409t181545_42_f__t0010	215.9469	448.7527	55762.97	11449.2	-171911		
cam3_browse_20200409t182540_43_f__t0010	217.8311	449.1567	54616.03	11213.67	-169520		
cam3_browse_20200409t183535_44_f__t0010	219.8723	449.6029	53465.15	10977.34	-167125		
cam3_browse_20200409t184530_45_f__t0010	221.9351	450.0434	52310.29	10740.2	-164728		
cam3_browse_20200409t185525_46_f__t0010	224.1043	450.5226	51151.37	10502.22	-162328		
cam3_browse_20200409t190520_47_f__t0010	226.35	451.006	49988.34	10263.39	-159924		
cam3_browse_20200409t191515_48_f__t0010	228.6762	451.5135	48821.14	10023.71	-157518		
cam3_browse_20200409t192510_49_f__t0010	231.1019	452.0368	47649.7	9783.157	-155108		
cam3_browse_20200409t193505_50_f__t0010	233.5827	452.5721	46473.97	9541.722	-152694		
cam3_browse_20200409t194500_51_f__t0010	236.2047	453.1554	45293.87	9299.389	-150277		
cam3_browse_20200409t195455_52_f__t0010	238.95	453.7579	44109.34	9056.144	-147856		
cam3_browse_20200409t200450_53_f__t0010	241.7742	454.364	42920.31	8811.975	-145431		
cam3_browse_20200409t201445_54_f__t0010	244.7679	454.9184	41726.71	8566.867	-143002		
cam3_browse_20200409t202440_55_f__t0010	247.764	455.6664	40528.47	8320.805	-140568		
cam3_browse_20200409t203435_56_f__t0010	250.9804	456.3624	39325.52	8073.772	-138129		
cam3_browse_20200409t204430_57_f__t0010	254.2666	457.0997	38117.79	7825.759	-135686		
cam3_browse_20200409t205425_58_f__t0010	257.8058	457.862	36905.2	7576.754	-133237		
cam3_browse_20200409t210420_59_f__t0010	261.7699	458.407	35687.68	7326.744	-130783		
cam3_browse_20210810t162926_06_f__t0004	798.3849	915.707	-25910.3	-33099.9	-74090.3		
cam3_browse_20210810t163226_07_f__t0004	800.856	885.9849	-26703.5	-31532.8	-76216.2		
cam3_browse_20210810t163526_08_f__t0004	803.1996	861.1662	-27456	-30204.9	-78195.3		
cam3_browse_20210810t163826_09_f__t0004	805.0938	841.6737	-28173.4	-29179.3	-80026.7		
cam3_browse_20210810t164126_10_f__t0004	807.0899	827.5432	-28860.9	-28521.1	-81707.9		
cam3_browse_20210810t164426_11_f__t0004	808.3685	819.5778	-29522.9	-28296	-83233.7		
cam3_browse_20210810t164726_12_f__t0004	810.1021	817.5069	-30161.6	-28562	-84596.1		
cam3_browse_20210810t165026_13_f__t0004	811.9018	817.4126	-30792	-29009.1	-85898.8		
cam3_browse_20210810t165326_14_f__t0004	813.5554	817.4226	-31421.8	-29455.9	-87200.5		
cam3_browse_20210810t165626_15_f__t0004	815.1498	817.4353	-32051.3	-29902.3	-88501.3		
cam3_browse_20210810t165926_16_f__t0004	816.2802	816.2852	-32643.3	-30256.1	-89845.7		
cam3_browse_20210810t170226_17_f__t0004	816.2212	812.1973	-33132.3	-30357	-91311		
cam3_browse_20210810t170526_18_f__t0004	814.3715	805.6996	-33510.9	-30209.3	-92895		

cam3_browse_20210810t170826_19_f__t0004	811.7464	796.4797	-33768.8	-29822.8	-94592.6		
cam3_browse_20210810t171126_20_f__t0004	806.8482	785.6607	-33891.6	-29209.1	-96397.4		
cam3_browse_20210810t171426_21_f__t0004	801.5469	772.3769	-33863	-28382.3	-98301.3		
cam3_browse_20210810t171726_22_f__t0004	793.8322	758.2118	-33665.6	-27358.6	-100295		
cam3_browse_20210810t172026_23_f__t0004	785.1641	742.4752	-33282.4	-26156.8	-102366		
cam3_browse_20210810t172326_24_f__t0004	774.7787	726.0393	-32698.2	-24797.8	-104502		
cam3_browse_20210810t172626_25_f__t0004	763.1751	708.8508	-31900.7	-23304.4	-106689		
cam3_browse_20210810t172926_26_f__t0004	750.1693	691.4209	-30881.6	-21701.3	-108910		
cam3_browse_20210810t173226_27_f__t0004	735.6758	674.034	-29637.8	-20014.3	-111150		
cam3_browse_20210810t173526_28_f__t0004	719.6689	657.0553	-28171.7	-18269.8	-113390		
cam3_browse_20210810t173826_29_f__t0004	703.1289	640.2479	-26492.3	-16494.4	-115614		
cam3_browse_20210810t174126_30_f__t0004	685.6586	624.1752	-24615.1	-14714.4	-117806		
cam3_browse_20210810t174426_31_f__t0004	667.4182	608.9142	-22562.7	-12954.8	-119951		
cam3_browse_20210810t174726_32_f__t0004	648.8445	594.547	-20364.2	-11239.3	-122036		
cam3_browse_20210810t175026_33_f__t0004	630.2616	581.1061	-18055.4	-9589.71	-124052		
cam3_browse_20210810t175326_34_f__t0004	611.7394	568.7818	-15677.7	-8025.47	-125992		
cam3_browse_20210810t175626_35_f__t0004	593.6963	557.5913	-13278.1	-6563.84	-127854		
cam3_browse_20210810t175926_36_f__t0004	576.4305	547.4576	-10908.1	-5219.74	-129637		
cam3_browse_20210810t180226_37_f__t0004	560.1046	538.7261	-8623.06	-4006.05	-131347		
cam3_browse_20210810t180526_38_f__t0004	545.3934	531.0217	-6481.21	-2933.9	-132990		
cam3_browse_20210810t180826_39_f__t0004	532.0828	524.6392	-4543	-2013.28	-134578		
cam3_browse_20210810t181126_40_f__t0004	520.8625	519.4304	-2870.26	-1253.71	-136123		
cam3_browse_20210810t181426_41_f__t0004	512.1877	515.454	-1525.42	-665.093	-137637		
cam3_browse_20210810t181726_42_f__t0004	505.9957	512.7631	-570.807	-258.742	-139134		
cam3_browse_20210810t182126_43_f__t0004	502.4756	511.2308	-10.797	-24.9002	-141118		
cam3_browse_20210810t192126_44_f__t0004	502.5328	511.2388	-5.6295	-26.9448	-170782		
cam3_browse_20210810t202126_45_f__t0004	502.5846	511.2768	-6.9944	-31.6848	-200318		
cam3_browse_20210810t212126_46_f__t0004	502.3699	511.3398	-8.3568	-36.4094	-229760		
cam3_browse_20210810t222126_47_f__t0004	502.4709	511.2931	-9.7111	-41.1188	-259128		
cam3_browse_20210810t232126_48_f__t0004	502.4952	511.2924	-11.0562	-45.8213	-288439		
cam3_browse_20210811t002126_49_f__t0004	502.6352	511.2416	-12.3995	-50.514	-317702		
cam3_browse_20210811t012126_50_f__t0004	502.4932	511.2735	-13.7402	-55.1991	-346927		
cam3_browse_20210811t022126_51_f__t0004	502.3893	511.2649	-15.0705	-59.8828	-376118		
cam3_browse_20210811t032126_52_f__t0004	502.4079	511.2774	-16.399	-64.5612	-405280		
cam3_browse_20210811t042126_53_f__t0004	502.3294	511.3651	-17.726	-69.2348	-434419		
cam3_browse_20210811t052126_54_f__t0004	502.353	511.3925	-19.0431	-73.909	-463535		
cam3_browse_20210811t062126_55_f__t0004	502.539	511.3446	-20.3636	-78.5769	-492633		
cam3_browse_20210811t072126_56_f__t0004	502.3898	511.2997	-21.6757	-83.2457	-521714		
cam3_browse_20210811t082126_57_f__t0004	502.47	511.3343	-22.9853	-87.9122	-550779		
cam3_browse_20210811t102126_59_f__t0004	502.3392	511.4898	-25.5942	-97.2413	-608871		
cam3_browse_20210811t112126_60_f__t0004	502.3647	511.2948	-26.8054	-101.828	-637899		
cam3_browse_20210811t132126_62_f__t0004	502.457	511.3491	-29.3877	-111.143	-695925		
cam3_browse_20210811t142126_63_f__t0004	502.3237	511.415	-30.6749	-115.8	-724924		
cam3_browse_20210811t152126_00_f__t0004	502.4803	511.2457	-31.959	-120.456	-753915		

cam3_browse_20210811t172126_02_f__t0004	502.2987	511.4608	-34.5178	-129.766	-811875		
cam3_browse_20210811t182125_03_f__t0004	502.3803	511.3323	-35.7951	-134.419	-840837		
cam3_browse_20210811t192125_04_f__t0004	502.4073	511.3119	-37.0665	-139.074	-869800		
cam3_browse_20210811t202125_05_f__t0004	502.5086	511.3369	-38.3366	-143.725	-898757		
cam3_browse_20210811t212125_06_f__t0004	502.4171	511.3642	-39.6017	-148.374	-927709		
cam3_browse_20210811t235805_11_f__t0005	502.1824	510.8957	253.3283	315.9869	-1003281		
cam3_browse_20210812t000405_12_f__t0005	501.4918	509.6355	1094.104	1665.898	-1006173		
cam3_browse_20210812t001005_13_f__t0005	500.2734	507.7721	2446.602	3833.899	-1009058		
cam3_browse_20210812t002205_15_f__t0005	496.9335	501.931	6555.159	10393.86	-1014781		
cam3_browse_20210812t003405_17_f__t0005	491.8809	494.0663	12314.96	19524.22	-1020381		
cam3_browse_20210812t004005_18_f__t0005	488.9406	489.4179	15729.96	24901.83	-1023111		
cam3_browse_20210812t004605_19_f__t0005	485.8583	484.3916	19455.68	30738.75	-1025783		
cam3_browse_20210812t005205_20_f__t0005	482.5072	479.1501	23456.68	36972.46	-1028390		
cam3_browse_20210812t005805_21_f__t0005	478.9782	473.4657	27696.67	43539.92	-1030924		
cam3_browse_20210812t010405_22_f__t0005	475.3016	467.6482	32138.43	50377.7	-1033382		
cam3_browse_20210812t011005_23_f__t0005	471.5147	461.7121	36743.75	57422.06	-1035760		
cam3_browse_20210812t011605_24_f__t0005	467.6424	455.5673	41473.4	64609.09	-1038059		
cam3_browse_20210812t014605_29_f__t0005	448.0146	425.7466	65540.81	100443.9	-1048521		
cam3_browse_20210812t015205_30_f__t0005	444.1957	420.2026	70134.71	107143.9	-1050475		
cam3_browse_20210812t015805_31_f__t0005	440.7056	415.027	74549.78	113539.8	-1052415		
cam3_browse_20210812t020405_32_f__t0005	437.3323	410.0286	78739.04	119568.4	-1054361		
cam3_browse_20210812t022205_35_f__t0005	428.8472	398.0389	89470.98	134815.9	-1060441		
cam3_browse_20210812t022805_36_f__t0005	426.7062	395.0025	92273.03	138740	-1062623		
cam3_browse_20210812t023405_37_f__t0005	425.0708	392.3501	94604.59	141977.5	-1064919		
cam3_browse_20210812t041402_61_f__t0005	422.0106	390.0292	102471	151405.2	-1111745		
cam3_browse_20210812t095023_61_f__t0005	419.8537	392.7924	120382.9	169047.8	-1271909		
cam3_browse_20210812t212756_40_f__t0005	414.6605	399.2768	161056.2	201417.4	-1603896		
cam3_browse_20210812t213356_41_f__t0005	414.5738	399.3772	161426.8	201670.9	-1606751		
cam3_browse_20210812t214556_43_f__t0005	517.9397	527.5713	-27043.5	-27002.2	-1632710		
cam3_browse_20210812t215756_45_f__t0005	626.7147	695.5173	-225716	-326303	-1590179		
cam3_browse_20210812t220356_46_f__t0005	677.2665	789.8967	-308947	-479649	-1539497		
cam3_browse_20210812t220956_47_f__t0005	726.1618	894.5532	-379597	-632336	-1470070		
cam3_browse_20211002t030349_43_f__t0020	171.7375	646.0093	29386.73	-12345.6	-78411.6		
cam3_browse_20211002t030649_44_f__t0020	188.3786	665.1785	28341.65	-14269.4	-79760.6		
cam3_browse_20211002t030949_45_f__t0020	205.8697	686.135	27172.46	-16407	-81044.5		
cam3_browse_20211002t031249_46_f__t0020	223.5571	709.0407	25891.24	-18761.8	-82239.6		
cam3_browse_20211002t031549_47_f__t0020	241.2497	734.015	24512	-21335.4	-83321.7		
cam3_browse_20211002t031849_48_f__t0020	259.103	760.8906	23050.69	-24127.4	-84266		
cam3_browse_20211002t032149_49_f__t0020	276.6642	790.0152	21525.09	-27134.9	-85047.9		
cam3_browse_20211002t032449_50_f__t0020	293.5719	821.4873	19954.81	-30352.2	-85643		
cam3_browse_20211002t032749_51_f__t0020	310.2049	855.3682	18361.03	-33771.1	-86028		
cam3_browse_20211002t033049_52_f__t0020	326.2644	891.8305	16766.38	-37380	-86181		
cam3_browse_20211001t234029_01_f__t0040	897.6054	25.1082	525.8813	-655.575	1155.275	-38.0296	-71.4295
	1007.068	87.7568	752.9151	-640.648	1289.789	-43.6679	-67.983

	911.5304	140.6609	617.719	-566.95	1310.347	-42.634	-72.7804
	961.0173	192.7271	760.5505	-537.091	1440.586	-47.1496	-71.582
cam3_browse_20211001t234159_03_f__t0040	719.008	228.6246	463.7827	-612.699	1892.558	-43.6679	-67.983
	653.732	265.7647	328.5861	-538.997	1913.099	-42.634	-72.7804
	705.0641	294.5379	471.4075	-509.132	2043.347	-47.1496	-71.582
cam3_browse_20211001t234459_08_f__t0010	401.256	343.8013	-338.254	-554.644	2939.376	-38.0296	-71.4295
	470.9672	356.3895	-111.252	-539.699	3073.943	-43.6679	-67.983
	432.1655	377.0658	-246.45	-465.99	3094.451	-42.634	-72.7804
	474.87	390.9367	-103.649	-436.11	3224.718	-47.1496	-71.582
	435.9962	316.5872	-220.058	-636.293	2900.115	-38.394	-67.0014
	382.5166	179.0337	-103.649	-436.11	3224.718	-47.1496	-71.582
cam3_browse_20211001t234629_12_f__t0010	346.3467	380.2233	-623.869	-512.825	3520.599	-38.0296	-71.4295
	406.7355	389.4237	-396.878	-497.874	3655.183	-43.6679	-67.983
	374.8722	407.014	-532.076	-424.16	3675.675	-42.634	-72.7804
	412.5853	418.2906	-389.285	-394.273	3805.952	-47.1496	-71.582
	374.483	358.1241	-505.671	-594.478	3481.353	-38.394	-67.0014
	324.1923	250.7846	-389.285	-394.273	3805.952	-47.1496	-71.582
cam3_browse_20211001t234759_16_f__t0010	306.5832	407.7248	-908.267	-468.752	4096.913	-38.0296	-71.4295
	360.0736	414.2929	-681.287	-453.795	4231.515	-43.6679	-67.983
	332.1827	429.6192	-816.485	-380.078	4251.99	-42.634	-72.7804
	366.5168	439.5297	-673.704	-350.183	4382.276	-47.1496	-71.582
	330.4638	388.1558	-790.067	-550.41	4057.683	-38.394	-67.0014
	283.5785	300.4892	-673.704	-350.183	4382.276	-47.1496	-71.582
cam3_browse_20211001t234929_20_f__t0010	254.3486	337.5436	-956.998	-304.431	4954.484	-47.1496	-71.582
	276.3777	428.5882	-1191.54	-423.017	4669.111	-38.0296	-71.4295
	324.9438	434.2079	-964.57	-408.053	4803.729	-43.6679	-67.983
	300.7894	447.619	-1099.77	-334.333	4824.188	-42.634	-72.7804
	331.4007	455.0894	-956.998	-304.431	4954.484	-47.1496	-71.582
	298.0908	411.6812	-1073.34	-504.68	4629.896	-38.394	-67.0014
cam3_browse_20211001t235059_24_f__t0010	253.5876	445.1382	-1473.79	-376.032	5237.824	-38.0296	-71.4295
	297.5295	449.5937	-1246.83	-361.063	5372.461	-43.6679	-67.983
	275.8232	461.8602	-1382.03	-287.338	5392.903	-42.634	-72.7804
	303.6968	468.0074	-1239.27	-257.429	5523.208	-47.1496	-71.582
	271.7614	430.5387	-1355.58	-457.7	5198.626	-38.394	-67.0014
	231.9338	366.0716	-1239.27	-257.429	5523.208	-47.1496	-71.582
cam3_browse_20211001t235229_28_f__t0010	234.4437	458.4227	-1755.11	-328.091	5803.562	-38.0296	-71.4295
	274.4715	462.1223	-1528.16	-313.116	5938.216	-43.6679	-67.983
	254.9648	473.3731	-1663.36	-239.387	5958.642	-42.634	-72.7804
	281.4014	478.5604	-1520.61	-209.471	6088.956	-47.1496	-71.582
	251.026	445.0744	-1636.91	-409.764	5764.379	-38.394	-67.0014
	214.1696	388.4488	-1520.61	-209.471	6088.956	-47.1496	-71.582
cam2_browse_20211001t233944_00_f__t0040	55.9639	295.5186	-589.53	-261.947	1101.785	-38.0296	-71.4295
	41.5823	393.9008	-697.435	-155.436	1261.094	-43.6679	-67.983
	48.5197	471.2384	-788.811	-48.2835	1454.858	-42.634	-72.7804

cam2_browse_20211001t234114_02_f__t0040	428.691	104.3617	-131.811	-602.645	1369.876	-47.1496	-71.582
	358.5152	345.7898	-324.617	-301.963	1785.1	-43.6679	-67.983
	235.8405	174.5146	-468.806	-548.061	1517.08	-42.634	-72.7804
cam2_browse_20211001t234245_04_f__t0040	688.216	100.7771	356.2284	-785.542	1794.645	-47.1496	-71.582
	583.9831	296.3716	163.4139	-484.86	2209.865	-38.0296	-71.4295
	517.5479	156.5536	19.2354	-730.983	1941.862	-43.6679	-67.983
cam2_browse_20211001t234414_06_f__t0010	735.1083	263.7053	639.4297	-658.358	2617.726	-42.634	-72.7804
	701.1518	146.1572	495.261	-904.506	2349.741	-47.1496	-71.582
	584.5695	134.4441	158.5744	-1010.34	2401.911	-38.394	-67.0014
	618.5531	226.2227	297.5609	-776.467	2607.933	-47.1496	-71.582
cam2_browse_20211001t234426_07_f__t0020	751.3449	260.5812	703.4896	-681.418	2672.233	-38.0296	-71.4295
	720.6565	144.1953	559.3222	-927.569	2404.25	-43.6679	-67.983
	595.1981	118.3768	222.6372	-1033.4	2456.424	-42.634	-72.7804
	638.0708	223.5725	361.6222	-799.531	2662.443	-47.1496	-71.582
cam2_browse_20211001t234545_10_f__t0010	847.0782	240.706	1124.44	-831.568	3028.597	-38.394	-67.0014
	716.9609	115.1278	643.6065	-1183.6	2812.821	-47.1496	-71.582
	746.6809	208.1831	782.5813	-949.709	3018.825	-38.0296	-71.4295
cam2_browse_20211001t234557_11_f__t0020	858.8837	239.2573	1188.262	-854.147	3082.382	-43.6679	-67.983
	733.0421	115.1289	707.4315	-1206.19	2866.611	-42.634	-72.7804
	730.861	300.5251	841.1053	-738.783	3500.911	-47.1496	-71.582
	761.5179	206.9286	846.4048	-972.292	3072.613	-38.394	-67.0014
cam2_browse_20211001t234714_14_f__t0010	805.9123	281.9649	1249.889	-882.443	3844.135	-47.1496	-71.582
	842.1816	195.5915	1255.19	-1115.97	3415.846	-47.1496	-71.582
cam2_browse_20211001t234726_15_f__t0020	816.4196	280.245	1313.481	-904.656	3897.35	-38.0296	-71.4295
	853.9015	194.3541	1318.782	-1138.18	3469.062	-43.6679	-67.983
cam2_browse_20211001t234844_18_f__t0010	878.6376	265.3868	1726.093	-1048.04	4241.647	-42.634	-72.7804
	919.0113	185.3509	1731.395	-1281.58	3813.368	-47.1496	-71.582
cam2_browse_20211001t234856_19_f__t0020	886.5372	263.9331	1789.462	-1069.95	4294.388	-38.394	-67.0014
	928.7665	184.2518	1794.764	-1303.5	3866.11	-38.0296	-71.4295
cam2_browse_20211001t235014_22_f__t0010	886.1509	158.6611	1804.615	-1589.67	4320.287	-43.6679	-67.983
	770.1447	214.1192	1464.508	-1543.07	4934.129	-42.634	-72.7804
	808.7813	266.4776	1706.855	-1297.33	5207.403	-47.1496	-71.582
	869.7251	279.6482	1994.001	-1171.59	5034.332	-38.394	-67.0014

Table 8 References to the image used for the SK optimization. Table reports image name, horizontal and vertical coordinates in pixel of the feature considered, 3d coordinate of the same feature in the camera reference system, latitude and longitude coordinates of the feature. These parameters are not defined if the center of the planet is defined as feature.