Coupling Mars ground and orbital views: generate viewsheds of Mastcam images from the Curiosity rover, using ArcGIS® and public datasets.

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Key Points

- Mastcam images from the Curiosity rover are available online but lacked a public method to be placed back in the Mars orbital context.
- This procedure permits to generate Mastcam image viewsheds: it identifies on Mars orbital view the terrains visible in a given Mastcam image.
- This procedure uses ArcGIS® and publicly available Mars datasets.

Abstract

The Mastcam (Mast Camera) instrument onboard the NASA Curiosity rover provides an exclusive view of Mars: the color high-resolution Mastcam images allow users to study Gale crater's geological terrains and landscapes along the rover path. This view from the ground complements the spatially broader view provided by spacecrafts from orbit. However, for a given Mastcam image, it can be challenging to locate on the orbital view the corresponding terrains. No method for collocating Mastcam onto orbital images had been made publicly available. The procedure presented here allows users to generate Mastcam viewsheds, using the ArcGIS® software and its built-in Viewshed tool as wells as Mars datasets exclusively public. This procedure locates onto Mars orbital view the terrains that are observed in a given Mastcam image. Because this procedure uses public datasets, it is applicable to the Mastcam images already available online and to the upcoming ones, as collected along Curiosity rover's path. In addition, this procedure constitutes material for a pedagogic GIS project in Geosciences or Planetary Sciences, to handle Mars datasets both orbital and from the Curiosity rover.

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1. Introduction

1.1. Complementarity of ground and orbital views of Mars for geological studies

Images of Mars's terrains and landscapes collected via the successive space missions keep refining our view and understanding of the red planet. Historically, the images collected with spacecrafts (e.g. Mariner 4 flyby in 1965) have offered a spatially-wide view of Mars that later got complemented by higher-resolution images collected from the ground with landers (e.g. Viking 1 landed in 1976 and InSight in 2018) and then rovers (Pathfinder landed in 1997, Spirit and Opportunity in 2004 and Curiosity in 2012). Orbital images have also been used for landing site selection of ground missions, and also to guide the path and the daily operations of rovers once landed, e.g. the Curiosity rover *[Stack et al., 2016]*. Because both orbital and ground views offer complementary information, their coupling is key for optimizing the study and interpretation of geological terrains and landscapes.

Orbital images, on one hand, are particularly useful for capturing a global or regional to local context, down to the meter scale, that cannot be provided by a typical rover visual range *[Stack et al., 2016]*. In particular, detailed orbital mapping based on high-resolution image datasets provides critical context for the more detailed rover measurements. However, the coverage of the surface of Mars by the most recent orbital imagers does not yet encompass the entire planet: the High Resolution Imaging Science Experiment (HiRISE) onboard the spacecraft Mars Reconnaissance Orbiter mapped ~0.55% of the surface at a scale from 25 to 60 cm/pixel, between October 2006 and December 2008 *[McEwen et al., 2010]*. Moreover, despite the increased sophistication of recent orbiter image-based geologic mapping efforts, the interpretation of Mars's geology based exclusively on orbital image datasets still carries considerable uncertainties *[Stack et al., 2016]*: three-dimensional outcrop exposures are difficult to observe in orbital data, thus limiting the geological interpretation of outcrop exposed as observed in orbital data. Also, even 25 cm/pixel HiRISE images provide limited to no information about the small-scale textural characteristics of geological material, which are critical for making depositional interpretations.

Ground images, on the other hand, offer a higher-resolution view of Martian terrains and provide "ground-truth" observations for orbital images. Ground-based images are needed to investigate the small-scale textural characteristics of outcrops, such as grain-size, lithology, internal sedimentary structures, or bedding styles, which are key for making depositional interpretations and paleoenvironmental reconstruction *[e.g. Stack et al., 2016; Banham et al., 2018; Lewis and Turner, 2019; Stein et al., 2020]*. However, *in-situ* observations of the Martian surface are limited to the locations visited by ground missions (8 landers and rovers, as of 2020).

In conjunction with each other, orbital and *in situ* observations provide an ideal, complementary approach to investigate a planetary surface. Because they offer complementary information, their coupling is key for optimizing the study and interpretation of geologic terrains and landscapes. Such complementary of datasets is also used for rover navigation, in particular to obtain precise rover localization *[e.g. Parker et al., 2013; Weishu Gong, 2015]* and to assist selection of rovers' routes (e.g. minimizing traverses across wheel-damaging terrains *[Arvidson et al., 2017]*).

1.2. Placing Mastcam images from the Curiosity rover into the Mars orbital context

Among the cameras present onboard the Curiosity rover from the NASA Mars Science Laboratory (MSL) mission, the Mastcam imagers provide an exclusive high-resolution color view of Mars (Fig. 1A). Mastcam (Mast Cameras) consists of a pair of color CCD imagers (Mastcam Left and Mastcam Right) mounted on the rover's mast at a height of 1.97 meters *[Bell et al., 2017; Malin et al., 2017]* (Fig. 1C). Mastcam Right (MR) has a 100-mm focal length and a field of view of 6.8°✕5.1° and Mastcam Left (ML) has a 34-mm focal length and a field of view of 20°✕15° *[Bell et al., 2017; Malin et al., 2017]*. MR and ML can respectively achieve pixel scales of ~150 µm and ~450 µm from 2 meters *[Malin et al., 2017]*. The Mastcam images allow for fine-scale study of the properties of outcrops and rocks *[e.g. Le Deit et al., 2016; Stein et al., 2018]*, landscape physiography [e.g. *Grotzinger et al., 2015]*, and properties sand [e.g. *Bridges et al., 2017; Ewing et al., 2017]*. They also provide visual context for the compositional analyses from Curiosity's instruments such as ChemCam (Chemistry and Camera) and APXS (Alpha Particle X-Ray Spectrometer) [e.g. *Wiens et al., 2017; Nachon et al., 2017; Thompson et al., 2016]*.

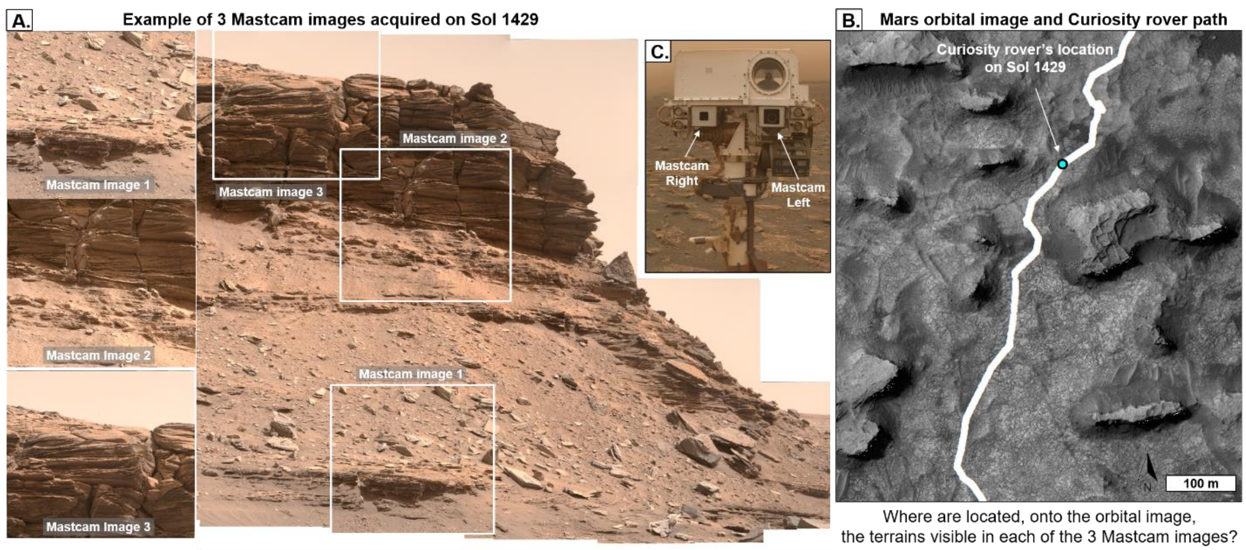


Figure 1: Illustration of the challenge of collocating Mastcam and orbital images, based on public datasets. ***A.*** *Example of 3 individual Mastcam images. Combined with other Mastcam images acquired on that Sol to generate a mosaic.* ***B.*** *Mars orbital view of Curiosity rover's location on Sol 1429.* ***C.*** *Mastcam imagers on Curiosity's mast.*

Mastcam images have been used alongside orbital images in several geologic studies of Gale crater's terrains, such as: (1) locating and mapping contacts between geologic units or members to establish the stratigraphy of the terrains (e.g. Sheepbed mudstone and overlying Gillespie Lake sandstone in the Yellowknife Bay formation *[McLennan et al., 2014]*); (2) interpreting the geologic origin of outcrops (e.g. aeolian Stimson formation *[Banham et al., 2018]*); (3) mapping geologic features too small to be observed from orbit, to determine their spatial and stratigraphic distribution in the different geologic units (e.g. light-toned veins *[Nachon et al., 2017]* and concretions *[Sun et al., 2019]*). As of January 2020, over 130,000 raw Mastcam images have been acquired (along the 20 km long path of the Curiosity rover) and have been publicly released (Table 1).

Despite the mentioned studies, no method for collocating Mastcam and orbital images has been made publicly available, presenting a roadblock to synchronous use of these datasets. As a result, geologic features present within Mastcam images can be challenging to identify within an orbital image of Gale crater, when using only public data. Most of Mastcam images contain geologic features tens to hundreds of meters away from the rover's traverse. It is difficult to deduce the spatial scale and location of features in these Mastcam images due to the combination of foreshortening and the lack of reference features. For example, the terrain imaged on Mastcam image 3 (Fig. 1A) acquired on Sol (Martian day) 1429 appears to depict the top of a butte; yet, on the orbital image of the rover on that Sol (Fig 1B), the location (how far from the rover, and in which direction) and the spatial extend of this terrain is not straightforward to identify..

Herein we describe a procedure that uses ArcGIS® and public Mars datasets to locate, onto Gale crater orbital view, the terrains that are visible in a given Mastcam image. By successfully correlating *in situ* and remote observations of Gale crater, Mars, we provide the Geoscience and Planetary Science communities access to tools for investigating Martian surface processes and geologic history.

2. Datasets and software

The datasets used are publicly available online (Table 1).

Dataset	File name	Source link
Mastcam images and associated labels. *See section 2.1*	Images are in .IMG format. Labels are in .LBL format.	https://pds-imaging.jpl.nasa.gov/volumes/msl.html Under successive volumes (MSLMST_00NN, where NN currently goes from 01 to 19), and in the "DATA" folders.
Gale crater orbital orthophoto mosaic. ("Gale crater mosaic") *See section 2.2*	MSL_Gale_Orthophoto_Mosaic_25cm_v3 Original 23 GB. File is in .tif format.	http://astrogeology.usgs.gov/search/map/Mars/MarsScienceLaboratory/Mosaics/MSL_Gale_Orthophoto_Mosaic_10m_v3
Gale crater DEM (Digital Elevation Model). *See section 2.2*	MSL_Gale_DEM_Mosaic_1m_v3 Original 3.6 GB. File is in .tif format.	http://astrogeology.usgs.gov/search/map/Mars/MarsScienceLaboratory/Mosaics/MSL_Gale_DEM_Mosaic_10m.
Rover path localization table. *See section 2.2*	Table "*localized_interp.csv*".	https://pds-imaging.jpl.nasa.gov/data/msl/MSLPLC_1XXX/DATA/LOCALIZATIONS/

Table 1: Mars datasets used and their respective public sources.

2.1. Mastcam datasets

Mastcam images and metadata are posted on the NASA PDS (Planetary Data System), Cartography and Imaging Sciences Node (Table 1) under successive volumes of conventional name "MSLMST_00NN" (where NN currently goes from 01 to 22), and in the "DATA" folders.

Mastcam data is released on a regular schedule (every 4 to 6 months, see http://pds-geosciences.wustl.edu/missions/msl/). It is also available via the MSL Analyst's Notebook (https://an.rsl.wustl.edu/msl/) that provides an interactive way of visualizing Curiosity's successive locations and of accessing the data collected by the rover on each Sol.

Mastcam data naming convention uniquely identifies an image or metadata product: in particular, the first 4 digits correspond to the Sol during which the image was acquired, and the letters in position 5 and 6 correspond to the camera name: "MR" for Mastcam Right or "ML" for Mastcam Left *[MMM DPSIS 2013, Table 3.4-1, Section 3.4]*.

Mastcam images

The Mastcam images on the PDS are in ".IMG" format (binary image data) *[MMM DPSIS 2013]*. Here we work with Mastcam RDR (Reduced Data Record) images: they have been decompressed, radiometrically calibrated, color corrected or contrast stretched, and linearized: this is reflected on their naming convention, where the digits in position 27 to 30 state "DRCL" *[MMM DPSIS 2013]*. For example, image 1429MR0070680050702586E01_DRCL.IMG posted on https://pds-imaging.jpl.nasa.gov/data/msl/MSLMST_0014/DATA/RDR/SURFACE/1429/.

Mastcam labels: images metadata

For each Mastcam image, its corresponding metadata is in an associated label (a text file in ".LBL" format) *[MMM DPSIS 2013, Appendix A]*. In particular, labels include information about images properties, and about the location of the rover when the image was acquired.

2.2. Orbital datasets and Curiosity rover's path at Gale crater

The mosaic covering the Curiosity rover's path area within Gale Crater is available on the USGS website (Table 1). It was assembled from High Resolution Imaging Science Experiment (HiRISE) images from Mars Reconnaissance Orbiter (MRO) *[Calef and Parker, 2016]*. The associated DEM (Digital Elevation Model) provides the topography of the terrains, at 1m/pixel resolution *[Calef and Parker, 2016]*. It was built from HRSC (High Resolution Stereo Camera) data from the ESA Mars Express spacecraft, CTX (Context Camera) and HiRISE data from MRO spacecraft, and MOLA (Mars Orbiter Laser Altimeter) data from MGS (Mars Global Surveyor) spacecraft *[Calef and Parker, 2016]*. Both the mosaic and the DEM are raster graphics images, in .TIF format. Curiosity rover's successive locations on each Sol are publicly available as a plain text table (in .CSV format) on the PDS (Table 1), where they are expressed both in rover coordinate frame ("Site" and "Drive", defined as successive position of the rover *[MSL Coordinate Systems, 2013]*) and in the corresponding latitude and longitude values.

2.3. ArcGIS®: GIS project and use of the Viewshed tool

The software ArcGIS® (version 10.5) is here used to build an interactive GIS (geographic information system) project that displays the rover path onto the Gale crater orbital mosaic and DEM.

The built-in ArcGIS® Viewshed tool uses the location of an observer on a DEM to identify raster cells that lie within and outside of the field of view of the observer at their precise location.. Because this tool allows to limit the region of the raster inspected, we use it to identify on the Mars orbital data the terrains that are visible (1) from the position of the rover onto the Gale crater DEM at the time a given Mastcam image was acquired and (2) from the Mastcam imager point of view at that given time (Section 3, Step 3). This process highlights on orbital view the area(s) that correspond to what is observed in the Mastcam image. We term these highlighted regions "Mastcam image viewsheds".

3. Mastcam image viewshed procedure: overview and illustrative example

This section presents our procedure for generating a Mastcam image viewshed in ArcGIS®, using data exclusively public. This allows to locate onto the Gale crater orbital view the terrains visible in a given Mastcam image (Fig. 2). The main steps of the procedure are: (1) gather the Mars public datasets and organize a GIS project to create a map of the Curiosity rover path as seen from orbit; (2) extract and calculate Mastcam image characteristics; (3) feed these characteristics into the GIS project and the ArcGIS® Viewshed tool. This procedure overview is furthermore illustrated by an example application (text in blue) based on Mastcam image 1429MR0070680170702598E01_DRCL. Extended descriptions of the procedure steps are provided in the supporting information and referenced along the manuscript.

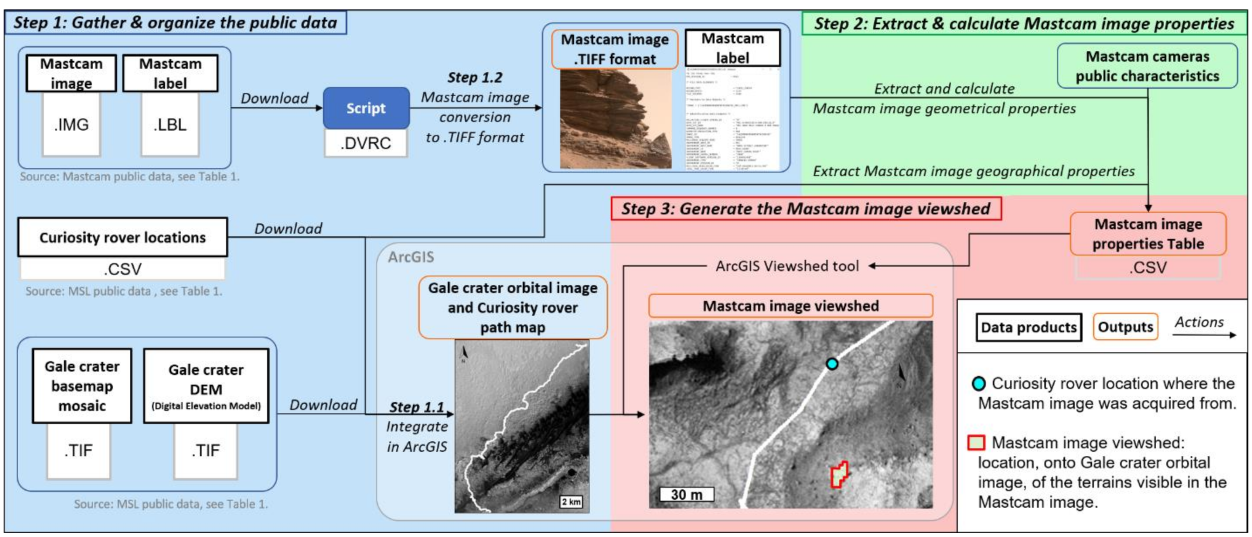


Figure 2: Flowchart of the procedure to generate a Mastcam image viewshed in ArcGIS® using data exclusively public. This allows to locate on Mars orbital view the terrains that are visible in a given Mastcam image.

Step 1: Gather and organize Mars public datasets

Step 1 first consists in downloading the Mars orbital and Mastcam datasets (Step 1.1). We also include an automated method for converting Mastcam images from .IMG into .TIFF format (Step 1.2). Step 1.3 is to integrate the Curiosity rover traverse map in ArcGIS®.

Step 1.1: Download datasets

All datasets use here are publicly available for download and include the Mastcam data (images and associated labels), Gale crater orthophoto mosaic, Gale crater DEM, and the Curiosity rover path localization table (Section 2 and Table 1).

Step 1.2 (Optional): Mastcam images conversion to .TIFF format

To convert the Mastcam images available online on the PDS (Table 1) from the binary format ".IMG" into ".TIFF" format, and automate this process to various Mastcam images, we provide a script (in DaVinci language) in the supplementary material. This format conversion allows the images to be visualized via more basic computer programs.

Step 1.3: Build the Curiosity rover traverse map in ArcGIS®

In ArcMap, import the Gale crater mosaic as well as the DEM covering the Curiosity rover's path area within Gale Crater, and the table of successive locations of Curiosity.

1.3.1 Launch ArcMap, select a new document, and save it.

1.3.2 To display the Gale crater imagery mosaic and the DEM:

- Download the Gale crater mosaic and the Gale DEM (see Table 1).
- In the ArcMap project, click ***File/Add data/ Add data.*** Select the Gale crater mosaic. Then do the same for adding the DEM.

1.3.3 To display the rover path in the ArcMap project:

- Download the rover path localization table ("localized_interp.csv") (see Table 1). The columns that contain information directly relevant for this ArcGIS® project are: (1) the rover coordinates columns ("planetocentric_latitude" and "longitude", as well as "site" and "drive"); (2) the elevation of the rover at a given location ("elevation"); (3) the corresponding martian days ("Sols") for each of the rover localizations.
- In the ArcMap project, click ***File/Add data/Add XY Data.*** In the window that appears, choose the "rover_path" table, and specify the fields for the X,Y and Z coordinates as follow: for X field select "longitude"; for Y field select "planetocentric_latitude"; for Z field select "sol".
- In the "Coordinate System and Input Coordinates", click on "Edit". Under the "Geographic Coordinate Systems/Solar System/Mars" folders, select "Mars 2000".

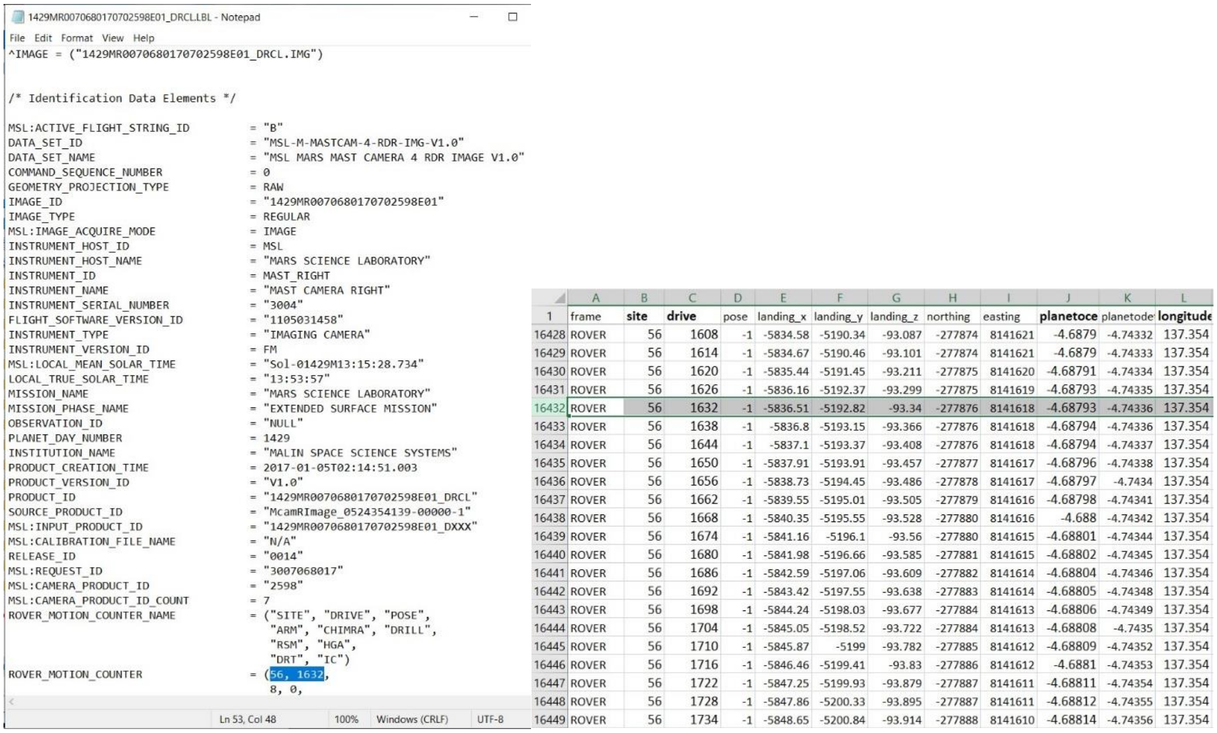
Step 2: Extract and calculate Mastcam image properties

For a given Mastcam image, Step 2 consists in extracting and calculating its geometrical and geographical properties that will be used (in Step 3) to ingest into the ArcGIS® Viewshed tool.

Step 2.1: Extract Mastcam image geographical properties

The geographical properties needed correspond to the location of the rover at the time the Mastcam image was acquired. A first order information about this location is provided by the Sol number, which is indicated by the first 4 digits of the image ID (section 2.1). Further information about this location is included in the Mastcam image label file (under the subsection "/* Identification Data Elements */"), as expressed in the rover coordinate frame: the "***SITE***" and "***DRIVE***" values (Section 2.2.). To obtain the actual coordinates corresponding to this location, we use the "Rover path localization table" (Table 1) that for each combination of "Site" and "Drive" values, provides the corresponding Mars coordinates (latitude and longitude).

For example, the label file of Mastcam image 1429MR0070680170702598E01_DRCL indicates that "***SITE***" value is 56 and "***DRIVE***" value is 1632. In the "Rover path localization table", for these values, the planetocentric latitude and the longitude are respectively -4.687932383° and 137.35402705°.



1429MR0070680170702598E01_DRCL.LBL - Notepad

File Edit Format View Help

```
^IMAGE = ("1429MR0070680170702598E01_DRCL.IMG")


/* Identification Data Elements */

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DATA_SET_ID                            = "MSL-M-MASTCAM-4-RDR-IMG-V1.0"
DATA_SET_NAME                          = "MSL MARS MAST CAMERA 4 RDR IMAGE V1.0"
COMMAND_SEQUENCE_NUMBER                = 0
GEOMETRY_PROJECTION_TYPE               = RAW
IMAGE_ID                               = "1429MR0070680170702598E01"
IMAGE_TYPE                             = REGULAR
MSL:IMAGE_ACQUIRE_MODE                 = IMAGE
INSTRUMENT_HOST_ID                     = MSL
INSTRUMENT_HOST_NAME                   = "MARS SCIENCE LABORATORY"
INSTRUMENT_ID                          = MAST_RIGHT
INSTRUMENT_NAME                        = "MAST CAMERA RIGHT"
INSTRUMENT_SERIAL_NUMBER               = "3004"
FLIGHT_SOFTWARE_VERSION_ID             = "1105031458"
INSTRUMENT_TYPE                        = "IMAGING CAMERA"
INSTRUMENT_VERSION_ID                  = FM
MSL:LOCAL_MEAN_SOLAR_TIME              = "Sol-01429M13:15:28.734"
LOCAL_TRUE_SOLAR_TIME                  = "13:53:57"
MISSION_NAME                           = "MARS SCIENCE LABORATORY"
MISSION_PHASE_NAME                     = "EXTENDED SURFACE MISSION"
OBSERVATION_ID                         = "NULL"
PLANET_DAY_NUMBER                      = 1429
INSTITUTION_NAME                       = "MALIN SPACE SCIENCE SYSTEMS"
PRODUCT_CREATION_TIME                  = 2017-01-05T02:14:51.003
PRODUCT_VERSION_ID                     = "V1.0"
PRODUCT_ID                             = "1429MR0070680170702598E01_DRCL"
SOURCE_PRODUCT_ID                      = "McamRImage_0524354139-00000-1"
MSL:INPUT_PRODUCT_ID                   = "1429MR0070680170702598E01_DXXX"
MSL:CALIBRATION_FILE_NAME              = "N/A"
RELEASE_ID                             = "0014"
MSL:REQUEST_ID                         = "3007068017"
MSL:CAMERA_PRODUCT_ID                  = "2598"
MSL:CAMERA_PRODUCT_ID_COUNT            = 7
ROVER_MOTION_COUNTER_NAME              = ("SITE", "DRIVE", "POSE",
                                          "ARM", "CHIMRA", "DRILL",
                                          "RSM", "HGA",
                                          "DRT", "IC")

ROVER_MOTION_COUNTER                   = (56, 1632,
                                          8, 0,
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Ln 53, Col 48 100% Windows (CRLF) UTF-8

	A	B	C	D	E	F	G	H	I	J	K	L
1	frame	**site**	**drive**	pose	landing_x	landing_y	landing_z	northing	easting	**planetoce**	planetode	**longitude**
16428	ROVER	56	1608	-1	-5834.58	-5190.34	-93.087	-277874	8141621	-4.6879	-4.74332	137.354
16429	ROVER	56	1614	-1	-5834.67	-5190.46	-93.101	-277874	8141621	-4.6879	-4.74333	137.354
16430	ROVER	56	1620	-1	-5835.44	-5191.45	-93.211	-277875	8141620	-4.68791	-4.74334	137.354
16431	ROVER	56	1626	-1	-5836.16	-5192.37	-93.299	-277875	8141619	-4.68793	-4.74335	137.354
16432	ROVER	56	1632	-1	-5836.51	-5192.82	-93.34	-277876	8141618	-4.68793	-4.74336	137.354
16433	ROVER	56	1638	-1	-5836.8	-5193.15	-93.366	-277876	8141618	-4.68794	-4.74336	137.354
16434	ROVER	56	1644	-1	-5837.1	-5193.37	-93.408	-277876	8141618	-4.68794	-4.74337	137.354
16435	ROVER	56	1650	-1	-5837.91	-5193.91	-93.457	-277877	8141617	-4.68796	-4.74338	137.354
16436	ROVER	56	1656	-1	-5838.73	-5194.45	-93.486	-277878	8141617	-4.68797	-4.7434	137.354
16437	ROVER	56	1662	-1	-5839.55	-5195.01	-93.505	-277879	8141616	-4.68798	-4.74341	137.354
16438	ROVER	56	1668	-1	-5840.35	-5195.55	-93.528	-277880	8141616	-4.688	-4.74342	137.354
16439	ROVER	56	1674	-1	-5841.16	-5196.1	-93.56	-277880	8141615	-4.68801	-4.74344	137.354
16440	ROVER	56	1680	-1	-5841.98	-5196.66	-93.585	-277881	8141615	-4.68802	-4.74345	137.354
16441	ROVER	56	1686	-1	-5842.59	-5197.06	-93.609	-277882	8141614	-4.68804	-4.74346	137.354
16442	ROVER	56	1692	-1	-5843.42	-5197.55	-93.638	-277883	8141614	-4.68805	-4.74348	137.354
16443	ROVER	56	1698	-1	-5844.24	-5198.03	-93.677	-277884	8141613	-4.68806	-4.74349	137.354
16444	ROVER	56	1704	-1	-5845.05	-5198.52	-93.722	-277884	8141613	-4.68808	-4.7435	137.354
16445	ROVER	56	1710	-1	-5845.87	-5199	-93.782	-277885	8141612	-4.68809	-4.74352	137.354
16446	ROVER	56	1716	-1	-5846.46	-5199.41	-93.83	-277886	8141612	-4.6881	-4.74353	137.354
16447	ROVER	56	1722	-1	-5847.25	-5199.93	-93.879	-277887	8141611	-4.68811	-4.74354	137.354
16448	ROVER	56	1728	-1	-5847.86	-5200.33	-93.895	-277887	8141611	-4.68812	-4.74355	137.354
16449	ROVER	56	1734	-1	-5848.65	-5200.84	-93.914	-277888	8141610	-4.68814	-4.74356	137.354

Step 2.2: Calculate Mastcam image geometrical properties

The geometrical properties correspond to the vertical and horizontal limits of the scan spanned in a given Mastcam image, from the rover location. To calculate them, 2 categories of information are used: (1) the fixed field of view of the Mastcam camera (Right of Left) used to collect the image; (2) the orientation of the Mastcam instrument (the vertical and horizontal angles it was pointing at) when the image was acquired.

First, the Mastcam Right and Left span a fixed FOV of respectively 6.8°✕5.1° and 20°✕15° *[Bell et al., 2017; Malin et al., 2017]*. The vertical and horizontal fields of view (vFOV and hFOV) correspond respectively to the angle of the view up-to-down, and of the view side-to-side. For a given Mastcam image, which of the Mastcam cameras (Right or Left) was used to collect the image is indicated in the Mastcam data ID (section 2.1). Mastcam image with ID "1429MR0070680050702586E01_DRCL" corresponds to a Mastcam Right image. Thus, its horizontal field of view (hFOV) is 6.8°, and vertical field of view (vFOV) is 5.1°.

Second, the Mastcam instrument can be pointed vertically and horizontally at variable degrees, depending on the analyses wanted by the MSL Team along the Curiosity rover traverse. The pointing parameters under which a given Mastcam image was acquired are indicated in the

Mastcam label file (under the subsection "/* Derived Data Elements */") by the following 2 parameters:

- The "***FIXED_INSTRUMENT_AZIMUTH***" (Fig. 3D) is the angle of the pointing direction of the Mastcam instrument with respect to the North. It is measured positively in the clockwise direction *[MMM DPSIS 2013].* An angle of 90° corresponds to a pointing of the camera towards the East.

- The "***FIXED_INSTRUMENT_ELEVATION***" (Fig. 3C) is the vertical angle of the pointing direction of the Mastcam instrument. It is measured from the plane which is perpendicular to the local gravity vector and which intersects the elevation axis around which the instrument rotates *[MMM DPSIS 2013]*. An angle of 0° corresponds to an horizontal pointing of the camera.

For image 1429MR0070680050702586E01_DRCL, the FIXED_INSTRUMENT_AZIMUTH value indicated in the label is 174.6128, and the FIXED_INSTRUMENT_ELEVATION is 11.4751. This indicates that the Mastcam instrument was pointed at 8.345 ° above the horizontal plane, and in a direction East/South-East, when the image was acquired.

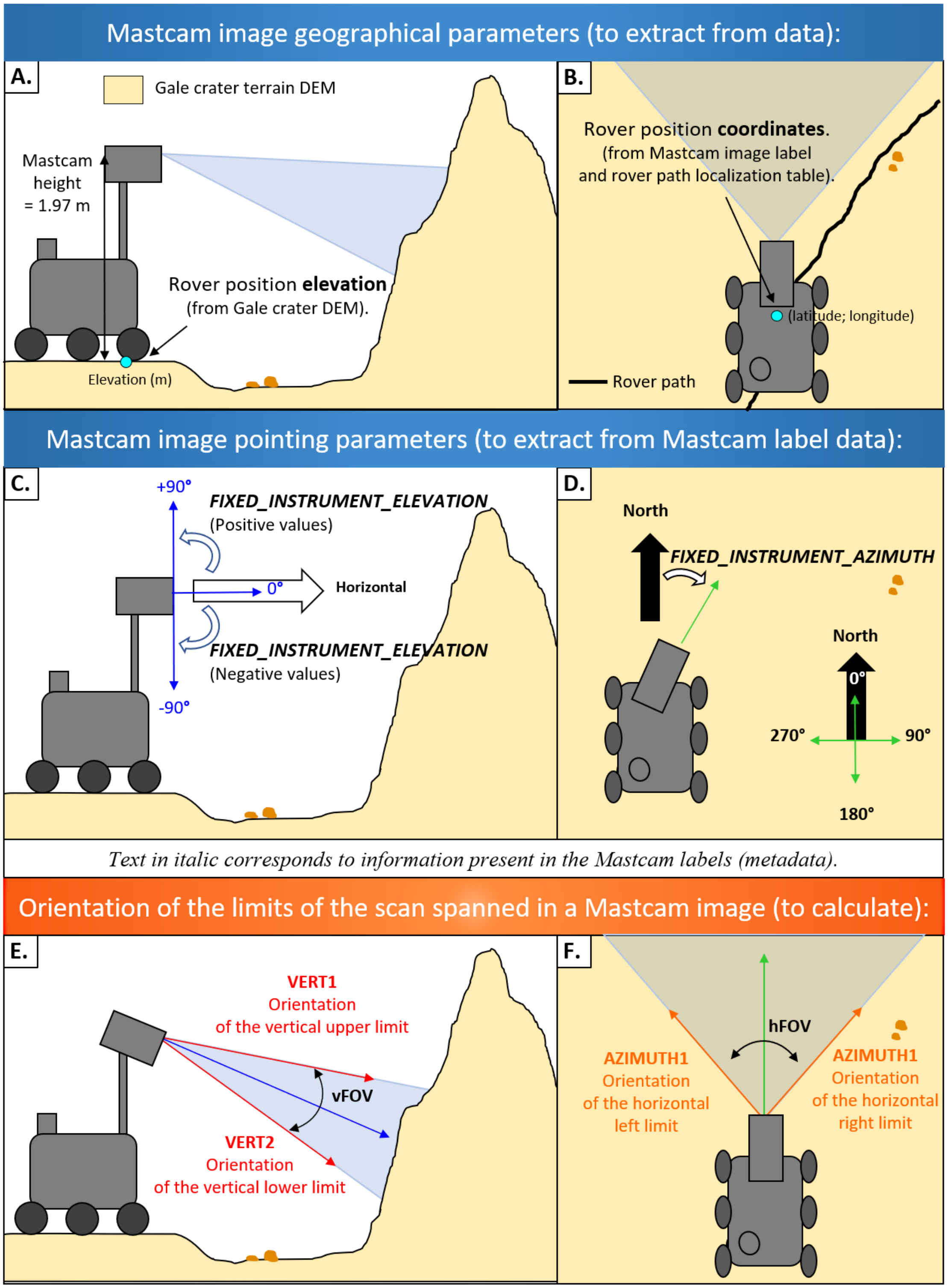

*Figure 3: Schematic of the geometrical and geographical properties of a Mastcam image, used to create a corresponding viewshed. Geographical properties include the rover location's elevation (**A.**) and coordinates at the time the Mastcam image was acquired (**B.**). The fixed instrument elevation (blue arrow) is the vertical angle of the pointing direction of the Mastcam camera (**C.**) The fixed instrument azimuth (green arrow) is the angle of the pointing direction of the Mastcam instrument with respect to the North (**C.**). Mastcam image vertical limits (red arrows) are the angles of the view limits up-to-down (**E.**), and the horizontal limits (orange arrows) is the orientation of the view limits side-to-side (**F.**).*

To calculate the orientation of the limits of the scan spanned in a given Mastcam image, we first address the vertical (upper and down) limits, and second the horizontal (left and right) limits.

First, the vertical orientation limits of the Mastcam image scan are defined with respect to the horizontal plane and are here called VERT1 and VERT2 (Fig. 3E). They are expressed in degrees between 90 and -90°, with positive values representing angles above the horizontal plane.

$$\text{Vertical upper limit: } \mathrm{VERT1} = \mathit{Fixed\_instrument\_elevation} + \left(\frac{\mathrm{vFOV}}{2}\right)$$

and

$$\text{Vertical lower limit: } \mathrm{VERT2} = \mathit{Fixed\_instrument\_elevation} - \left(\frac{\mathrm{vFOV}}{2}\right)$$

For image 1429MR0070680050702586E01_DRCL:

$$\mathrm{VERT1} = \mathit{Fixed\_instrument\_elevation} + \left(\frac{\mathrm{vFOV}}{2}\right) = 11.4751 + \left(\frac{5.1}{2}\right) = 14.0251$$

and

$$\mathrm{VERT2} = \mathit{Fixed\_instrument\_elevation} - \left(\frac{\mathrm{vFOV}}{2}\right) = 11.4751 - \left(\frac{5.1}{2}\right) = 8.9251$$

The vertical scan limits spanned in this image range from 8.9251° to 14.0251° above the horizontal plane.

Second, the horizontal angle limits are defined with respect to the North and are here called AZIMUTH1 and AZIMUTH2 (Fig. 3F). The sweep proceeds in a clockwise direction from the first azimuth to the second. The values for the angle are given in degrees from 0 to 360°, with 0° oriented to North.

$$\text{Horizontal left limit: } \mathrm{AZIMUTH1} = \mathit{Fixed\_instrument\_azimuth} - \left(\frac{\mathrm{hFOV}}{2}\right)$$

and

$$\text{Horizontal right limit: } \mathrm{AZIMUTH2} = \mathit{Fixed\_instrument\_azimuth} + \left(\frac{\mathrm{hFOV}}{2}\right)$$

For image 1429MR0070680050702586E01_DRCL:

$$\mathrm{AZIMUTH1} = \mathit{Fixed\ instrument\ azimuth} - \left(\frac{\mathrm{hFOV}}{2}\right) = 174.6128 - \left(\frac{6.8}{2}\right) = 171.2128$$

and

$$\mathrm{AZIMUTH2} = \mathit{Fixed\ instrument\ azimuth} + \left(\frac{\mathrm{hFOV}}{2}\right) = 174.6128 + \left(\frac{6.8}{2}\right) = 178.0128$$

The horizontal scan limits spanned in this image range from 171.2128° to 178.0128° with respect to North, which corresponds to a South/South-East direction.

Step 3: Generate the Mastcam image viewshed with the ArcGIS® Viewshed tool

We use the fact that in ArcGIS® the built-in Viewshed tool allows to identify the cells of a raster that can be seen from a given observation location (Section 2.2). For generating a Mastcam image viewshed, the information to ingest into the ArcGIS® Viewshed tool is:

- The input rater, that corresponds to the Gale crater DEM (Section 2.2), to provide both the elevation of rover location from where a given Mastcam image was taken, and the topography of the surrounding terrains.
- The point observer feature, that here corresponds to a shapefile comprising the Mastcam image properties extracted and calculated in step 2.2.: the rover coordinates from where

the Mastcam image was collected as well as the values for the following Viewshed tool build-in items *[ArcGIS® "Using Viewshed and Observer Points for visibility analysis"]*:

- OFFSETA: indicates the "vertical distance in surface units to be added to the z-value of the observation point". Here it corresponds to the height of the Mastcam instrument with respect to the Mars ground, i.e. 1.97 meters *[Bell et al., 2017]*.
- VERT1 and VERT2 that define the vertical angle limits to the scan.
- AZIMUTH1 and AZIMUTH2 that define the horizontal angle limits to the scan.

3.1 Create an excel table with the viewshed items corresponding to the Mastcam image:
The table should include 7 columns (latitude, longitude, OFFSETA, AZIMUT1, AZIMUT2, VERT1 and VERT2) and 2 rows (the first one with the names of the items, the second with the corresponding values of these items). The names of the items should be kept as is: they are parameters used by the tool. Save the table in format .xls Excel2003.

3.2 Load the excel table into ArcGIS® and convert into shapefile
Go to: **File/Add Data/Add XY Data** and select the table. Once it is loaded, in the Table of Contents window right click on it. Click **Data/Export Data**. In the Export Data window that appears, under "Output feature class" select "Save as type" as "Shapefile". Click ok.

3.3 Apply the ArcGIS® viewshed tool:
- In the Menu Customize/Toolbars, verify that the Spatial Analyst is checked.
- Go to the menu Geoprocessing, click on ArcToolbox. Find the "Viewshed" tool, under Visibility. Or in the Search For Tools window, search for viewshed.
- Launch the Viewshed tool window:

As Input raster: select the Gale crater DEM (MSL_Gale_DEM_Mosaic_1m, ref). As Input point: select the shapefile created above. As Output raster: select a path where to store the viewshed, and name it. Click on *Environments*. Under the Workspace menu, specify the folder where data is. Under the Processing Extent extend menu, you can select "Same as display", in order to make the Viewshed tool run for the current view displayed in your ArcMap project. This is a way to accelerate the calculations.

3.4 The output will typically display the terrains "Visible" (the viewshed) in green, and in pink the terrains that are "not visible" (that are not the viewshed). The pink color can be set to "No color" in order to only left highlighted the terrains that correspond to the viewshed, while still being able to visualize the terrains surrounding: right click on the "No Visible" symbol, select "No color". Also, the transparency of the viewshed can be tuned (ArcGIS® source: https://desktop.ArcGIS®.com/en/arcmap/10.3/map/working-with-layers/how-to-set-layer-transparency.htm): right click on the "Visible" layers, go to ***Layer Properties*** and ***Set transparency***.

Examples of 4 Mastcam image viewsheds (Fig. 4B) generated for 4 Mastcam images acquired on Sol 1429 (Fig. 4A) are presented. Mastcam images 3 and 4 display terrains corresponding to outcrops tops. Their respective viewsheds show they correspond to 2 distinct buttes. Mastcam image 1 corresponds to a lower part of the butte slope, compared to the other 3 images. It corresponding viewshed indeed appears closer to the rover location at the moment the Mastcam image was acquired (blue dot). Finally, Mastcam images 2 and 3 slightly overlap (as visible in the Mastcam mosaic on Fig 1A), and this configuration is captured in the viewsheds.

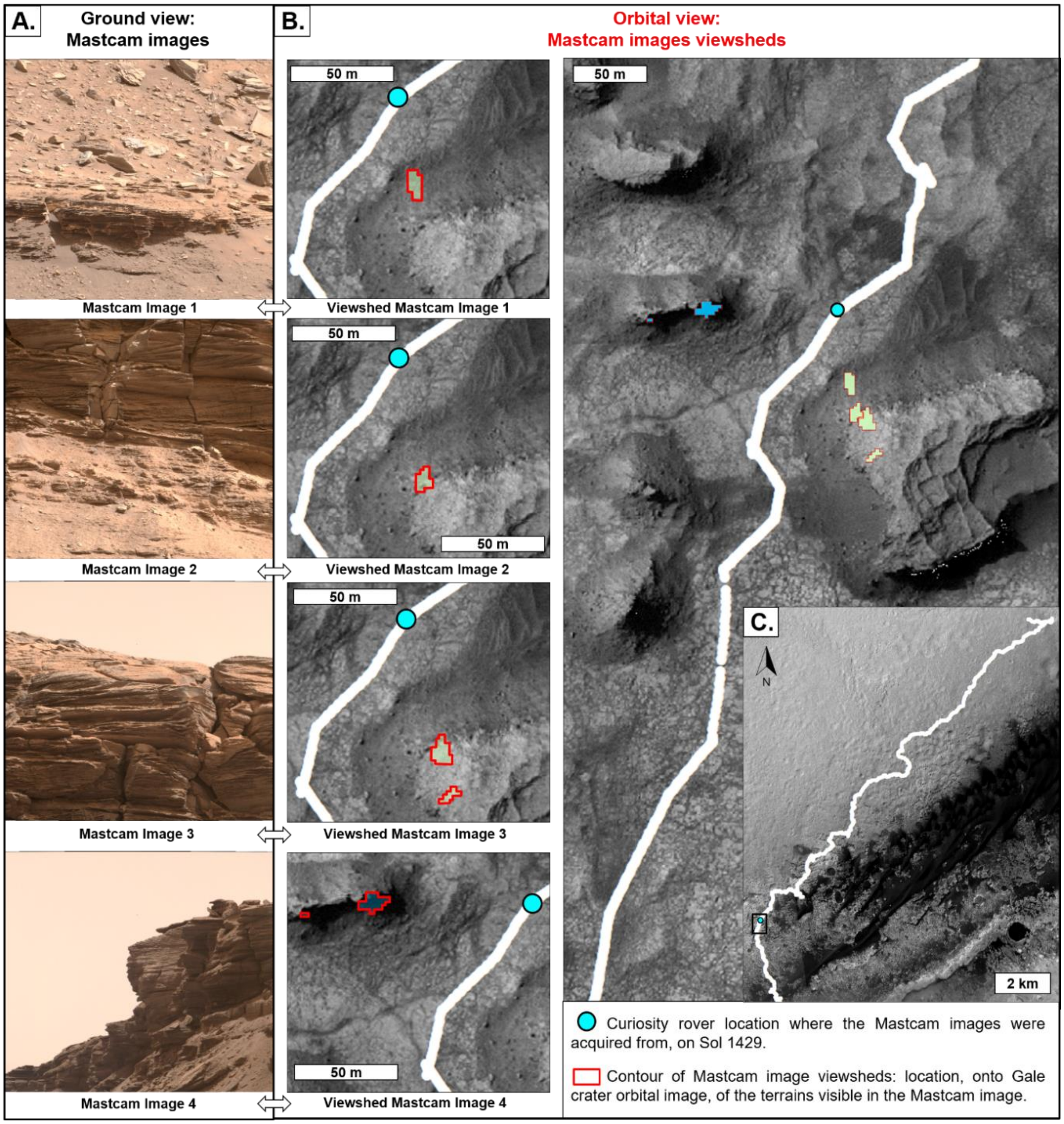

*Figure 4: Illustration of our procedure for generating Mastcam image viewsheds. **A.** Four Mastcam images, acquired on Sol 1429. **B.** Their respective viewsheds. Viewsheds 3 and 4 both correspond to two areas, because their corresponding Mastcam images 3 and 4 both display*

terrains with "false horizons": a part of the butte, distinct than the one in the foreground, is present in the images background. ***C.*** *Orbital view of the Curiosity rover's path.*

4. Conclusions and perspectives

Here is provided a procedure that for a given Mastcam image acquired with the Curiosity rover, locates on Mars orbital view the terrains that are visible in this Mastcam image. Using the ArcGIS® software (to build a GIS project and to use the build-in ArcGIS® Viewshed tool) and Mars datasets exclusively public, the procedure allows users to place the color higher-resolution Mastcam image into the spatially-broader orbital context, and thus allow coupling both the ground and orbital view of given terrains in Gale crater. This is particularly relevant for analyzing and interpreting the geological terrains along the rover's route on Mars. Because this procedure uses public datasets, it is applicable at will to both the already released Mastcam images available online and to the upcoming ones, as Curiosity rover keeps being driven on Mars. In addition, this procedure can be practical material for a pedagogic GIS project in Geosciences or Planetary Sciences, to handle Mars data both orbital and from the Curiosity rover. Perspectives include automation of this procedure, in order to automatically generate multiple Mastcam image viewsheds.

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