Panagiotis Sidiropoulos

Introduction to Auto Co-Registration & Orthorectification (ACRO)

RPIF-3D workshop supported by Europlanets & FP7 i-Mars project

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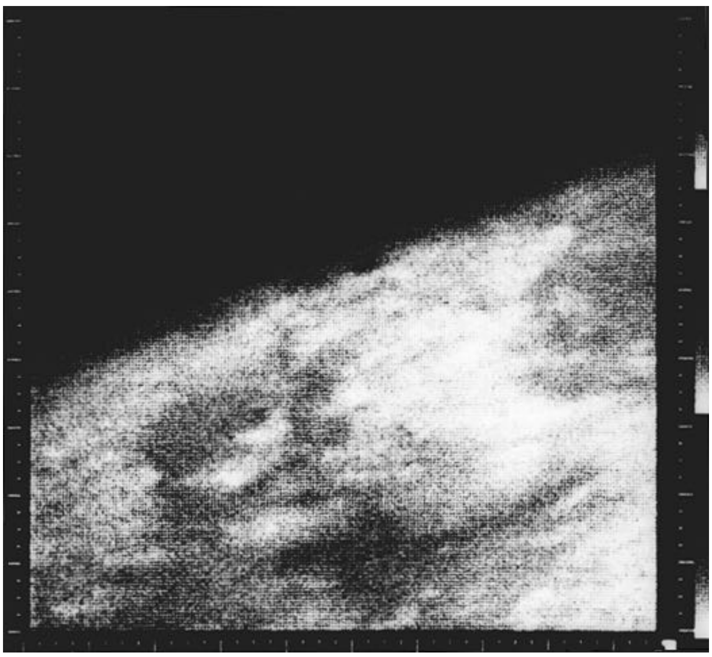
First Mars fly-by image: Mariner 4, Elysium Planitia (Res: 5km/pix.)



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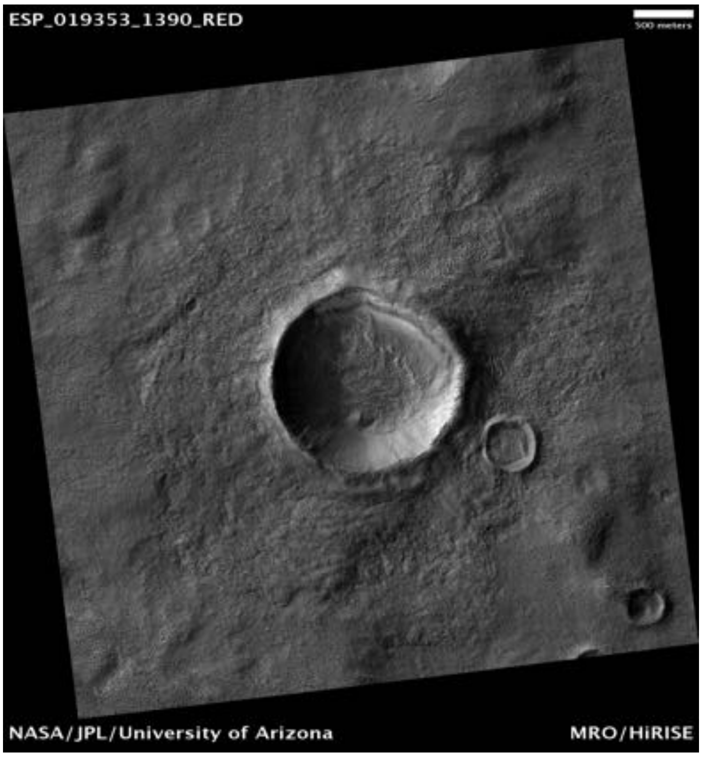
One of the latest orbiter high-resolution images (Res: 0.25cm/pix.)



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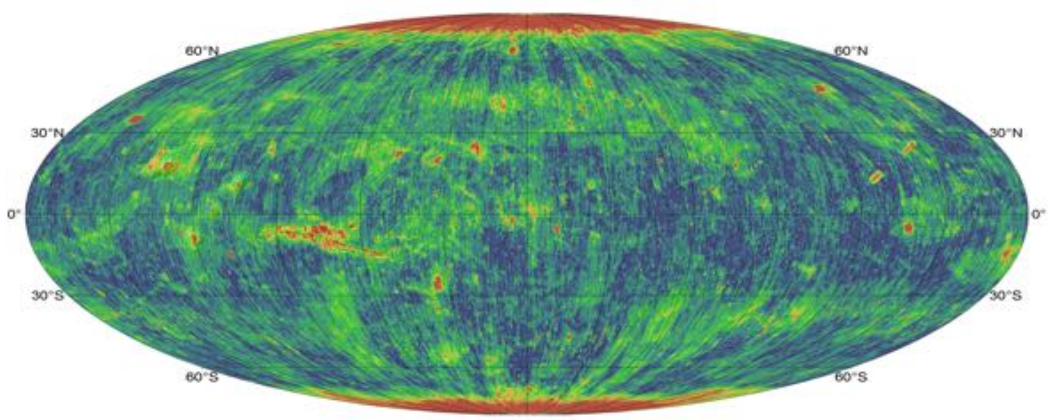
In the meantime… (Mars coverage with high-resolution images)



Martian Surface Coverage, Res<100m, MY12-31 (1976-2013)

Greyscale shaded map: NASA/MOLA science team

Repeat
High : >19
Low : 1

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Mars Orbiters with high-resolution visible cameras

Spacecraft	Launch date	Start operations	Finish	Camera instruments
Viking Orbiter (NASA)	20-Aug-75	22-Jun-76	17-Aug-80	VIS (8m-1km)
Mars Global Surveyor (NASA)	7-Nov-96	11-Sep-97	5-Nov-06	MOC-NA (1.5m-12m)
2001 Mars Odyssey (NASA)	7-Apr-01	24-Oct-01	N/A	THEMIS-VIS (17m-75m)
Mars Express (ESA)	2-Jun-03	25-Dec-03	N/A	HRSC (11m-100m)
Mars Reconnaissance Orbiter (NASA)	12-Aug-05	10-Mar-06	N/A	CTX (5-6m),HIRISE (0.25m-0.5m)
Mars Orbiter Mission (ISRO)	5-Nov-13	24-Sep-14	N/A	MCC (19.5m -4km)
Trace Gas Orbiter (ESA)	14-Mar-16	N/A	N/A	CASSIS (4.5m)

High-resolution imagery data characteristics

- Almost 500,000 images with resolution finer than 100m/pixel
  - (0 in 1970) ~10K in 1980
  - ~10K in 1990
  - ~50K in 2000
  - ~300K in 2010
- Raw data volume: ~150Tb, adding ~25Tb per year
  - Only the (1) orbiter (2) high-resolution (3) visible spectrum image data
  - Until 2014,each Mars region was mapped on average 5.5 times
    - Res < 100m/pix.
- Images coming from very different instruments
  - Different technology (from the 70s until now)
  - Distinct point spread functions
  - Different type of cameras
- Each image to its own coordinate system!

Basic Definitions (1): Co-registration & Orthorectification

- Image Geocoding: The projection of an image onto a datum of known geometric coordinates
- Image Co-registration: Image registration when the coordinate system comes from another geocoded image (image-to-image registration)
  – In planetary science, it is needed for terrain analysis, mosaicing, change detection, etc.
- Orthorecification: The transformation of one image to orthographic projection
  – Looking from the top, down at infinity
  – Distances on the image are analogous to real-world distances
    - Orthorectified images can be used to measure characteristics of objects
    - Real World Distance/Pixel Distance = R (image resolution)

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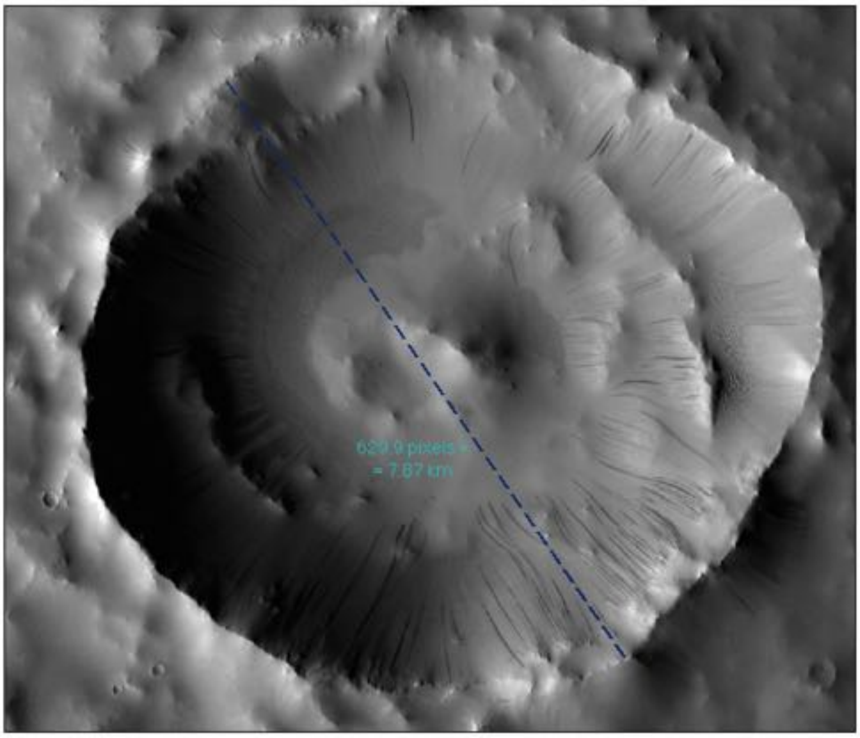
Orthorectified image example



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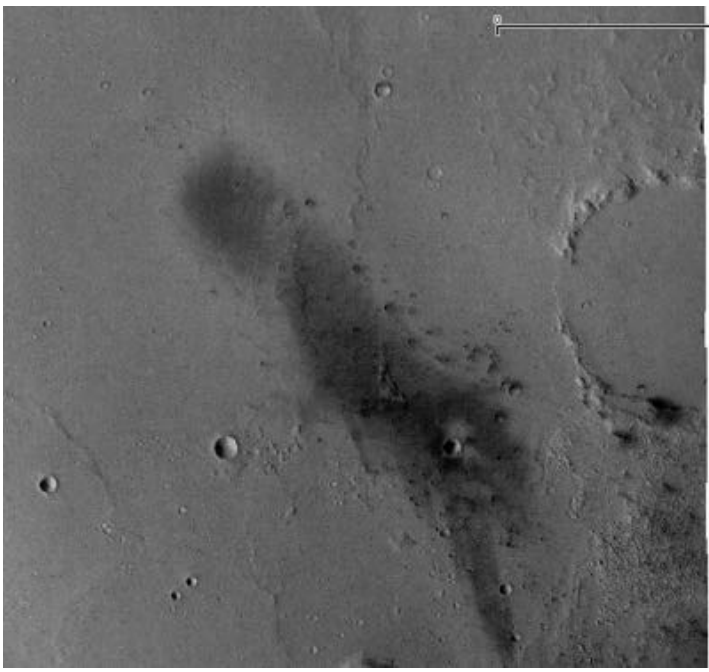
Basic Definitions (2)

- Image Resolution: The digital equivalent to an analogue map scale
  - What is the maximum detail that can be identified
  - Constant for all pixels if-f the image is orthorectified
- Digital Terrain Model (DTM) or Digital Elevation Model (DEM)
  - A grey-scale where the value of each pixel corresponds to the height of the mapped region
  - Horizontal Resolution: grid-spacing of the DTM (as in a “normal” image)
  - Vertical Resolution: Measurement precision of the heights
- Input image or Target Image or Level-1 Image
  - The input image that we want to co-register

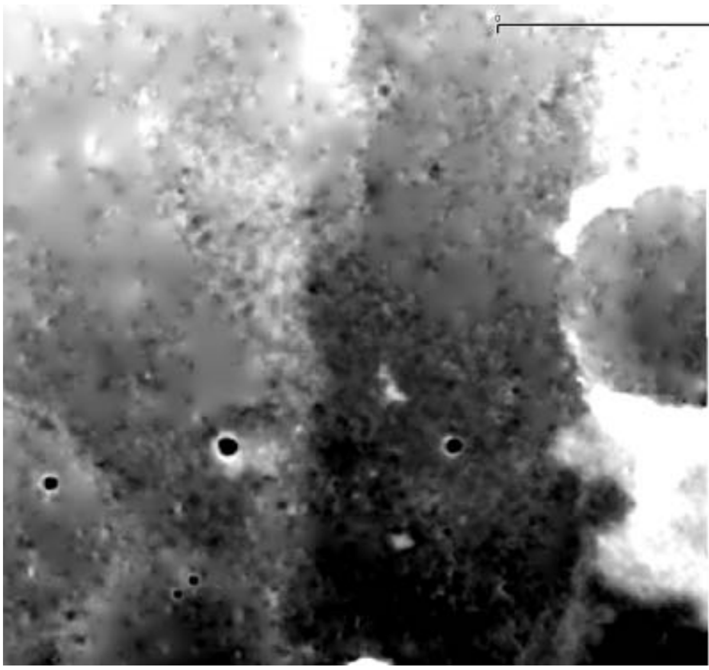
DTM Example (MER-A Landing Site): Nadir Image

HRSC orthorectified
image: H4165_0000_ND4
Date: 3-Apr-2007



DTM Example (MER-A Landing Site): DTM

Corresponding HRSC DTM:
H4165_0000_DT4
Date: 3-Apr-2007



Co-registration-Orthorectification

- Theoretically, co-registration and orthorectification are two distinct tasks
- If co-registration uses as a baseline an orthorectified image (nadir image), then we achieve both co-registration and orthorectification at the same time
- A pair of Nadir-DTM gives 3D coordinates of each image pixel
  - X,Y from the nadir image
  - Z from the DTM
- ESA's HRSC is the only stereo camera around Mars
  - HRSC nadir -> 12.5 m/pix. resolution, DTM -> 50 m/pix. resolution
  - HRSC DTMs available for ~50% of Mars
  - In this case study, we use HRSC as a baseline
    - It is not a systematic requirement

Why orbital data are not co-registered from scratch

- Actually, due to the (large) orbiter-ground distance
- Orbiter missions keep positional data for the spacecraft and for their instruments in a standardised format for planetary data
  - – SPICE kernels: Position, orientation, date, etc.
- **But,**
  1. Even very small inaccuracies cause substantial mis-registration errors
     - E.g. when Mapping from 250km distance (as in MRO), 1 minute of arc = 73m error
  2. Finer resolution means increase of the sensitivity to mis-registration
     - 73m = 292 HiRISE pixels, but only 12 CTX pixels
  3. As a result of solar terminator thermal shock, sporadic non-systematic noise that can reach up to several pixels
     - Jitter

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The need for automation (1)

- Original paradigm: Acquired planetary data are given to expert scientists for analysis
  - – Any data manipulation is conducted after running a pre-processing step from the same people that will analyse the data
- Current trend 1: Data acquisition and transmission capabilities have increased exponentially the amount of data
  - – Viking Orbiter acquired 40Gb of data over 4 years (1976-80)
  - – HiRISE camera since 2006 is acquiring 30Gb per day
  - – Estimation: Laser transmission technology from orbit to Earth will increase the data amount by at least an order of magnitude
- Current trend 2: Instruments are becoming more elaborate
  - – Software has become too complex, sometimes almost undecipherable
    - Scientists waste a significant amount of time in pre-processing

The need for automation (2)

- Paradigm Shift: Automatic processes to replace the tedious manual processing in all stages, leaving expert scientists to focus on the knowledge extraction

- Long-term objective: To establish the basic principles for a computer-science intermediate community that will act as a link between "mission teams" and the "scientific community"
  - Develop software that works (using Software Engineering)
    - Simple, as-automated-as-possible, fast, reliable
  - Following the latest computer-science achievements (Science)
    - Planetary datasets present a very challenging case study

- MSSL Imaging Group leads in this domain

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The need for automation (3)

1. Automated Co-Registration & Orthorectification (ACRO) software
   - 8 June 2016 11:30-12:30
2. Automated change detection from high-resolution co-registered imagery
   - 9 June 2016 10:00-11:00
3. Automatic planetary image quality assessment
   - 9 June 2016 10:00-11:00

Fundamental design principle: The developed software should require the minimum user involvement

- Automatic means that you don't need to spend hours tweaking the parameters each and every time

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Developed ACRO Software Characteristics

- Fully automatic
  - Can be used as a “black box”: the user doesn’t need to know anything about the processing chain
- Uses a hard-coded set of parameters
  - No need for parameter adjustment
- Can be used for batch-mode processing
  - CTX: 5 hours/image in a single core
  - THEMIS-VIS: 25 minutes/image in a single core
- It is independent from the baseline type
  - Can be used for co-registration of products from Mars, the Moon, Mercury, etc.
- It has a large resolution range
  - For HRSC baseline (12.5m/pix.), it has been tested on images of resolution 1-100 m/pix

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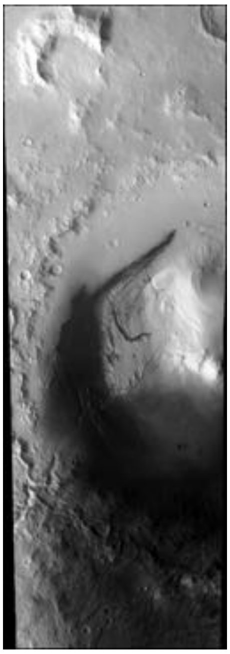
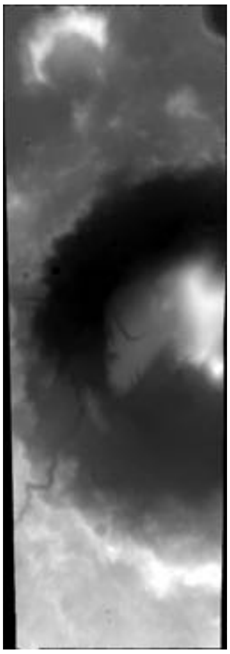
ACRO software input (Curiosity landing site)



h4235_0001_ND4
(HRSC nadir)



h4235_0001_DT4
(HRSC DTM)

P06_003453_1752_XI_04S222W
(CTX input)

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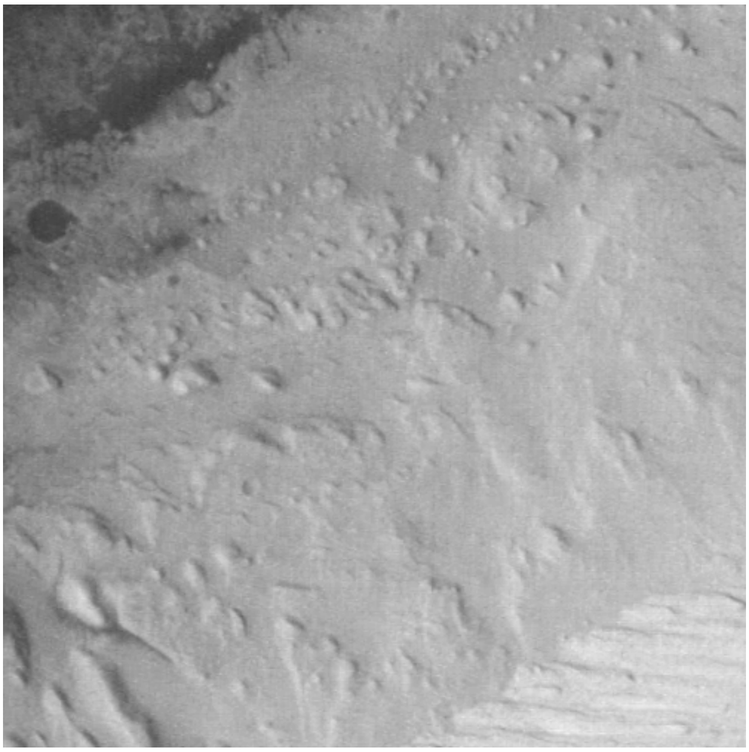
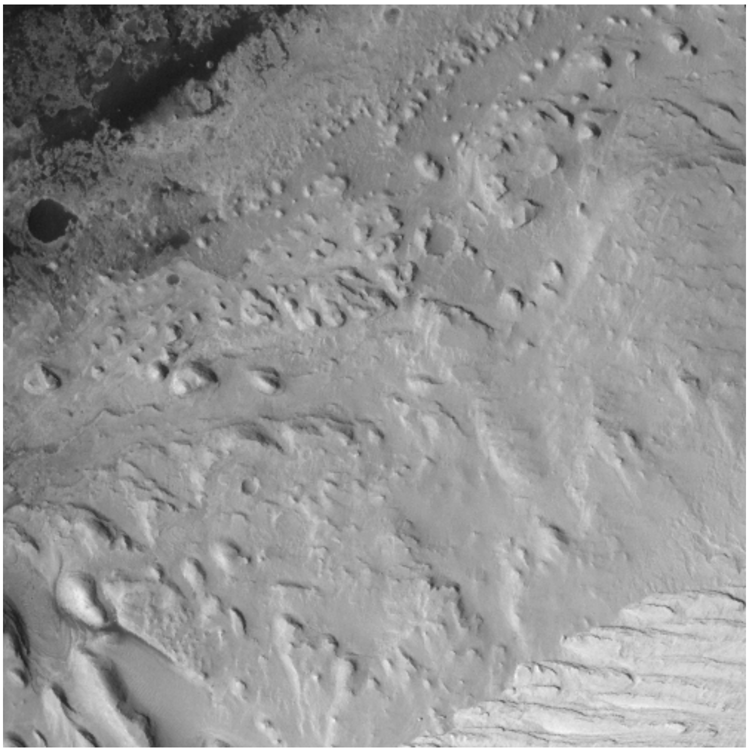
P06_003453_1752_XI_04S222W output

Corresponding h4235_0001_ND4 area

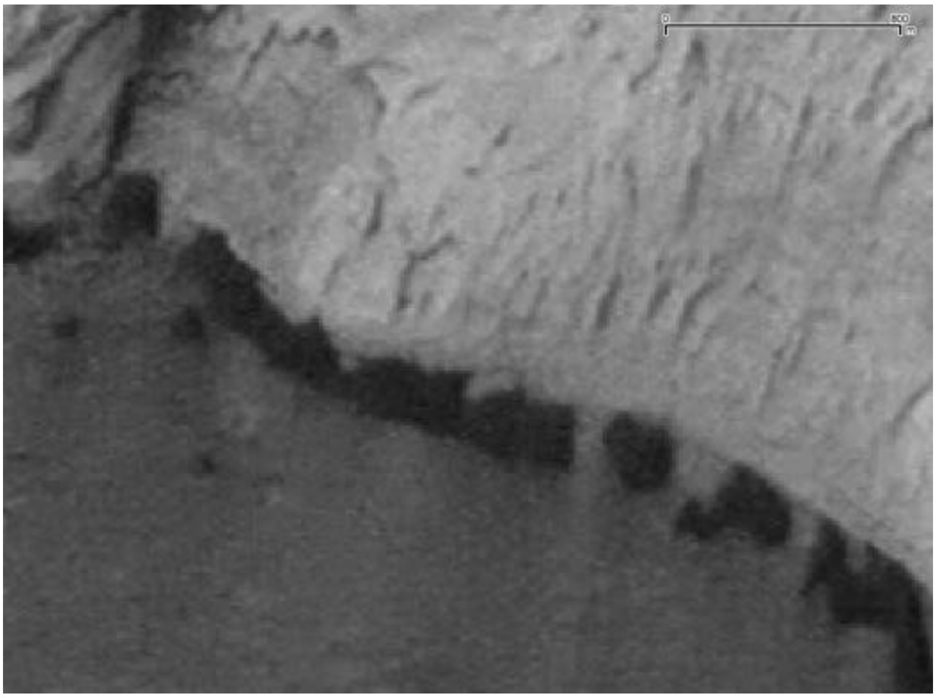
6km X 6km detail (h4235_0001_ND4)



6km X 6km detail (P06_003453_1752_XI_04S222W)



HRSC MC11-E sub-image



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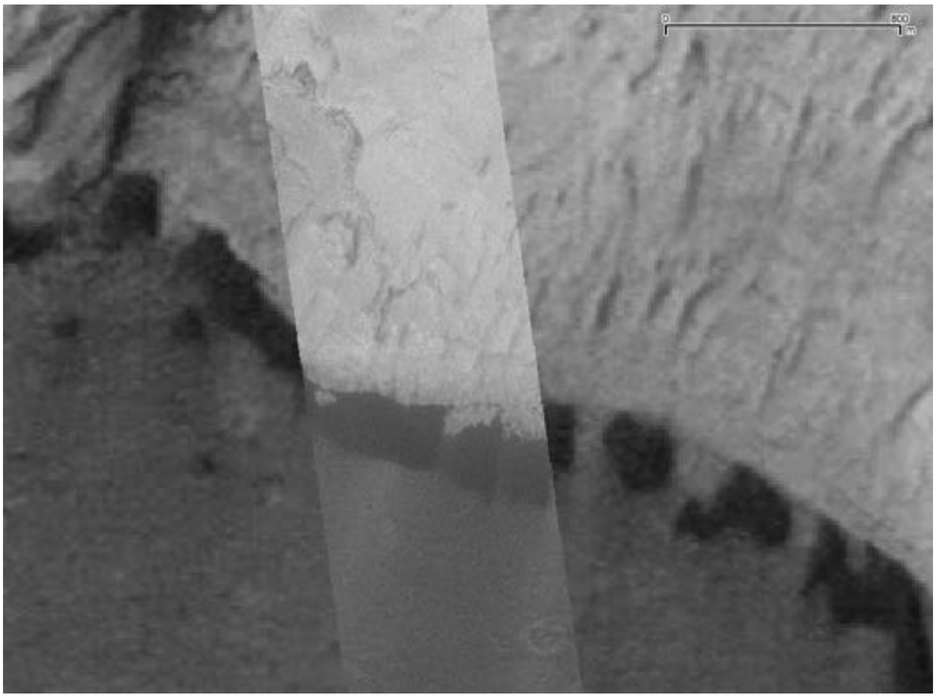
MOC-NA m0802650 not co-registered



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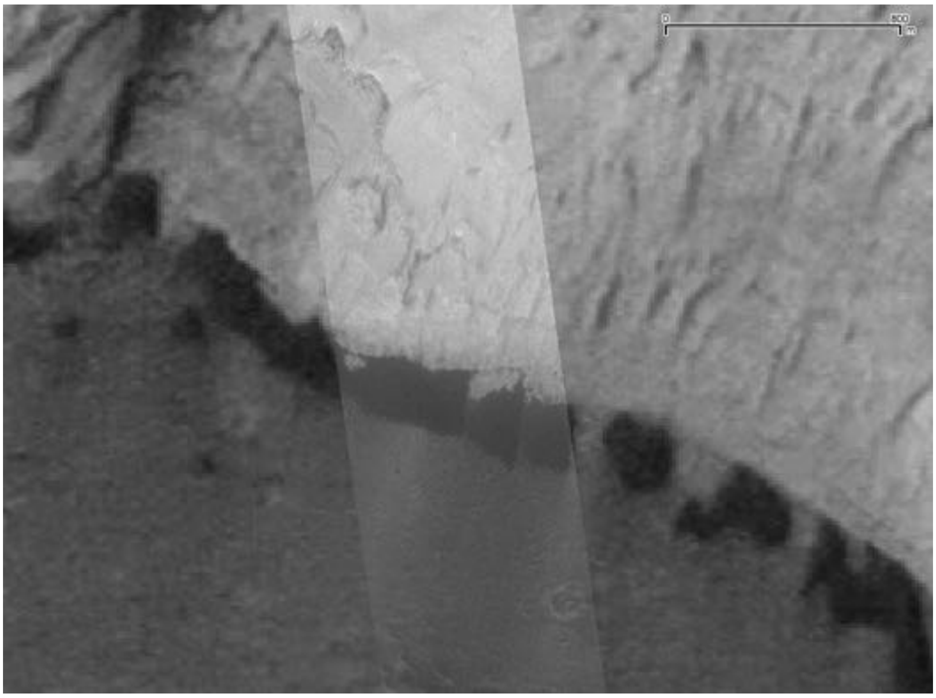
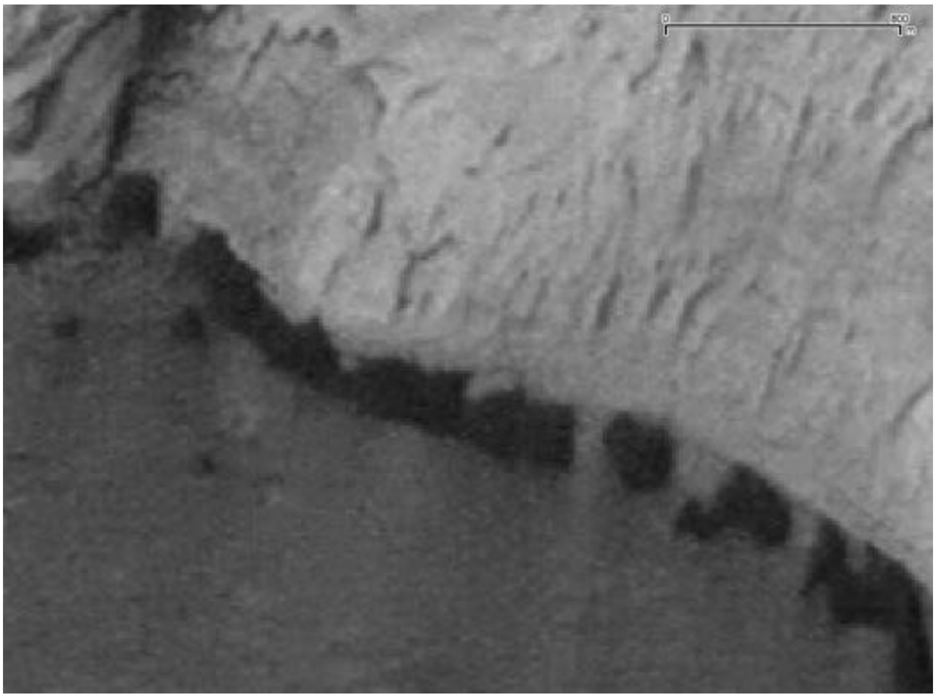
MOC-NA m0802650 co-registered



HRSC MC11-E sub-image



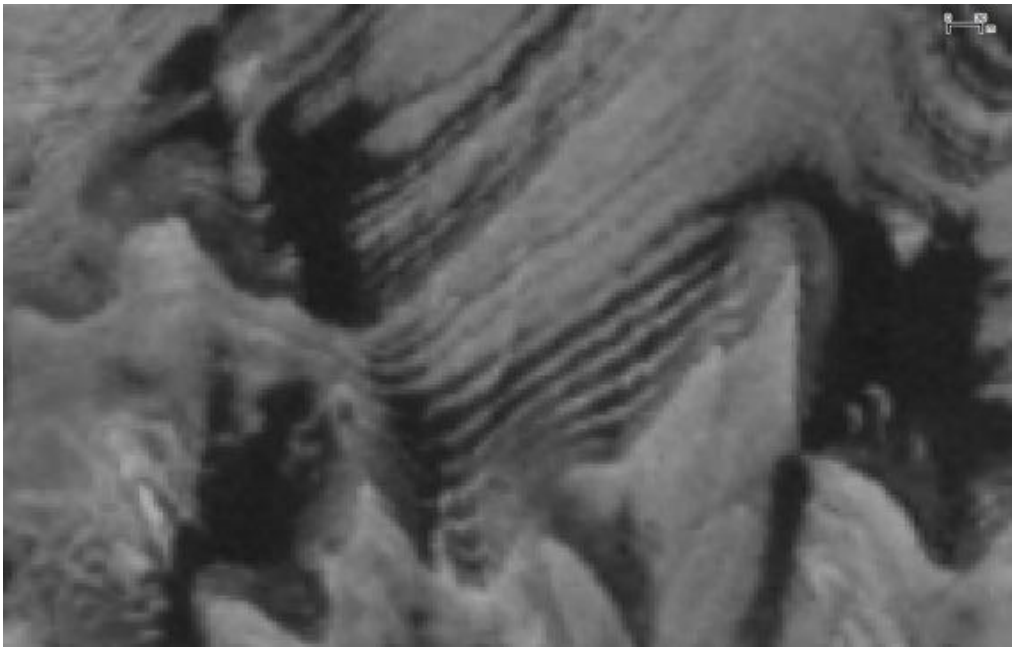
Mis-registration errors

- In the case of MOC-NA image m0802650 the distance between the before and after image is 160-170 metres
  - Manually selected 25 corresponding points in the two images
  - Resolution is 1.11m/pixel: 144-153 pixels difference
  - To make it worse, this is an average value
    - Maximum depends on the standard deviation, which is difficult to be modelled
  - After the co-registration, the average mis-registration error with HRSC is less than 6.25 metres (i.e. 0.5 HRSC pixel)
- When two images are compared, the mis-registration vectors don't coincide, so the distance may be even larger

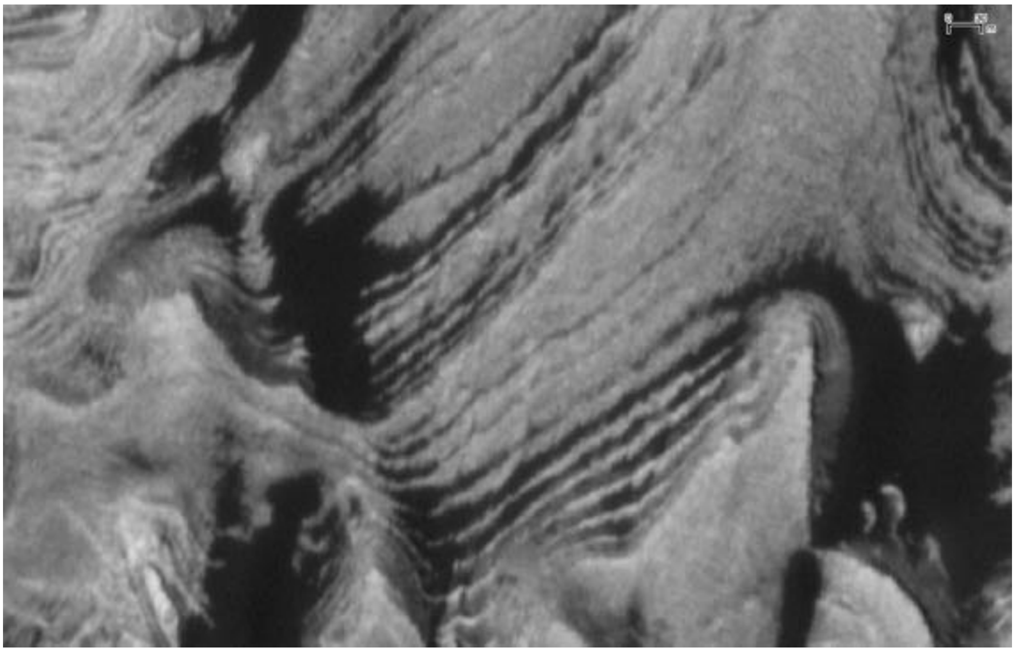
Consistency Check

- Datasets are not co-registered to each other, but what happens for images of the same instrument
  - If a team releases products that are co-registered to each other, then co-registration to HRSC is of less importance
  - Even worse, what if our co-registration pipeline increase the mis-registration error of images of the same instrument?
    - This would happen if all images of a dataset are "just" shifted by a constant value, in comparison to the baseline
- We have examined this consistency and have found that we can improve it by an order of magnitude
- Example: (1) Two map-projected MOC-NA images, released by the MOC-NA team vs (2) Our co-registered images
  - E15/00025 and M17/00387
  - Beckerel crater -> Both images in i-Mars webGIS

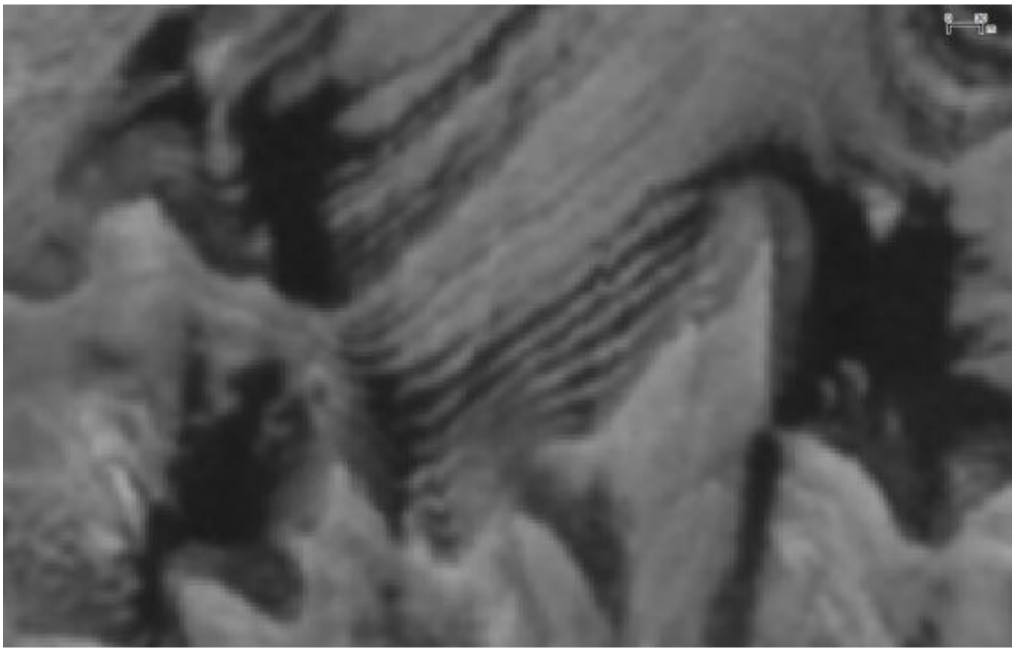
E15/00025 as released by the MOC team



M17/00387 as released by the MOC team



E15/00025 as released by UCL



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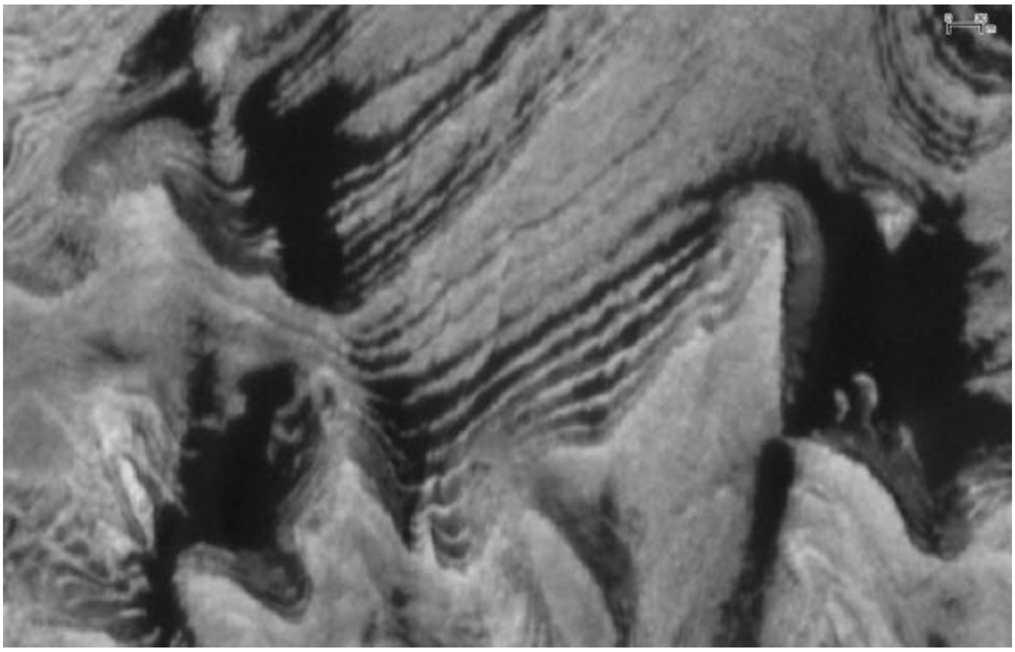
M17/00387 as released by UCL



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A little bit about the algorithm

1. Extract features from the input image and the baseline image
2. Match the features in the two images
3. Clean matches to discard outliers
   - Get point correspondences (p,q) in input image with (p’,q’) in the baseline image
4. Find the world coordinates (X,Y,Z) of the pixels (p’,q’)
   - Use the fact that (1) (p’,q’) belong to an orthorectified image and (2) correspond to DTM pixels, from which we can estimate the height
5. Use the correspondences (p,q) <-> (X,Y,Z) to build a rigid camera model for the input image
6. Orthorectify the input image and estimate systematic residuals
7. Suppress the systematic residuals and produce the final, ACRO’d image

A little bit about the algorithm – Novel Features

1. Extract features from the input image and the baseline image
2. Match the features in the two images
3. Clean matches to discard outliers
   - Get point correspondences (p,q) in input image with (p’,q’) in the baseline image
4. Find the world coordinates (X,Y,Z) of the pixels (p’,q’)
   - Use the fact that (1) (p’,q’) belong to an orthorectified image and (2) correspond to DTM pixels, from which we can estimate the height
5. Use the correspondences (p,q) <-> (X,Y,Z) to build a rigid camera model for the input image
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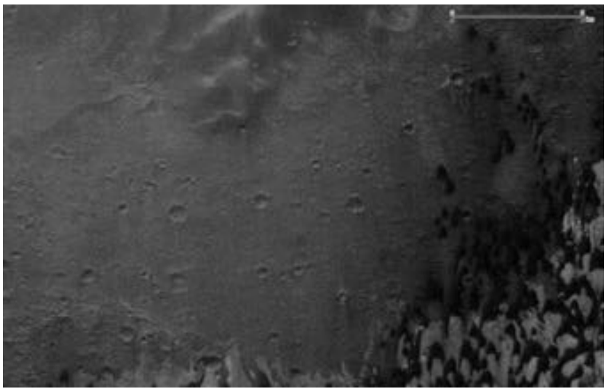
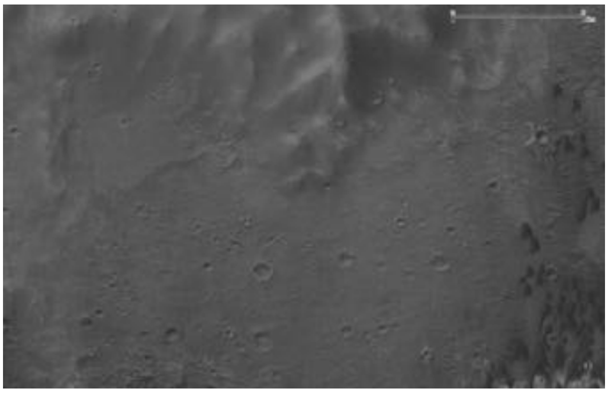
Manual matching -> Look for common features

HRSC MC11-E mosaic



CTX P01_1546_2016



Automatic Image Matching (1)

1. Extract features
2. Compare the features between the images and find common features
   – Their coordinates determine the image-pair tie-points
3. Build a feature structure to clean the tie-points dataset

- First Issue: Which features?
  - State-of-the-art features: SIFT (Scale Invariant Feature Transform) points
  - Feature based on the human visual system
  - Robust (but not invariant, due to aliasing) to scaling, robust to mild rotations, invariant to translation, noise robust
  - SIFT was not designed for planetary images, and it is not perfect when applied to planetary images
    - A lot of errors, both outliers and missed matches

Automatic Image Matching (2)

- Second Issue: How to match SIFT points between two images
- Simple strategy:
  - For each SIFT point with coordinates (p,q) in the input image:
    1. Compare it to all the SIFT points (p',q') of the baseline image
    2. Find the two nearest points and estimate the distance to them, d_1 and d_2
    3. Estimate the ratio (d_2/d_1) and compare it to a threshold T
    4. If $(d_2/d_1) > T$ then declare a match between (p,q) and its nearest neighbour in the baseline image
- This strategy was <u>not</u> designed for planetary images
  - Comparison with all the points of the baseline image makes the technique to slow
  - Comparison with all the points of the baseline image increase the false negatives (missed matches)
  - T is not easy to be optimally selected

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Automatic Image Matching (3)

- Second Issue: How to match SIFT points between two images
- Coupled Decomposition[1]: Exploit the known geometry of the images to impose geometric (progressively tighter) constraints

[1]P. Sidiropoulos and J.-P. Muller, "Matching of large images through coupled decomposition", IEEE Transactions on Image Processing, Vol. 24, No. 7, 2124-2139

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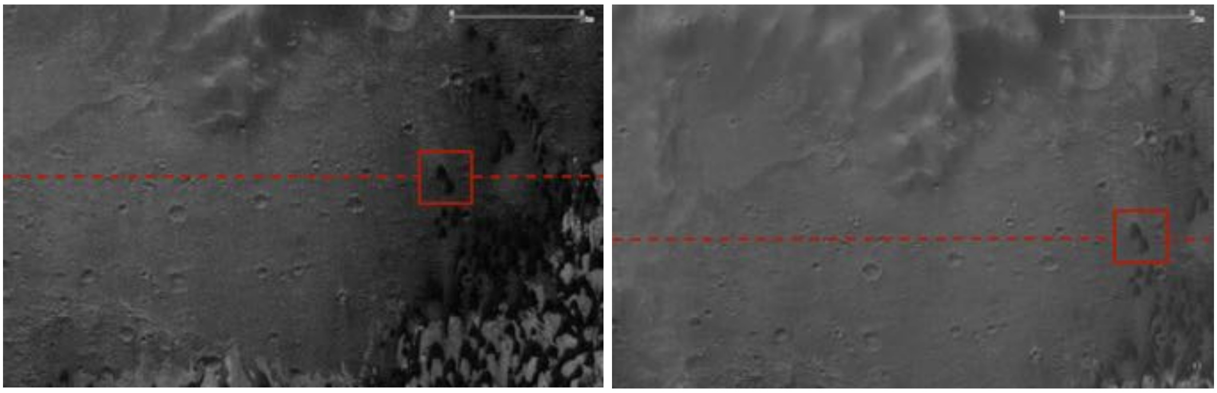
Automatic Image Matching (3)

- Second Issue: How to match SIFT points between two images
- Coupled Decomposition[1]: Exploit the known geometry of the images to impose geometric (progressively tighter) constraints



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Automatic Image Matching (4)

- Through coupled decomposition we decompose both images to an adaptive grid
  - Points are compared only to points of the other image that belong to the corresponding cell
- What is achieved through coupled decomposition
  - Faster matching
  - Less false negatives (more tie-points)
  - Less false positives (less outliers)
  - Less sensitivity from the threshold T
    - T is reduced as the grid becomes more dense
- Planetary images come with metadata that can be used on imposing constraints
  - E.g. North direction, image resolution, etc.

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Automatic Image Matching (5)

- Third Issue: How to discard the outliers?
- RANSAC: From a set of points, find the largest sub-set that satisfy some geometric property
- RANSAC fails when the outlier rate is very large
- Single-instrument pairs
  - Outlier rate: 50-70% (ok for RANSAC)
- Multi-instrument pairs
  - Outlier rate (without coupled decomposition): >95% (RANSAC fails most of the times)
  - With coupled decomposition: 60-90% (RANSAC fails 40-50% of the times)
- We have developed a RANSAC variation, tuned for planetary images
  - Outlier rate: 40-70%
  - We can match even very low quality images
  - <u>Will be published over the next few months, along with the overall method</u>

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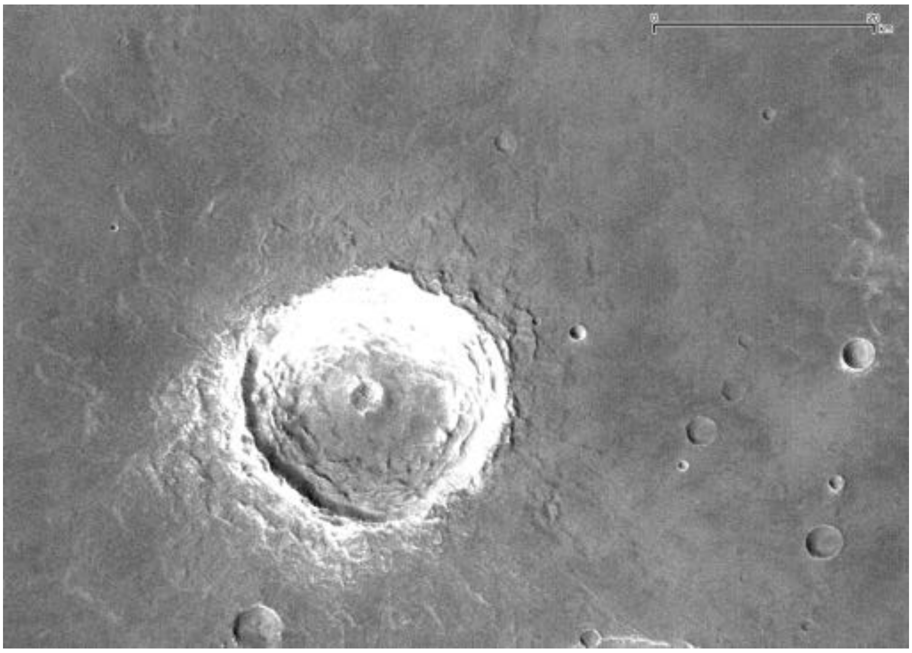
MC11-E Viking Orbiter ACRO example (MC11E mosaic)



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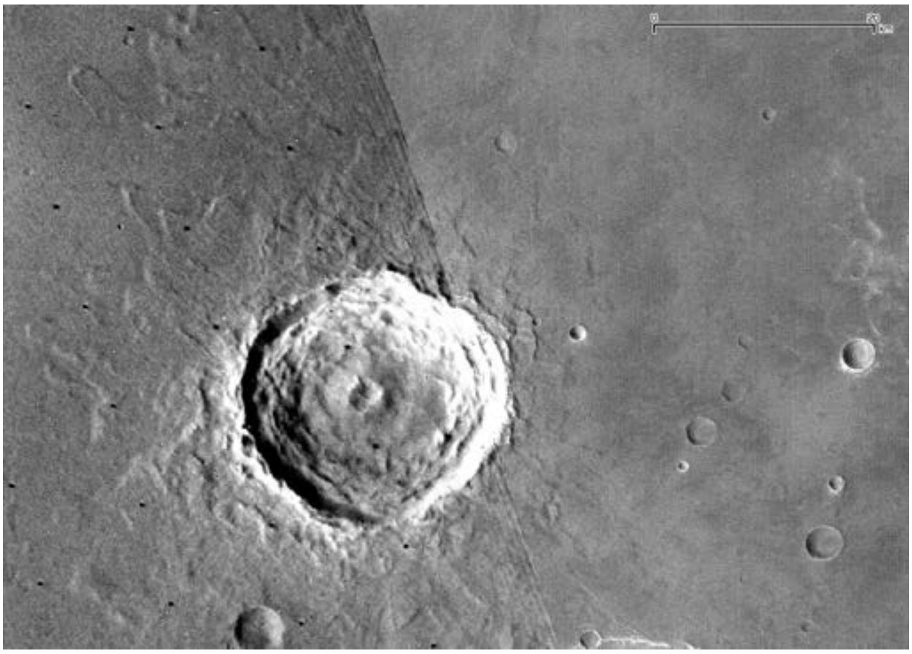
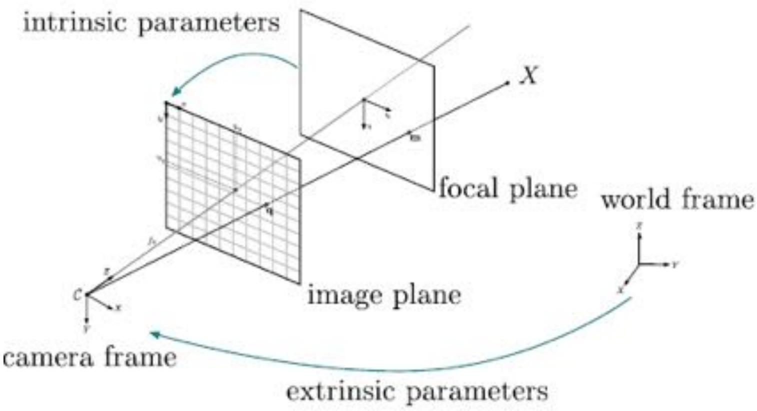
MC11-E Viking Orbiter ACRO example (f209a17 VO image)



Camera Types (1) – Pinhole (Frame) Cameras

- (Common) Frame Cameras
- 11 parameters
  - 3 position vectors of the camera, 3 rotation angles of the camera, 2 resolution values for (x,y) direction, 2 the principal point coordinates in the image (usually the centre), 1 the focal distance, i.e. the distance between the two planes



Camera Types (2) – Frame Vs. Pushbroom Cameras

- Frame cameras are ok for everyday use
  - Two-dimensional CCD that acquires one image at a time
  - Not ideal for remote sensing, let alone planetary images
    - Limited size
    - Sensitive to noise
    - Doesn't use the fact that the camera is onboard a spacecraft
- Pushbroom Cameras
  - One-dimensional CCD
  - Follows the spacecraft trajectory
  - Acquires one line at a time

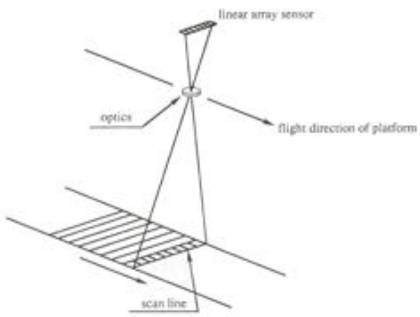


Figure 2.11.1 schematic diagram of data acquisition by push broom scanner

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Camera Types (3) – Linear Pushbroom Cameras

- Linear pushbroom camera model
  - Simplify the linear pushbroom camera
- Depends on 11 parameters
  - 3 initial position parameters of the camera
  - 3 initial rotation angles of the camera
  - 3 spacecraft velocities on (X,Y,Z) axis
  - 1 resolution on the CCD-array
  - 1 focal length distance
- At least 6 matched points to estimate the camera model
- Almost all cameras on orbiters are pushbroom cameras
  - HiRISE, CTX, THEMIS-VIS, MOC-NA, HRSC
  - Viking Orbiter is frame camera (old technology)

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Developed Software

- Main script in Matlab®
  - Matlab® can be used for both scripting and processing
  - (Matlab® stands for "matrix laboratory") Matlab® has optimised routines for matrix manipulations
    - Images are matrices
  - Matlab® has a huge number of build-in functions, routines and a large community of users that share their programmes
- C++ is used for the pipeline parts where we need speed
  - SIFT extraction
  - SIFT point matching
- ISIS is used for pre-processing, denoising, etc.

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Software

Requirements

- OS: Linux and Mac
  - Not windows, due to ISIS
- Dependencies: Matlab, C, ISIS

Processing Steps

1. Open a Matlab session
2. Define 4 paths
   1. The path of the image to be co-registered (inpath)
   2. The path of the nadir-DTM (should be in the same folder) (basepath)
   3. The path that ISIS is installed (isispath)
   4. The path of the parameter-file (parampath)
3. Type orthorectification(inpath, basepath, isispath, parampath) and press Enter

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Processing Statistics

- Failure Rate: 7.25% (CTX), 20.21% (THEMIS-VIS), 34.55% (MOC-NA)
  - In most of the cases failure happens due to low-quality
  - After 2 improvements RANSAC is still the most sensitive part of the algorithm (more than 90% of the failures happen there)
- Computational time: 5.5 hours/image (CTX), 25 min/image (THEMIS-VIS), 30min/image (MOC-NA)
- Mean Accuracy:
  - CTX: X -> 6.487 metres, Y -> 6.081 metres
  - MOC-NA: X -> 5.334 metres, Y -> 4.851 metres
  - THEMIS-VIS: X -> 7.012 metres, Y -> 6.849 metres

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Current Status

- The pipeline is ready and fully working, processing the imagery of MC11-E
- The processing is done by another person, who isn't familiar with the algorithm
  - Confirm that training is not needed for this task
- Next, we will co-register as much of Mars as possible
  - Apart from SPRC and MC11-W, regions haven't been prioritised yet for scientific applications
    - This is where you can play an important role through collaborations
- We will share our resulting ACRO'd products
- But, we can co-register the imagery of your interest
  - Send an email to p.sidiropoulos@ucl.ac.uk

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What we will do next

- Co-register high-resolution Mars imagery
  - If possible, all the available images
- Test the technique to infrared (THEMIS-IR) and CRISM data
- Co-register Moon data
  - LRO has hundreds of thousands of images that need to be co-registered
  - For the Moon, more than one global reference exist
- Co-register other planetary data
  - Mercury, Pluto

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Thanks

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