Training workshop
Stereo reconstruction and application to MRO dataset

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Overview

- Introduction to stereo photogrammetry
- Stereo reconstruction applied to Mars images
- Introduction to NASA Ames Stereo Pipeline (ASP)
- Introduction to Co-registered ASP with Gotcha Optimisation (CASP-GO)
- Exercises with ASP & Gotcha
- Introduction to CTX stereo products over the MC11E area

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Stereo Photogrammetry

- Epipolar Geometry
- Image Rectification
- Sparse correspondence
- Dense correspondence
- Triangulation
- Other methods: Shape from X

Epipolar Geometry

- Given a pixel in one image, we want to compute its correspondence to a pixel in the other image.
- Various techniques can be used to match pixels based on their local appearance.
- With additional information on positions and calibration data for cameras available.
- How can we exploit this information to reduce the number of potential correspondences and hence speed up the matching and increase its reliability?

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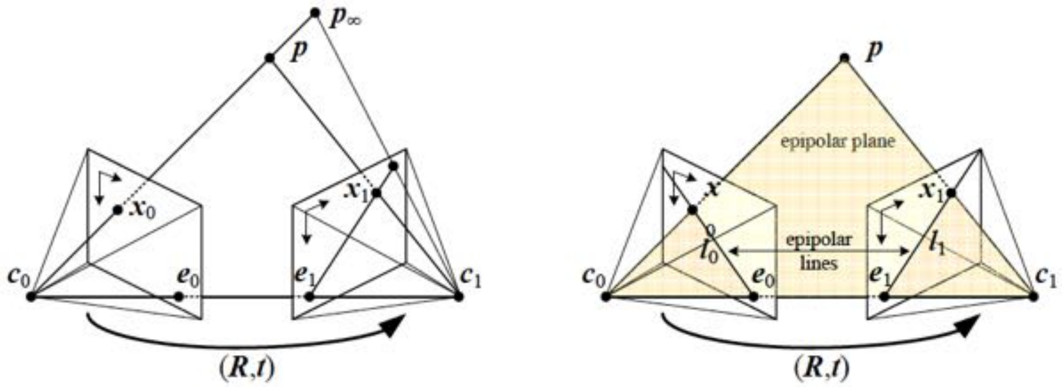
Epipolar Geometry



- Epipolar geometry: (left) epipolar line segment corresponding to one ray; (right) corresponding set of epipolar lines and their epipolar plane.

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Image Rectification

- From last slide we know that the epipolar geometry for a pair of cameras is implicit in the relative pose and calibration of the cameras and can easily be computed from seven or more point matches.
- Once this geometry has been computed, we can use the epipolar line corresponding to a pixel in one image to constrain the search for corresponding pixels in the other image.

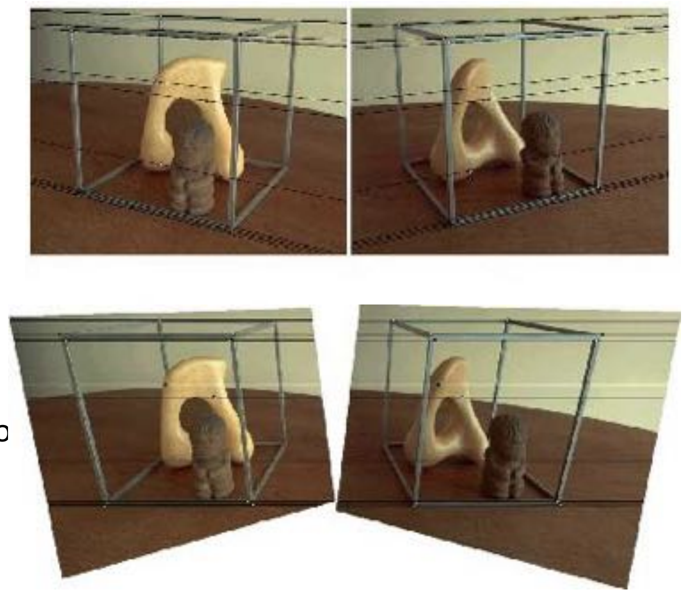

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Image Rectification

- The resulting standard rectified geometry is employed in a lot of stereo camera setups and stereo algorithms, and leads to a very simple inverse relationship between 3D depth, Z, and disparities d,

$$d = f*B/Z$$

where f is the focal length (measured in pixels), B is the baseline, and

$$x' = x + d(x, y),\ y' = y$$

- describes the relationship between corresponding pixel coordinates in the left and right images

Sparse Correspondence

- Feature-based stereo matching algorithms.
- Extract a set of potentially matchable image locations using either interest operators or edge detectors, then search for corresponding locations using a patch-based metric
- Better approaches focus on first extracting highly reliable features and then use these as seed-points to grow additional matches

Dense Correspondence

- More stereo matching algorithms today focus on dense correspondence
- Dense correspondence algorithms consist of a set of modules,
  - matching cost computation
  - Cost aggregation
  - Disparity computation and optimization
  - Disparity refinement.
- For example, SSD, normalised cross-correlation, rank transform, etc.
- Hierarchical (coarse-to-fine) algorithms
- More recently, robust measures, including truncated quadratics and *contaminated* Gaussians, have been proposed, to limit the influence of mismatches during aggregation

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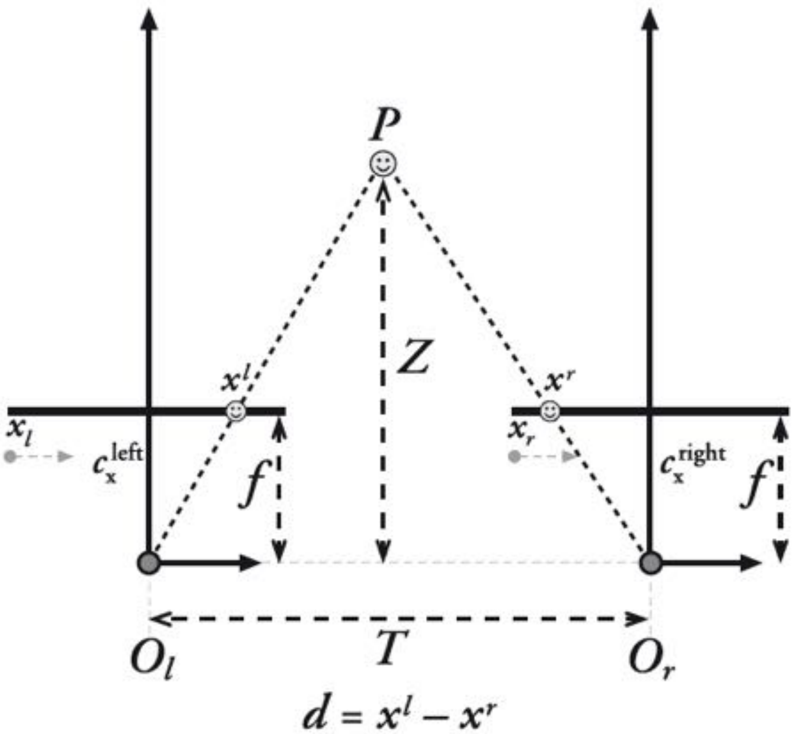
Triangulation



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Other methods: Shape from X

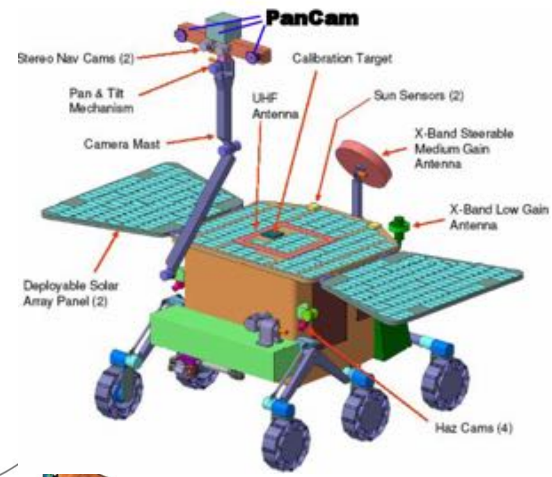
- In addition to binocular disparity, shading, texture, and focus all play a role in how we perceive depth/shape.
- Shape from shading: as the surface normal changes, the apparent brightness changes as a function of the angle between the local surface orientation and the incident illumination
- Shape from texture: algorithms require a number of processing steps, including the extraction of repeated patterns or the measurement of local frequencies in order to compute local affine deformations, and a subsequent stage to infer local surface orientation.
- Shape from focus: the amount of blur increases as the object's surface moves away from the camera's focusing distance

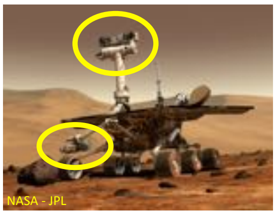
Stereo Reconstruction Applied to Mars Images

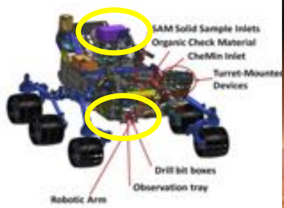
- Introduction to Mars 3D imaging data
- The difference between planetary and general stereo reconstruction methods
- DTM and orthorectified image

Introduction to Mars 3D imaging data

- Rover imagery: Pancam, Navcam, Mastcam
- Orbital imagery: MOC, HRSC, CTX, HiRISE







The difference between planetary and general stereo reconstruction methods

- Camera modelling
- Map projection
- Pre-processing (least squares bundle adjustment, normalisation, filtering)
- Area based matching
- Initial disparity estimation
- Pyramidal, tiled processing
- DTM and orthorectified image

Introduction to NASA Ames Stereo Pipeline

- Installation and documentation
- Introduction to the ASP 3D reconstruction workflow
- Processing example and parameters

Installation and documentation

- The starting place for the Ames Stereo Pipeline: http://byss.arc.nasa.gov/stereopipeline/daily_build/asp_book.pdf
- Installation:
  - Download and install USGS-ISIS: https://isis.astrogeology.usgs.gov/documents/InstallGuide/index.html
  - Set the ISIS path and start-up ISIS
  - Download NASA NGT ASP: http://ti.arc.nasa.gov/tech/asr/intelligent-robotics/ngt/stereo/

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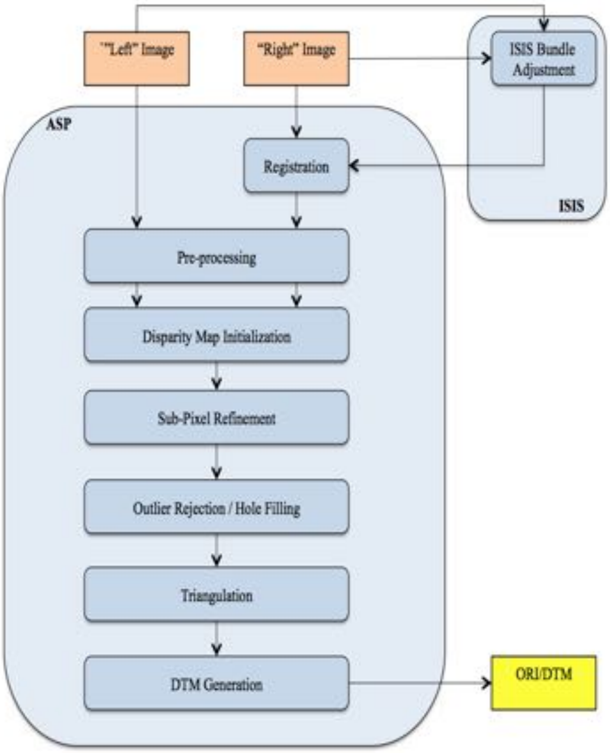
Introduction to the ASP 3D reconstruction workflow

- (a) pre-processing
- (b) disparity map initialisation
- (c) sub-pixel refinement to obtain sub-pixel correlation from the integer estimates; (d) triangulation that uses the geometric camera models stored in ISIS cub files to find the closest point of "intersection" of the two camera rays from disparity map
- (e) DTM and ORI generation.



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Processing example and parameters

- Interactive session

```
# Integer Correlation / stereo_corr
########################################################################

# Select a cost function to use for initialization:
#
# 0 - absolute difference (fast)
# 1 - squared difference  (faster .. but usually bad)
# 2 - normalized cross correlation (recommended)
cost-mode 0

# Initialization step: correlation kernel size
corr-kernel 25 25

# Initializaion step: correlation search range
#
# Uncomment the following to use explicit search ranges. Otherwise, a
# value will be choosen for you.
# corr-search -100 -100 100 100

# Subpixel Refinement / stereo_rfne
########################################################################

# Subpixel step: subpixel modes
#
# 0 - disable subpixel correlation (fastest)
# 1 - parabola fitting (draft mode - not as accurate)
# 2 - affine adaptive window, bayes EM weighting (slower, but much more accurate)
subpixel-mode 2

# Subpixel step: correlation kernel size
subpixel-kernel 25 25
```

```
# Pre-Processing / stereo_pprc
########################################################################

# Pre-alignment options
#
# Available choices are (however not all are supported by all sessions):
#    NONE       (Recommended for anything map projected)
#    EPIPOLAR   (Recommended for Pinhole Sessions)
#    HOMOGRAPHY (Recommended for ISIS and DG Sessions)
alignment-method homography

# Intensity Normalization
force-use-entire-range       # Use entire input range

# Select a preprocessing filter:
#
# 0 - None
# 1 - Subtracted Mean
# 2 - Laplacian of Gaussian (recommended)
prefilter-mode 2

# Kernel size (1-sigma) for pre-processing
#
# Recommend 1.4 px for Laplacian of Gaussian
# Recommend 25 px for Subtracted Mean
prefilter-kernel-width 1.4
```

```
# Post Filtering / stereo_fltr
########################################################################

# Fill in holes up to 100,000 pixels in size with an inpainting method
# disable-fill-holes

# Automatic "erode" low confidence pixels
rm-half-kernel 5 5
rm-min-matches 60
rm-threshold 3
rm-cleanup-passes 1

# Triangulation / stereo_tri
########################################################################

# Size max of the universe in meters and altitude off the ground.
# Setting both values to zero turns this post-processing step off.
near-universe-radius 0.0
far-universe-radius 0.0
```

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Introduction to CASP-GO

- General workflow
- Maximum likelihood sub-pixel refinement
- Outlier rejection schemes
- Gotcha (Adaptive Least Square Correlation with region growing) densification
- Co-kriging grid-point interpolation
- ORI co-registration and DTM adjustment

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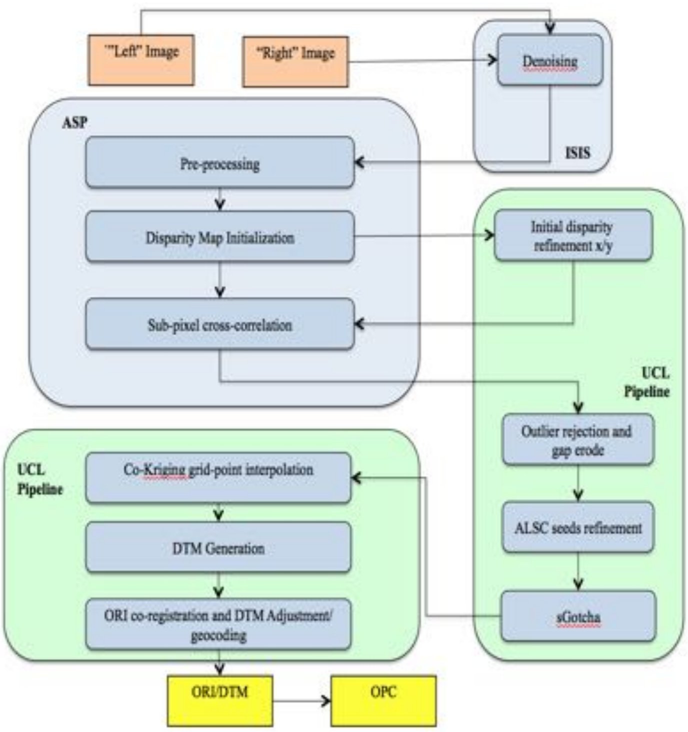
CASP-GO Workflow

- USGS-ISIS De-noising
- Pre-processing (image normalisation, LoG filtering,
  pre-alignment)
- ASP disparity map initialisation (pyramid cross-
  correlation and building a rough disparity map)
- Maximum likelihood sub-pixel refinement and building of a float initial disparity map
- ASP sub-pixel correlation
- Rejection of mis-matched disparity values and erode matching gaps
- Adaptive Least Square Correlation (ALSC) sub-pixel refinement
- Gotcha (ALSC with region growing) densification of disparity maps
- Co-kriging grid-point interpolation to generate ORI and DTM as well as height uncertainties
- ORI co-registration/geocoding with reference to HRSC orthoimage and DTM adjustment
- Generation of Object Point Cloud (OPC) at JR



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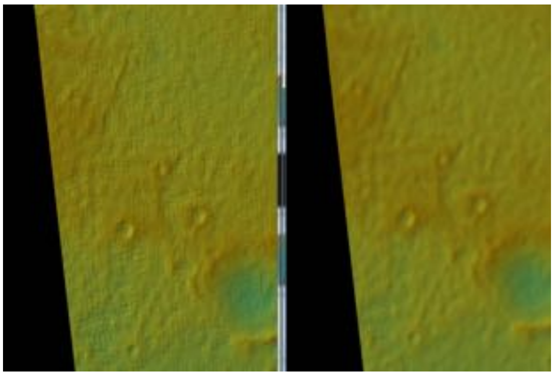
Maximum likelihood sub-pixel refinement

- Pixel locking with coarser integer disparity map – staircase artefact
- Generate integer disparity estimates at the same resolution of final sub-disparities, or generate float disparity estimates at lower resolution.
- A fast Maximum Likelihood image matcher from (*Olson, 2002*): seek for maximum likelihood estimation of template positions, i.e. the joint probability density function (PDF) for the distances.
- The joint density is modelled as the sum of the error density when an edge pixel is an inlier and probability density of the distances when the edge is an outlier.



Outlier Rejection Schemes

- Sub-pixel disparity maps obtained from the refined initial disparity map is still not perfect
- Two obvious problems are unmatched areas (no disparity available, i.e. errors of omission) and mismatched areas (wrong disparity, i.e. errors of commission).
- Matching search kernel vs. search range?
- Larger kernel + smaller search range + reject mis-matches

Outlier Rejection Schemes

- (a) disparity value differs than a threshold by a percentage of pixels in a kernel;
- (b) kernel with standard deviation higher than a threshold;
- (c) difference of the mean value of a kernel and neighbouring kernel is higher than a threshold;
- (d) kernel with a neighbouring kernel being rejected by a threshold percentage;
- (e) adjacent disparity values from (a), (b) and (c).

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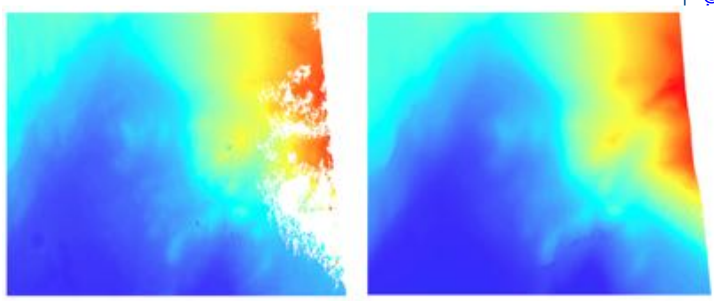
Gotcha

- (a) with given sub-pixel disparity values, retrieve seed tie-points (point correspondences) on the border (within 5-11 pixel width) according to the x and y translation (disparity);
- (b) run ALSC on seed tie-points and store similarity value;
- (c) sort seed tie-points by similarity value;
- (d) a new matching is derived from the adjacent neighbours of the initial tie-point with highest similarity value;
- (e) if the new match is verified by ALSC then it is considered as seed tie-points in next growing;
- (f) this region growing process repeats from (c) to (e) until there are no more acceptable matches;
- (g) retrieve final disparity map after densification.



ASP result CASP-GO result

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Co-kriging

- Use a weighted average, which depends on both the distance of point pairs and spatial variation, of neighbouring known elevation values to predict a missing elevation value.
- CASP-GO uses the Geostatistics Template Library (GsTL)'s co-kriging implementation
- Uncertainty estimate for each point interpolated based on the estimated quality of the data, which can be indicated from
  - ALSC similarity
  - spatial variation of the terrain
  - maximum eigenvalue of the covariance matrix that reflects uncertainty in the positioning of the matching window
  - measure of local consistency of line disparities,
  - Optional parameters of radiometric gain and shift, and skewness from the camera model
  - the actual distance between the camera rays at the closest point of intersection

ORI co-registration and DTM adjustment

- HiRISE and CTX datasets are generally not co-registered with the HRSC ORI/DTM (DLR processed v50 products) and MOLA dataset.
- The Mutual Shape Adapted Scale Invariant Feature Transform (MSA-SIFT) algorithm
- Take HRSC ORI as reference image for CTX ORI co-registration and subsequent shift of CTX DTM according to the CTX ORI to HRSC ORI transformation

Exercises with CASP-GO

- Interactive session

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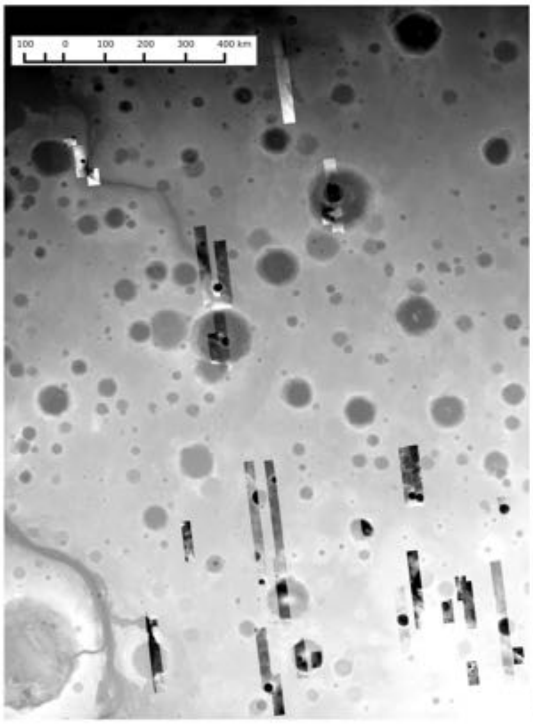
Introduction to pre-processed CTX stereo products over MC11E area



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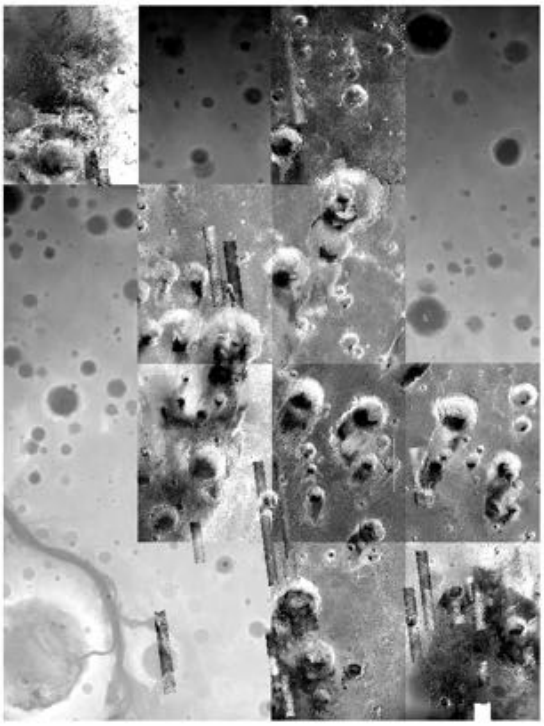

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