Meter-scale topography and slopes of the MSL landing sites from HiRISE stereogrammetry

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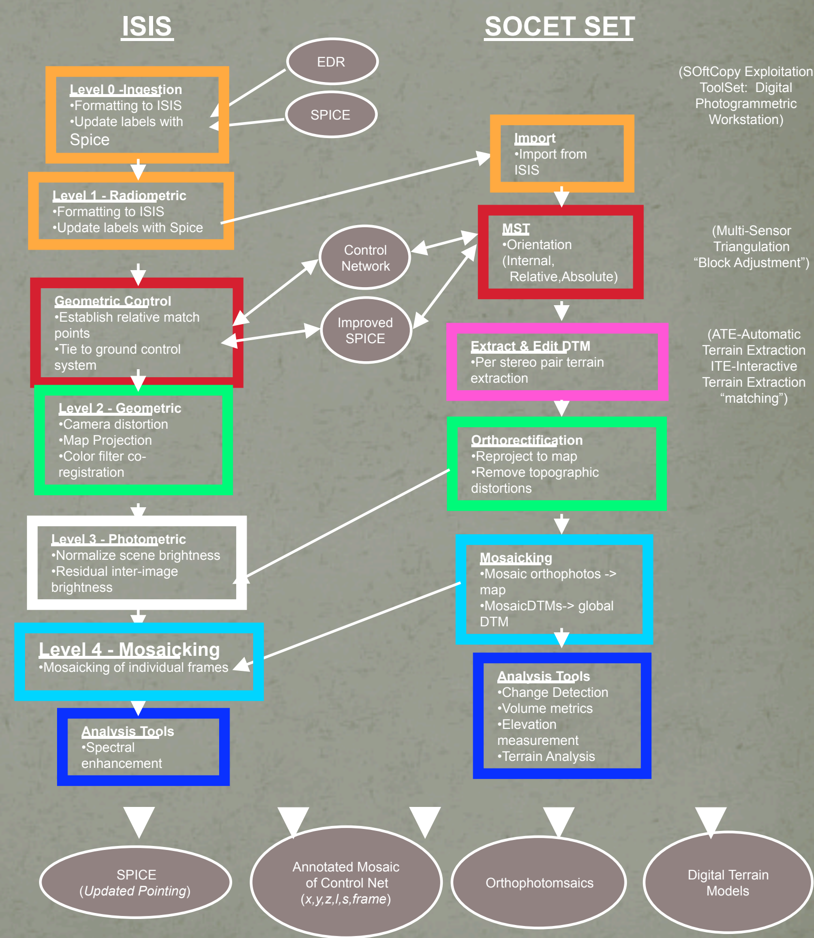
4th MSL Landing Site Workshop
Monrovia, CA 28 September 2010

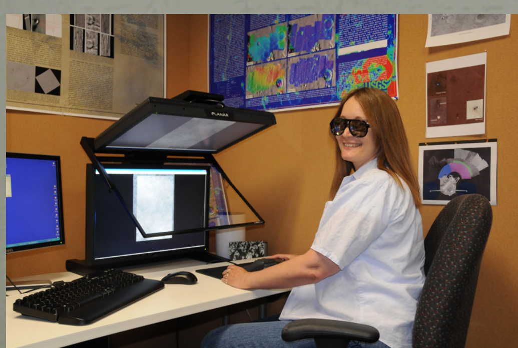
Outline

- DTM Production Methodology
- Slope Accuracy Issues
- DTMs and Slope Maps
- Slope Statistics

USGS DTM Production and Slope Accuracy Issues

- Methodology
  - Image preparation in ISIS
  - Automated stereo matching followed by manual editing in SOCET SET
- “Ordinary” matching errors
  - Vertical precision, horizontal resolution
  - Structure of errors
  - Consequences for slope errors
- Degradation of matching performance with image quality
- Jitter and its remediation



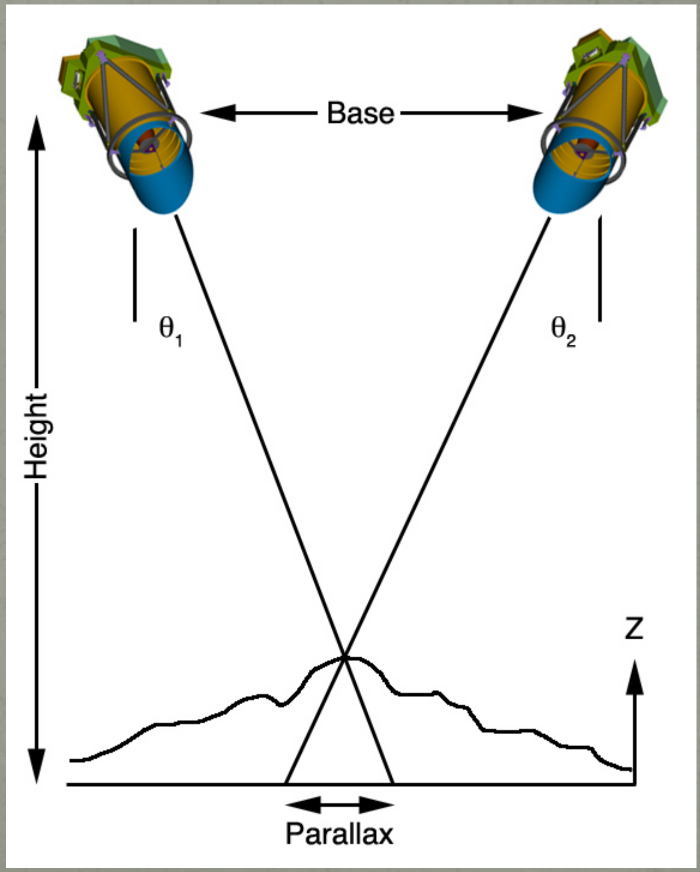


Elpitha (Annie) Howington-Kraus with our 4th generation SOCET Set digital photogrammetric workstation

Expected Vertical Precision (EP) and Horizontal Resolution of Stereo DTMs

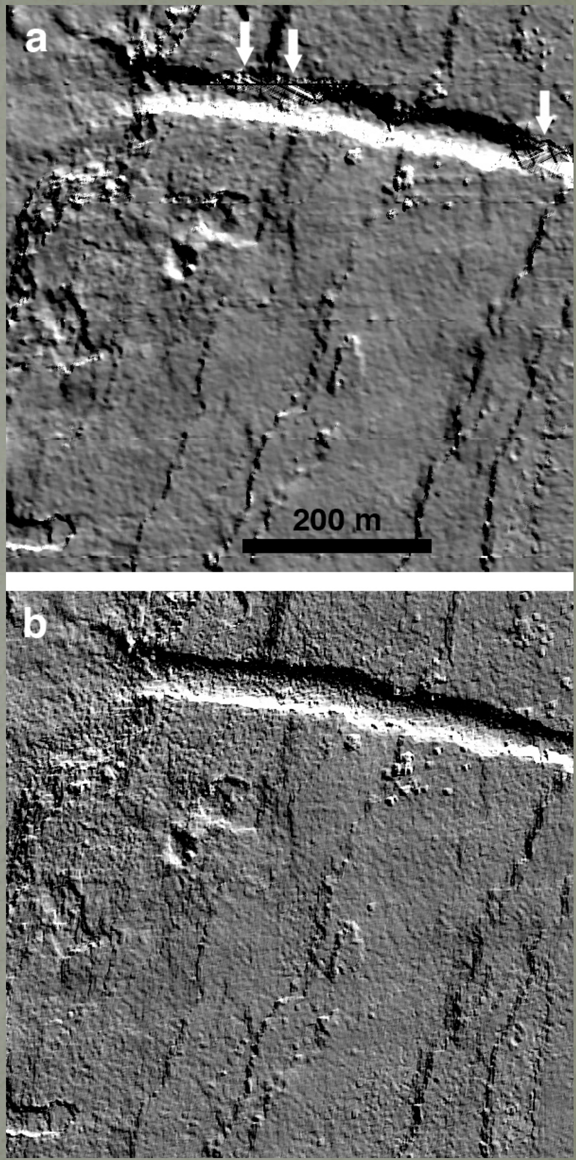
- *Vertical* precision depends on
  - Image "resolution" (GSD)
  - Base to height ratio (b/h)
  - Ability to match features—measured in pixels (ρ)
- "Rule of thumb" is ρ=0.2 pixels RMS match error
- We have evaluated for numerous datasets in numerous ways
- All results correspond to 0.2-0.3 pixel RMS error
- Horizontal resolution is no better than 3–5 pixels (minimum patch size for comparing images)
- Slopes also depend on the *structure* of the errors

EP = ρ GSD / (b/h)

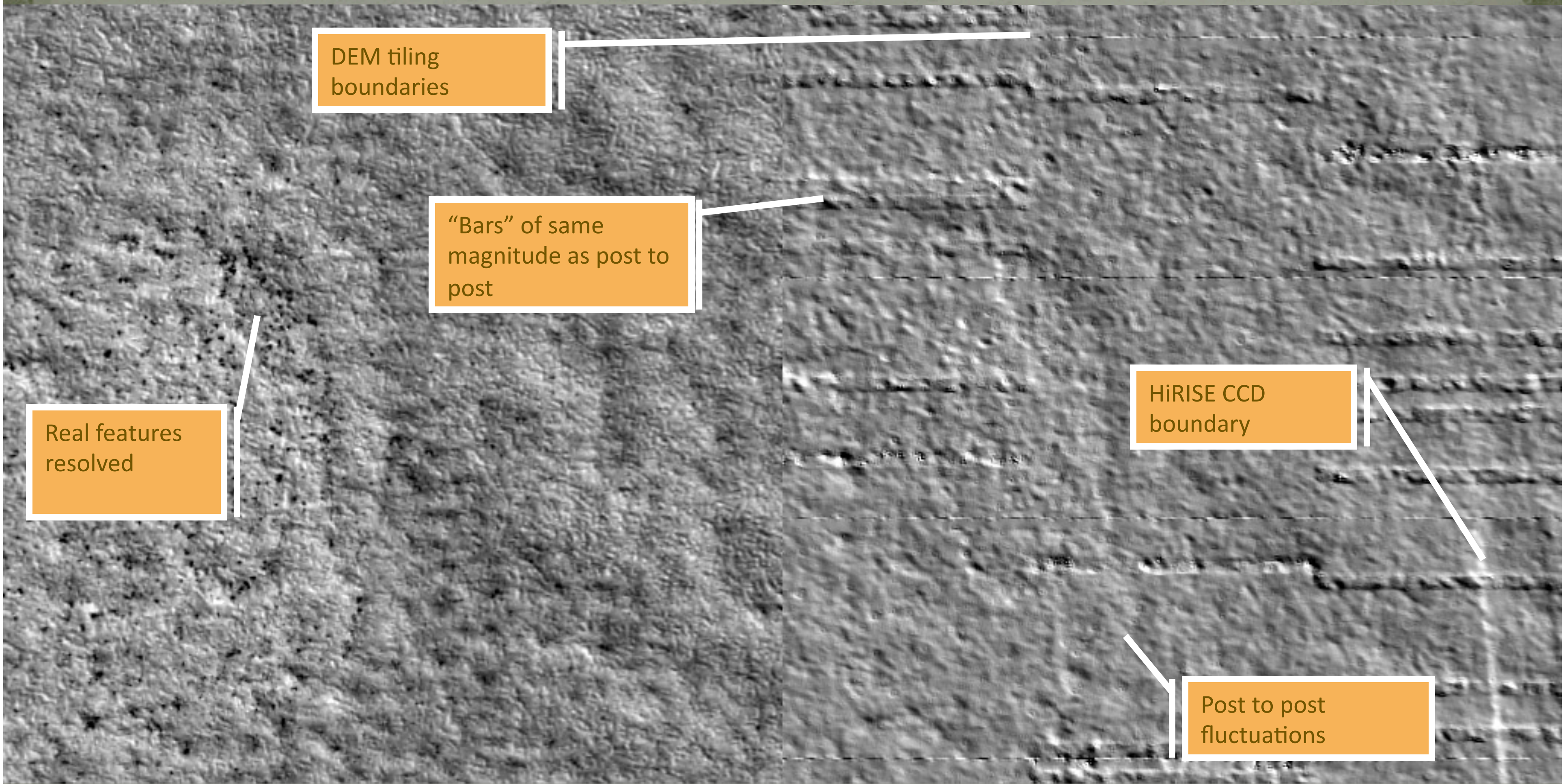


NGATE vs ATE

- ATE = Automatic Terrain Extraction (older SOCET algorithm, a)
- NGATE = Next Generation Automatic Terrain Extraction (new, b)
  - Yields higher DTM resolution from same images
  - Reduces matching errors (angular artifacts at arrows in a)
  - DTM often has "blocky" appearance
- As a result, slopes will be underestimated on tops of "blocks" and drastically overestimated on the sides
  - Latest patch has a bug fix that should reduce the blockiness, but we have not yet tested it
- Because slopes are critical to MSL, we normally make a DTM with NGATE and then perform one or two matching passes at full resolution with ATE.
  - Retains the good overall error rate of NGATE
  - Smooths the blockiness so slopes are more realistic
  - No worse than just smoothing the DTM with a filter, and probably better because ATE works by comparing the images
- Thus, for this application it's the structure and errors of the ATE algorithm that are important



ATE "Ordinary" DEM artifacts, visible here because of low relief of Phoenix landing site

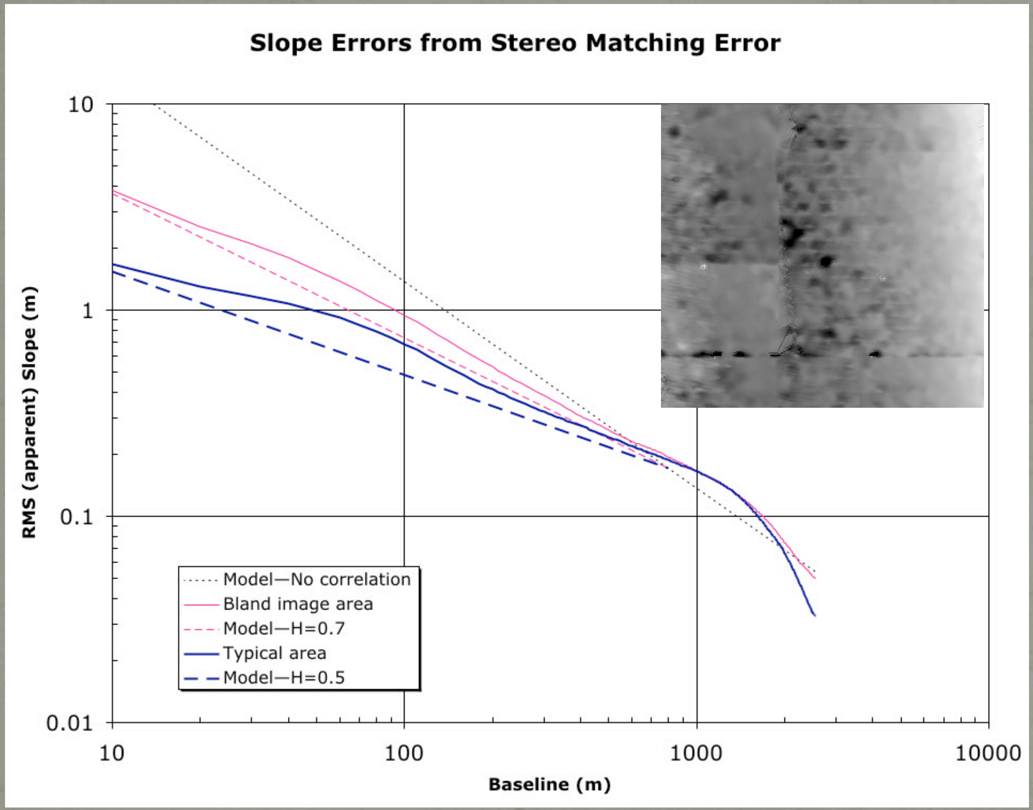


HiRISE Image of candidate Phoenix site

DEM shaded relief (same area)

Matcher Test: Slope Errors from “Ordinary” DEM Statistics

Based on matching a MOC image to itself after warping to approximate the 2nd image of a stereo pair
Any “topography” in the result reflects matching errors only

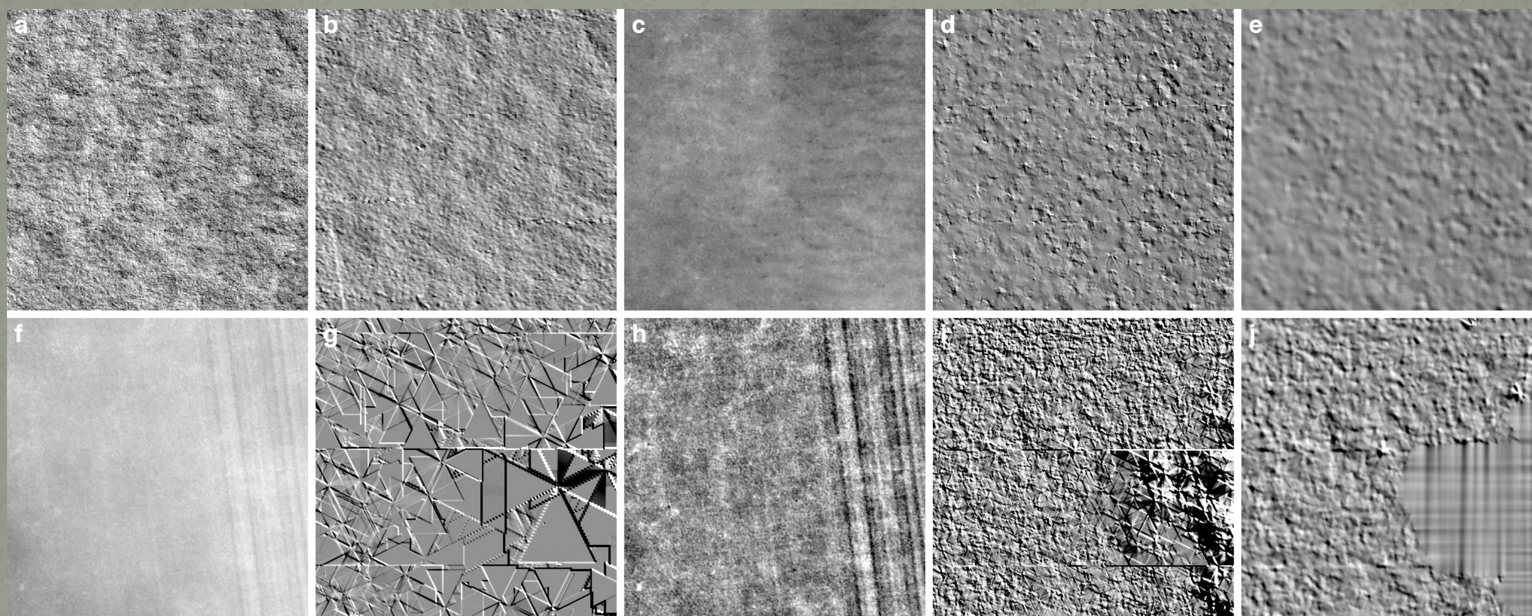


- EP for this pair = 1.6 m
- RMS “height” = 1.7 m
- Adjacent DEM posts are partly correlated
- Hurst exponent H = 0.5 for base ≤ 80 posts
- Yields RMS “slope” due to matcher errors that is 9x less than if posts were independent
- Errors are less correlated, slope errors greater in bland image areas (but these would normally be edited to smooth them)

Scaling to typical HiRISE stereopair —> Slope error ~1° at 2m baseline

Degradation of DEM with Image Quality

HiRISE Images of candidate Phoenix landing site



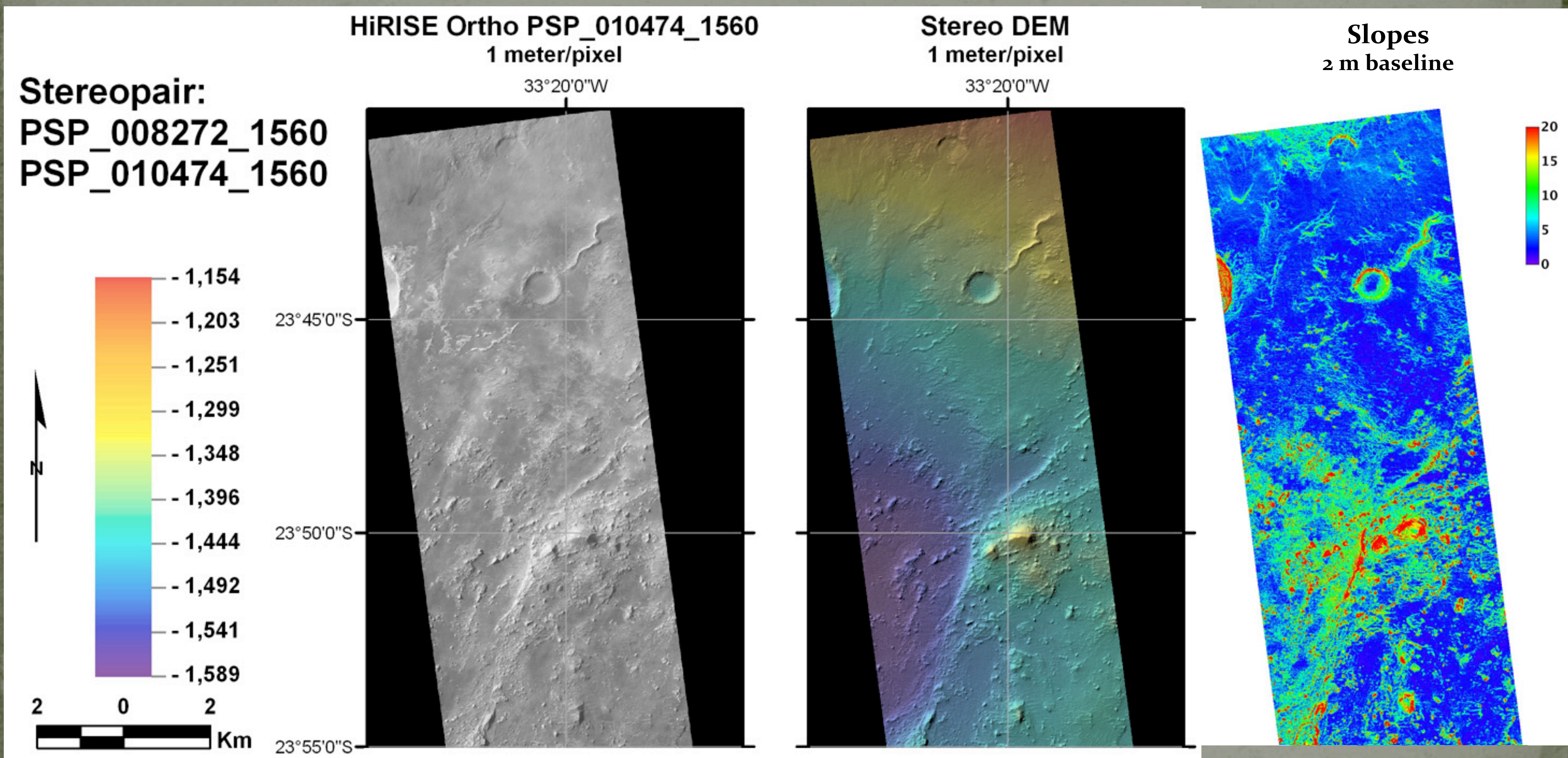
a,b: “Decent” quality image (Phoenix landing site) and DEM shaded relief

c–e: Cloudy image, DEM shade, DEM shade after smoothing

f–g: Very cloudy and noisy image, raw DEM shade with “snow angels” or “crystals”

h–j: DoG filtered image, DEM from filtered image, DEM with area editing and smoothing

Effect of Illumination and Jitter on DTM: Eberswalde W of Center

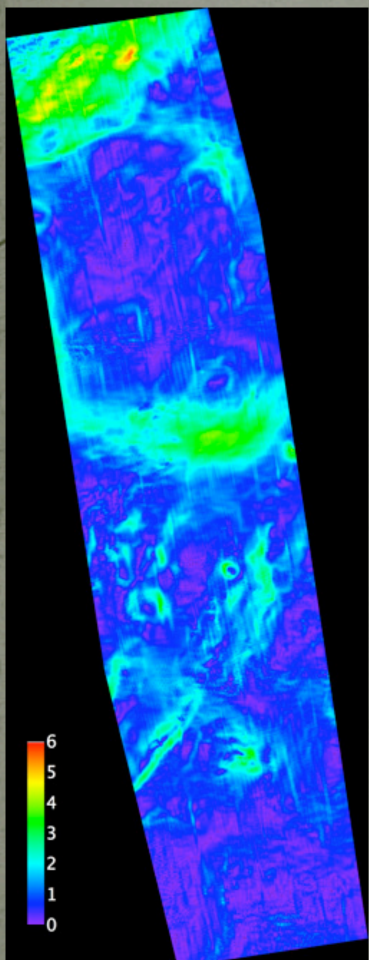


Final DTM
New images with
Better illumination, jitter

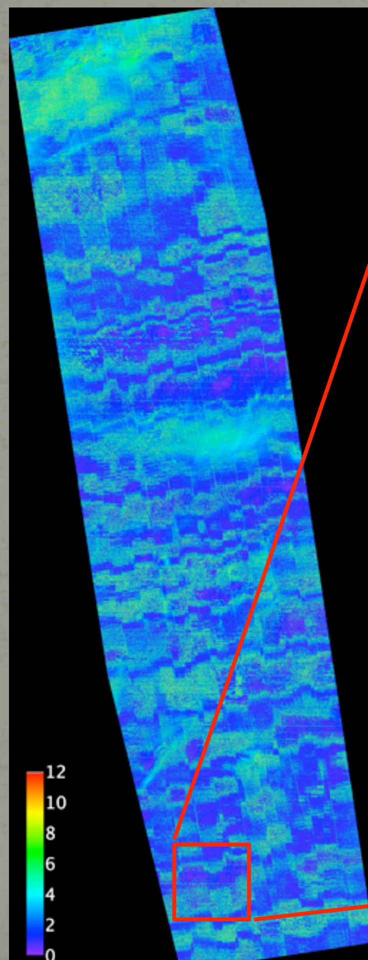
Jitter: Effects and Cure

- "Jitter" = high-frequency motion of spacecraft during acquisition of a pushbroom image. Various activities on spacecraft cause jitter of varying severity.
- In direction of stereobase (crosstrack for HiRISE), creates pseudo-parallax leading to "washboard" ripples in DEM. In HiRISE this leads to "cliffs" at the CCD boundaries because adjacent detectors see the same point at a different time
- Perpendicular to stereobase, misaligns the images and can interfere with stereo matching. Amplitude <2 pixels is tolerable, >3 pixels leads to noisy DEMs.
- Simplest remedy is to re-image the target until a low-jitter stereopair is obtained
- "HiJACK" (HiRISE Jitter Adjusted Camera Kernel) algorithm is based on matching features where adjacent CCDs overlap
  - Estimate the absolute jitter motion from its time differences
  - Remove the modeled jitter while images are being resampled to combine the CCDs into a single large image for processing

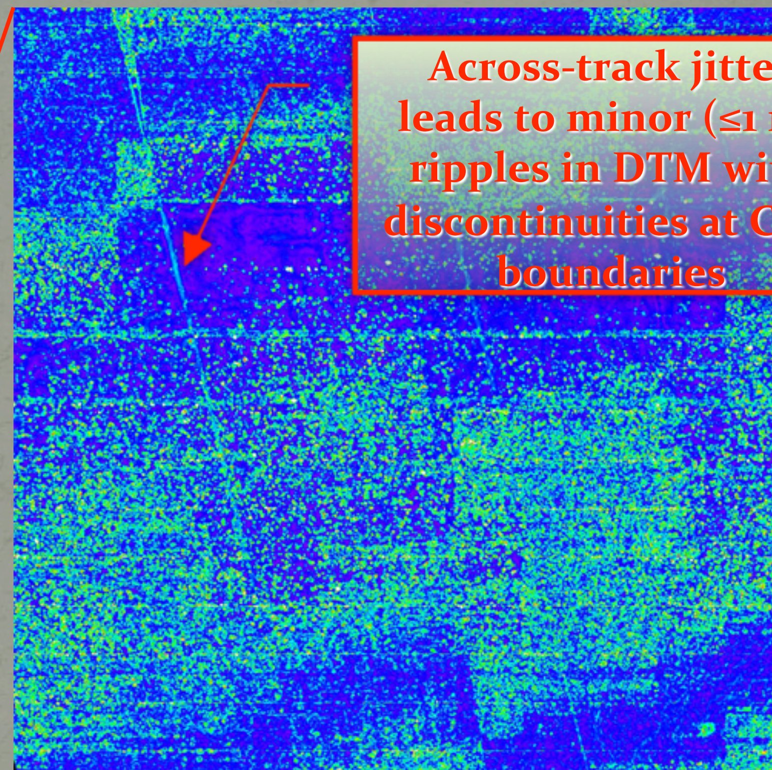
Complex HiRISE Design –> DEM Degradation by Jitter is Complex



Slopes over
100 m baseline



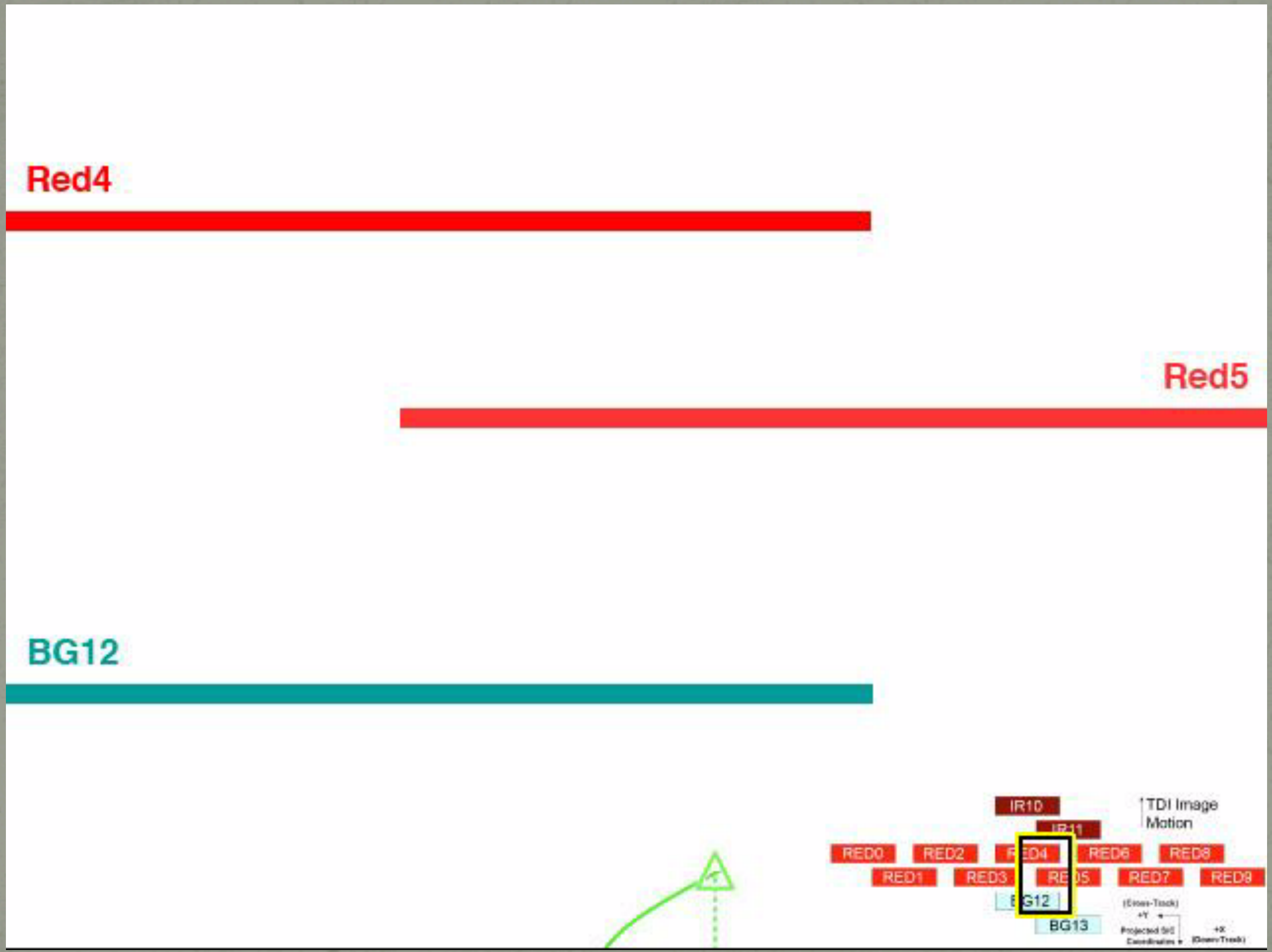
Slopes over
2 m baseline



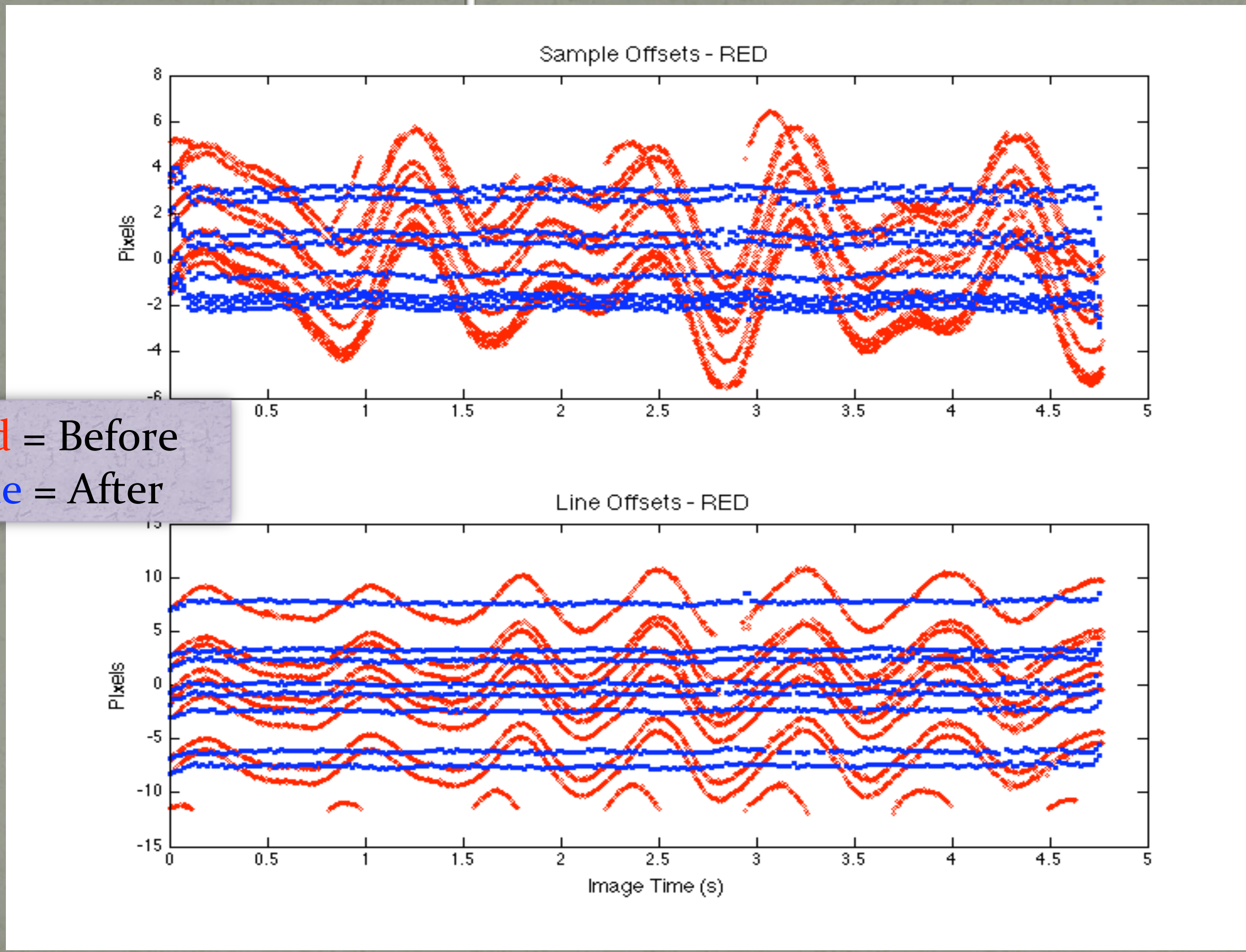
Across-track jitter leads to minor (≤1 m) ripples in DTM with discontinuities at CCD boundaries

Stereo matching becomes "noisy" where images are out of alignment along-track because of jitter
Problem for ≥2 pixels jitter, severe if >3

The Basis of HiJACK: Overlapping CCDs Sample The Jitter Motion

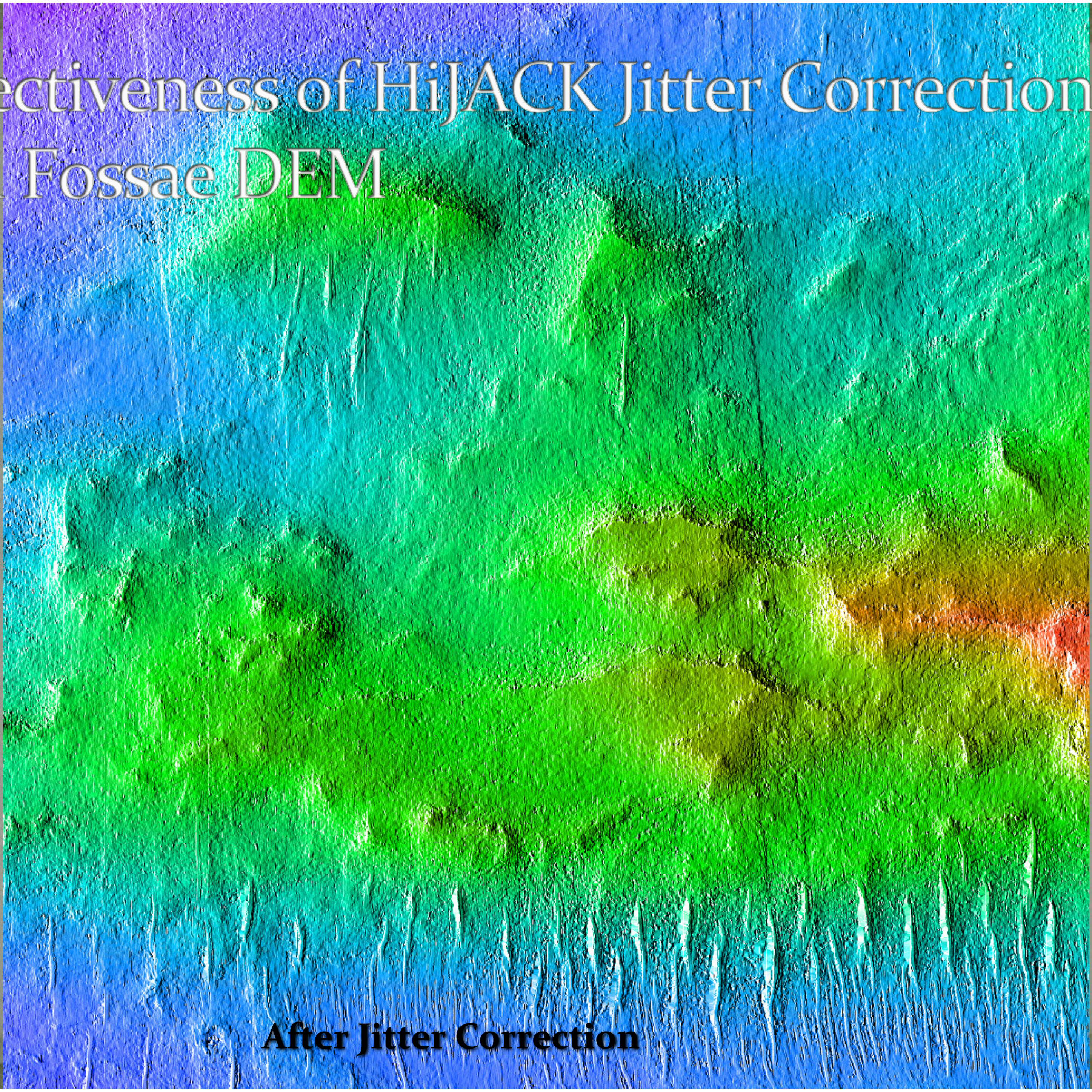


HiJACK Example: Nili Fossae



Red = Before
Blue = After

Effectiveness of HiJACK Jitter Correction: Nili Fossae DEM



DTM Count

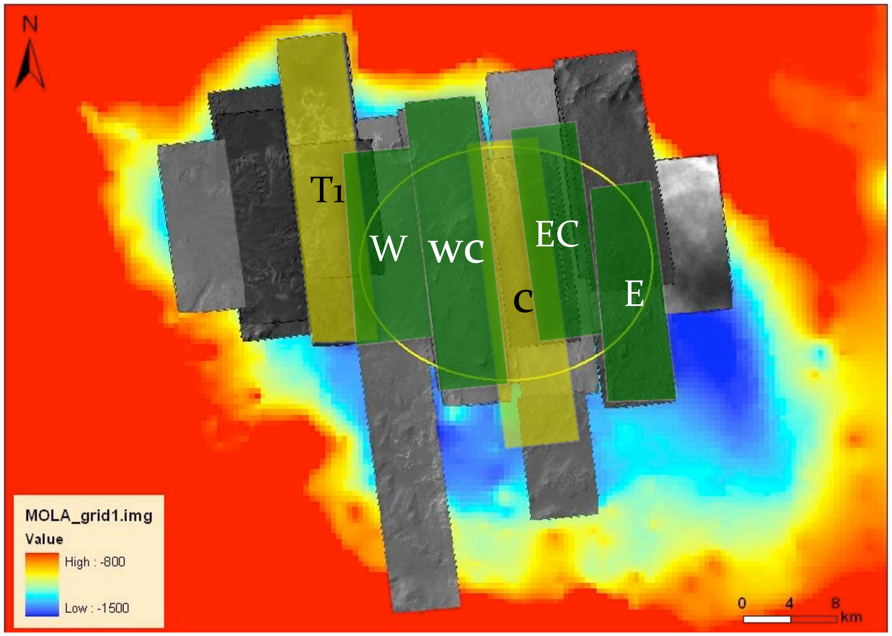
- 2 DTMs in de-selected sites (Mawrth 4, Nili Fossae)
- 15 DTMs in "Final 4" ellipses
- 2 DTMs covering science traverses (Gale, Holden)
- 2 "do-overs" (Eberswalde West of Center—incompatible lighting; Holden Southwest—low SNR)
  - Availability of HiJACK means we no longer require "do-overs" for jittery images
- 4 additional stereopairs/DTMs requested

Total data volume ~7x the pre-MOLA USGS global Mars DTM (a decade-long project)!

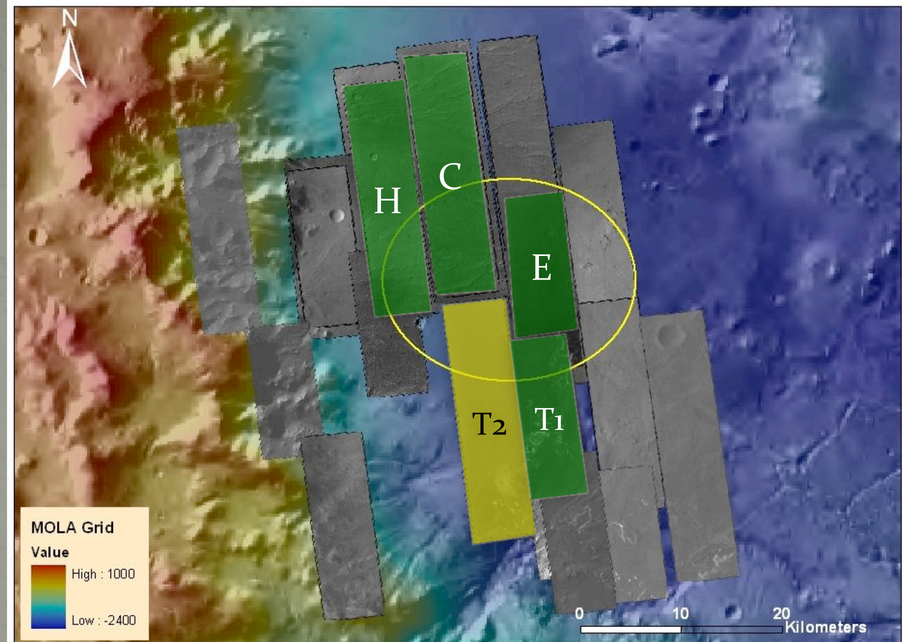
HiRISE Image and DTM Coverage in Ellipses

Ellipses Exact Images Georeferenced

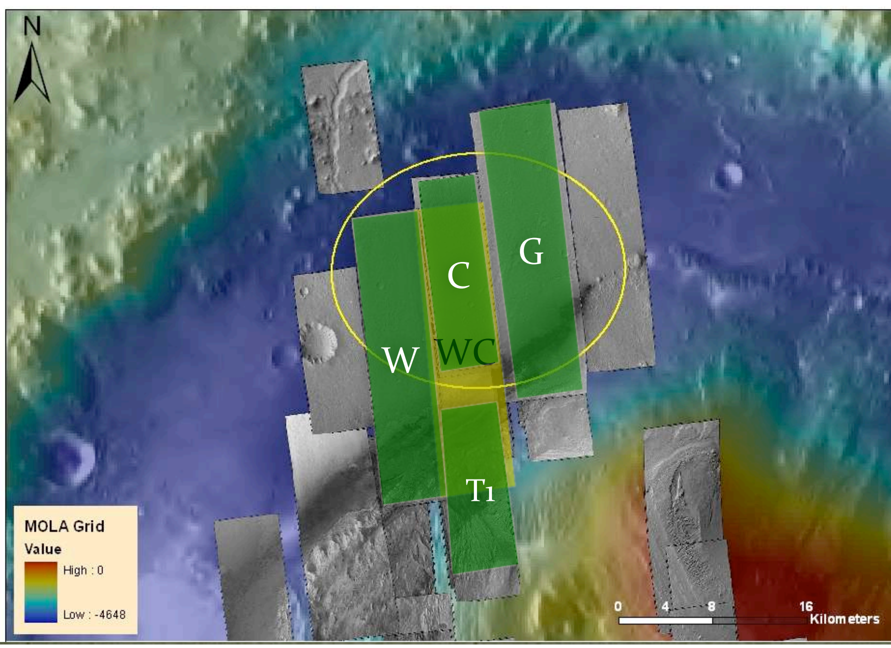
Eberswalde Crater HiRISE



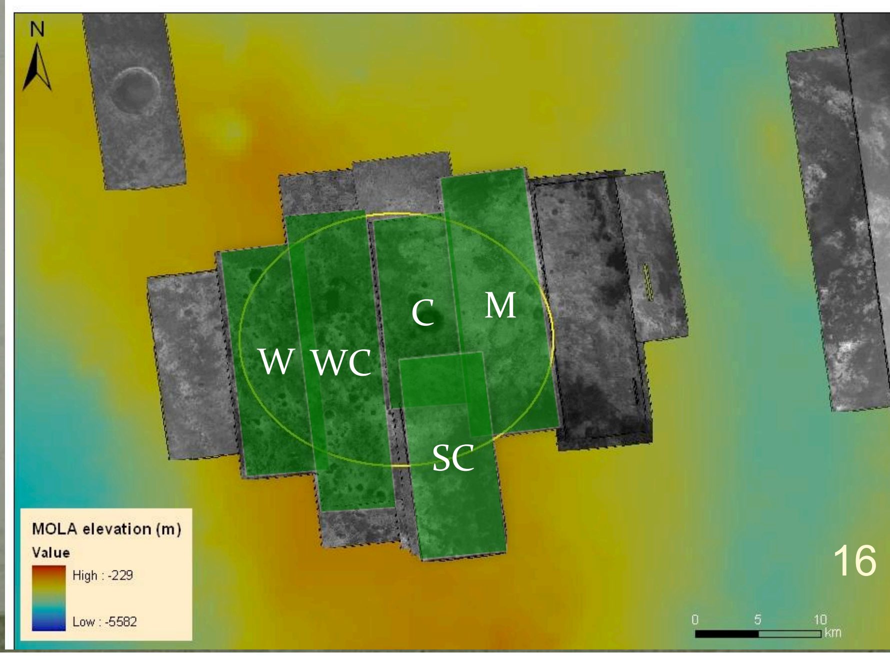
Holden Crater HiRISE



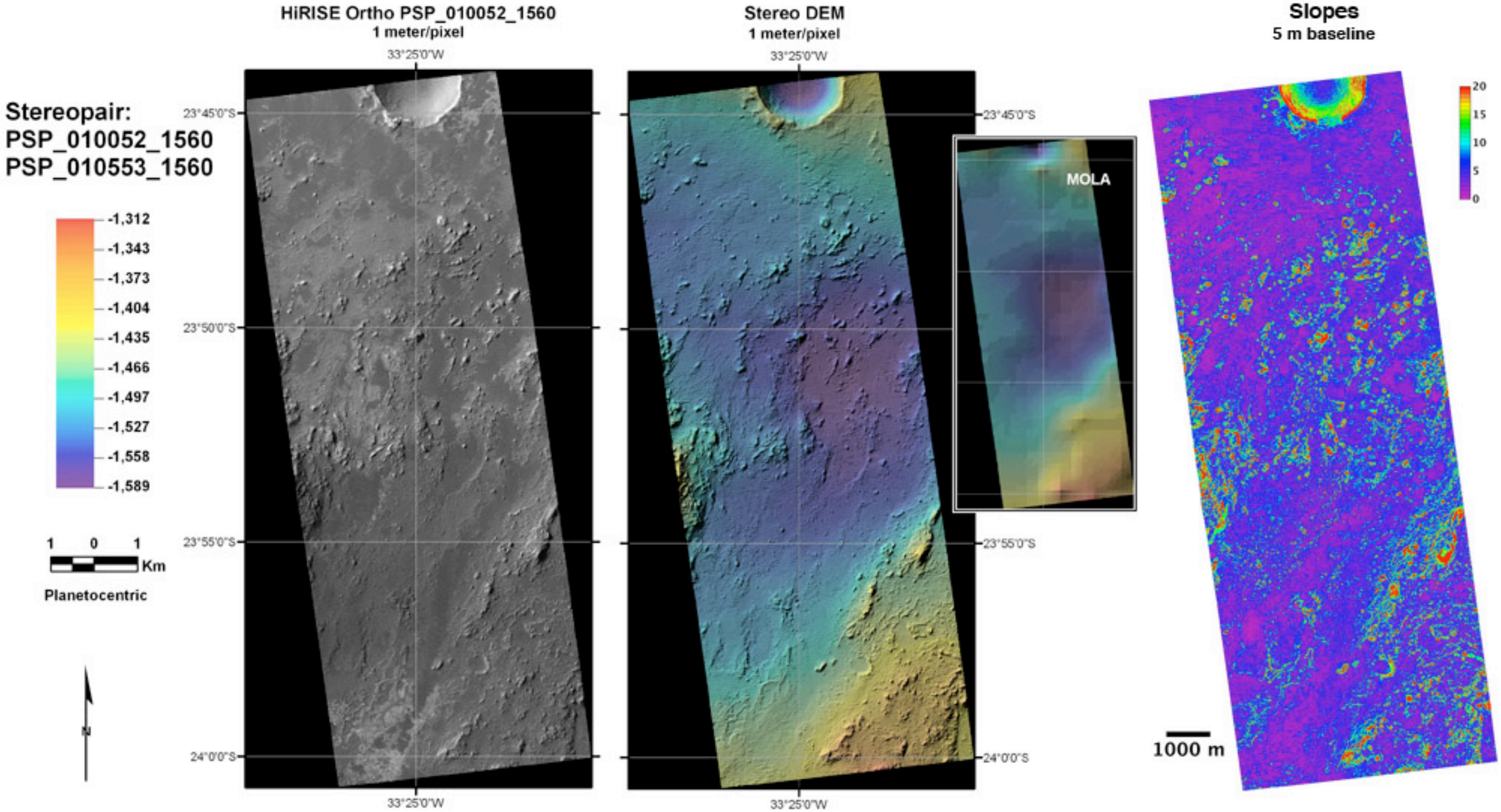
Gale Crater HiRISE



Mawrth Vallis HiRISE

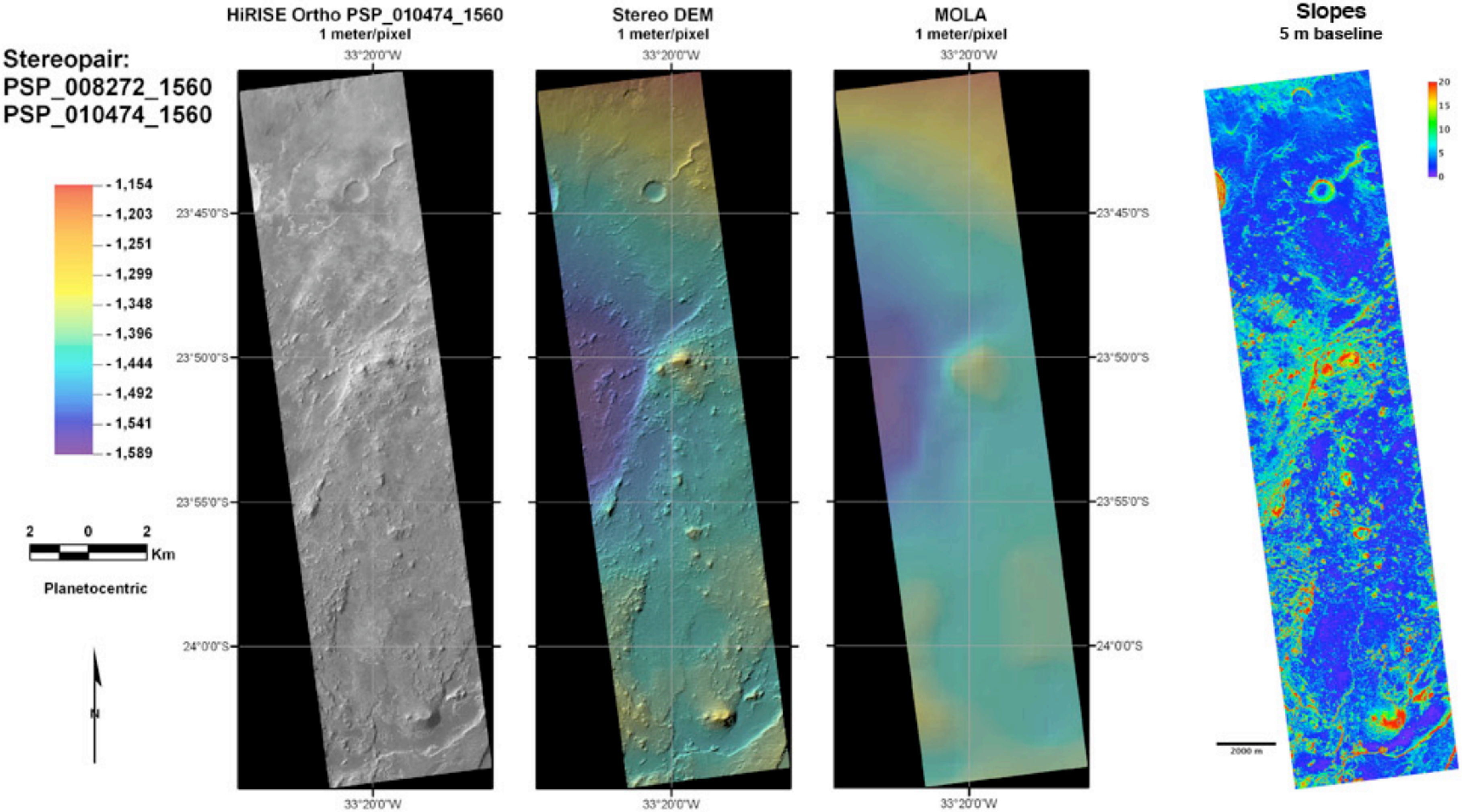


Eberswalde W

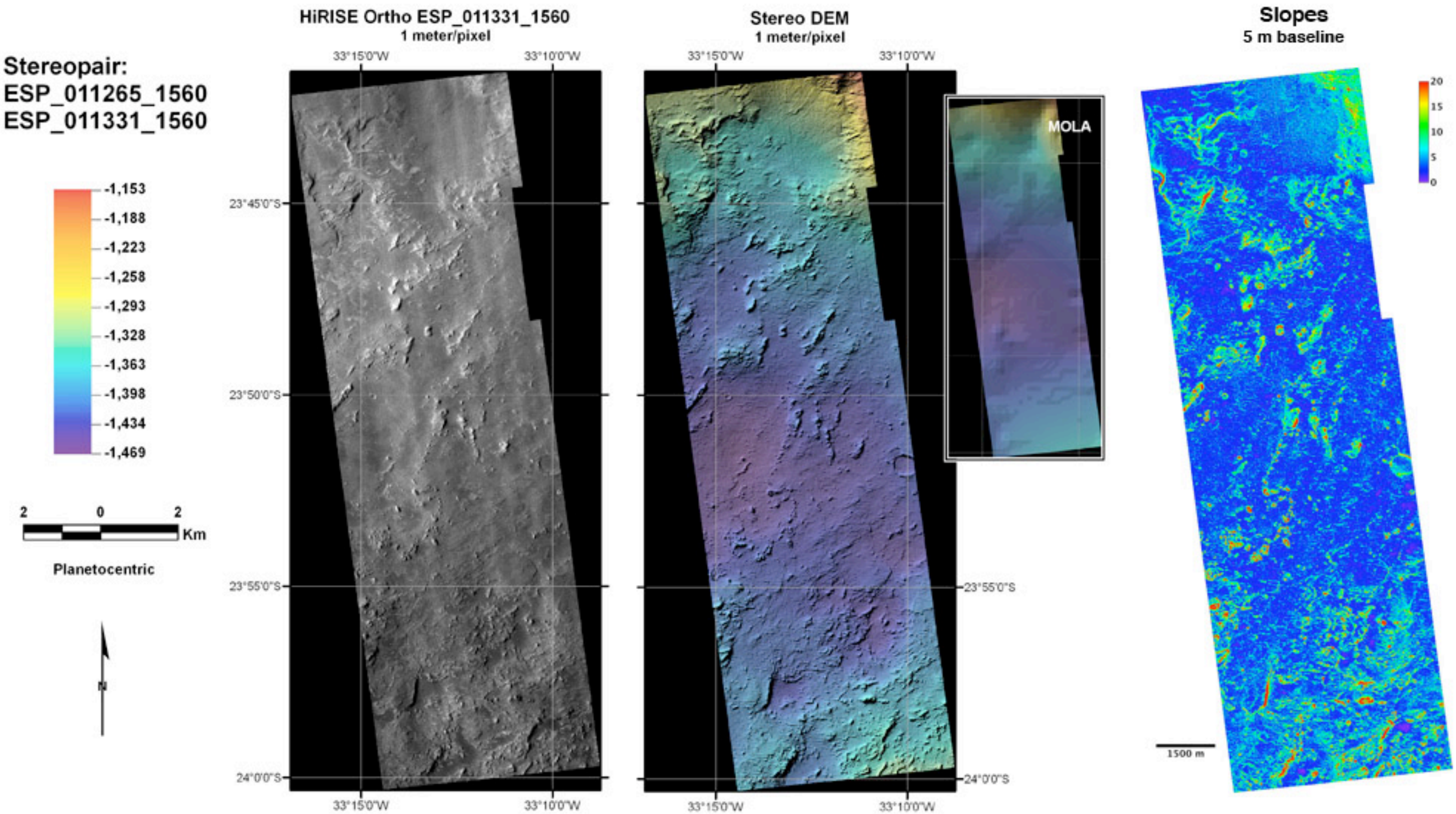


Eberswalde W of Center

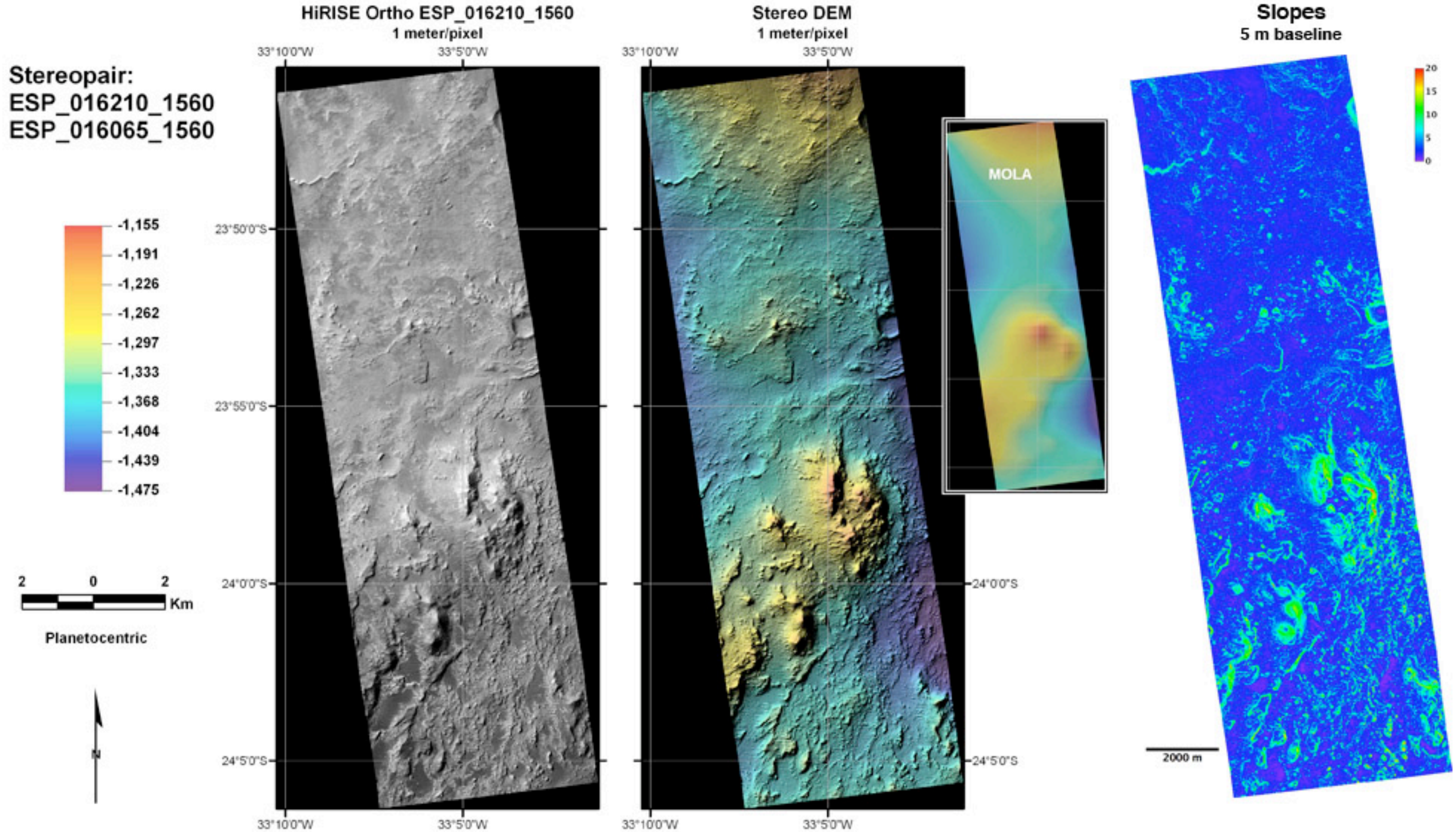
Stereopair:
PSP_008272_1560
PSP_010474_1560



Eberswalde E of Center

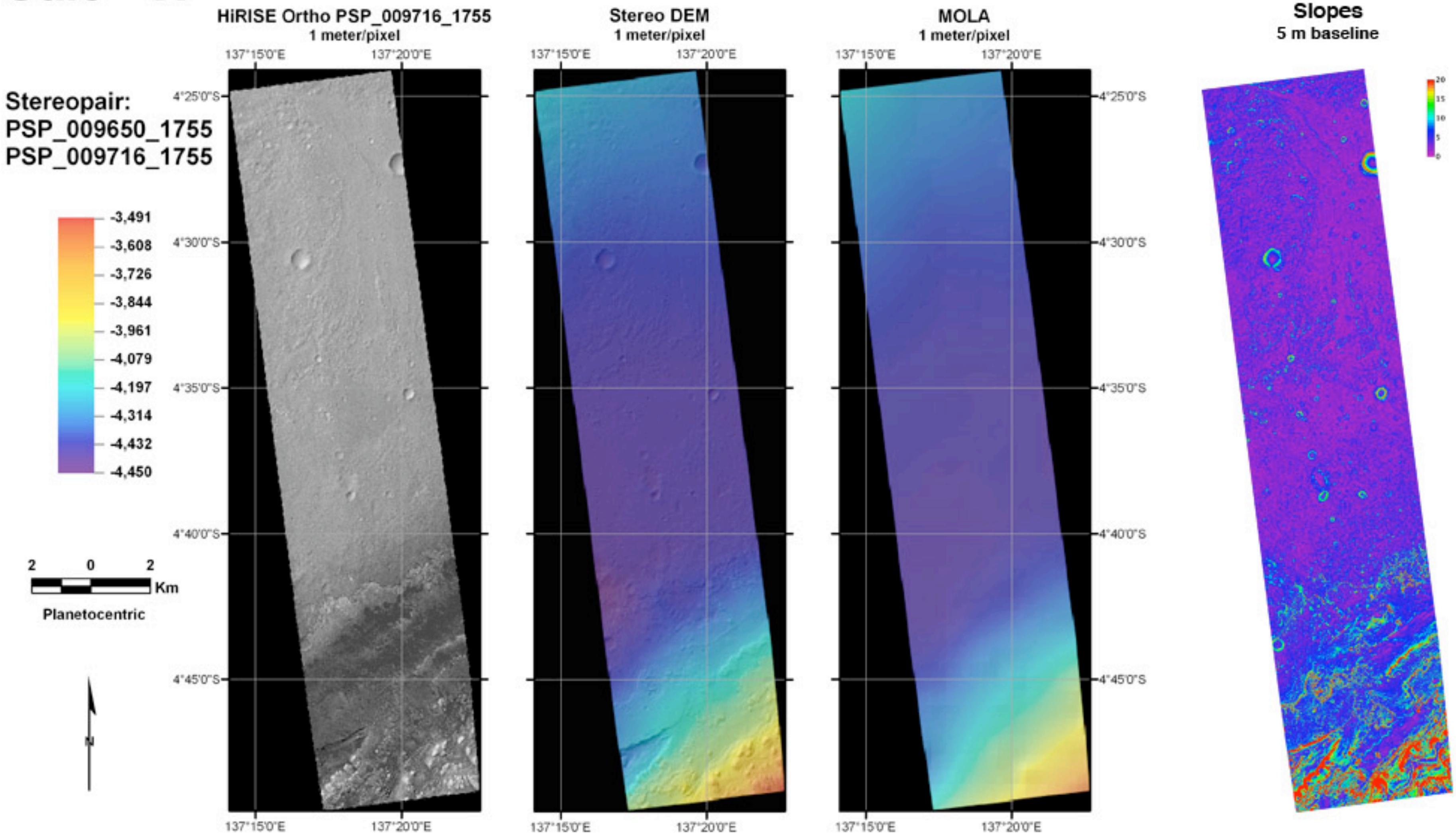


Eberswalde East



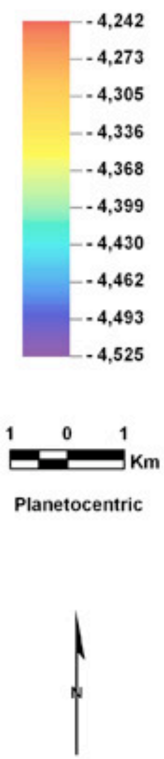
Gale - W

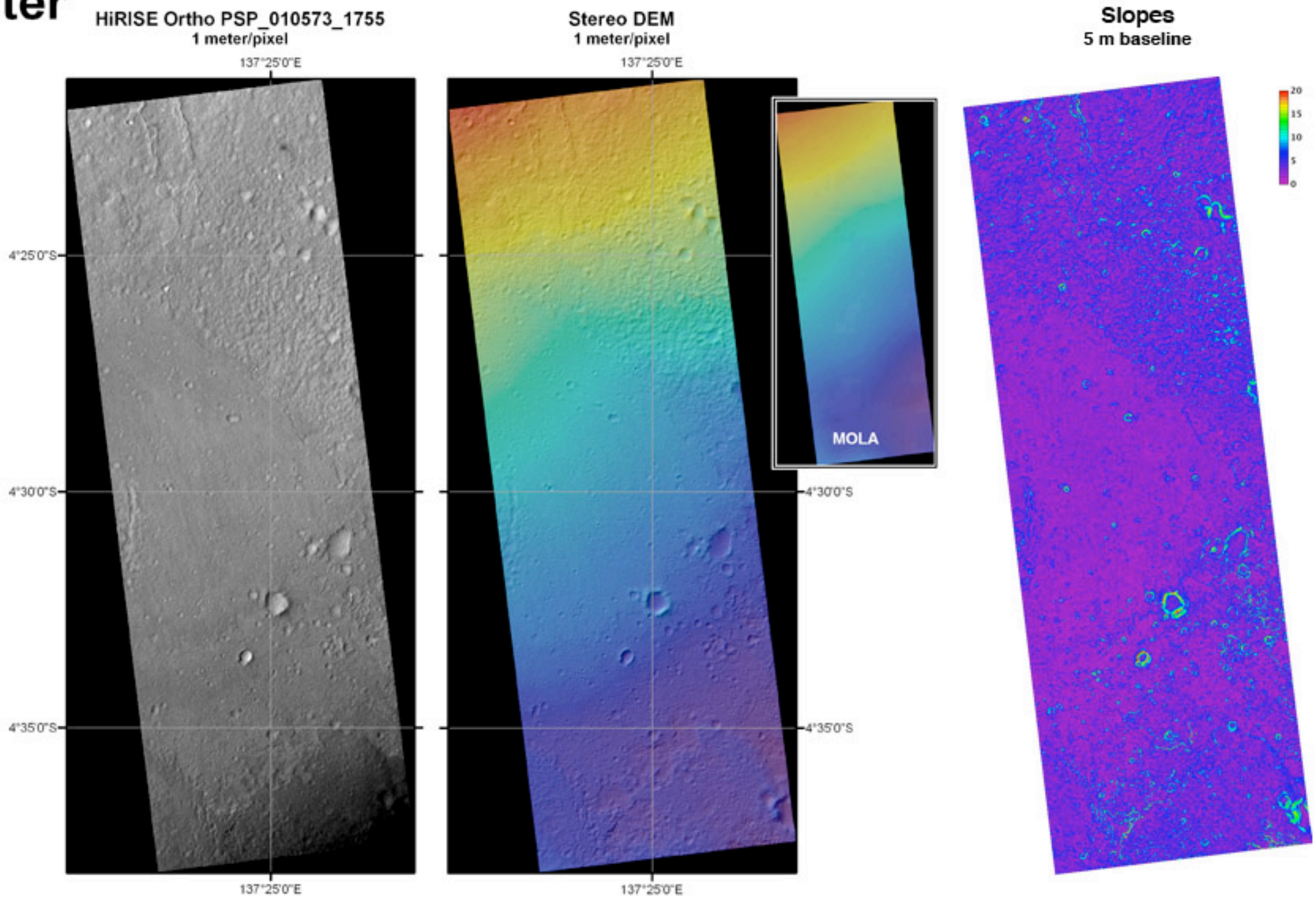
Stereopair:
PSP_009650_1755
PSP_009716_1755



Gale - Center

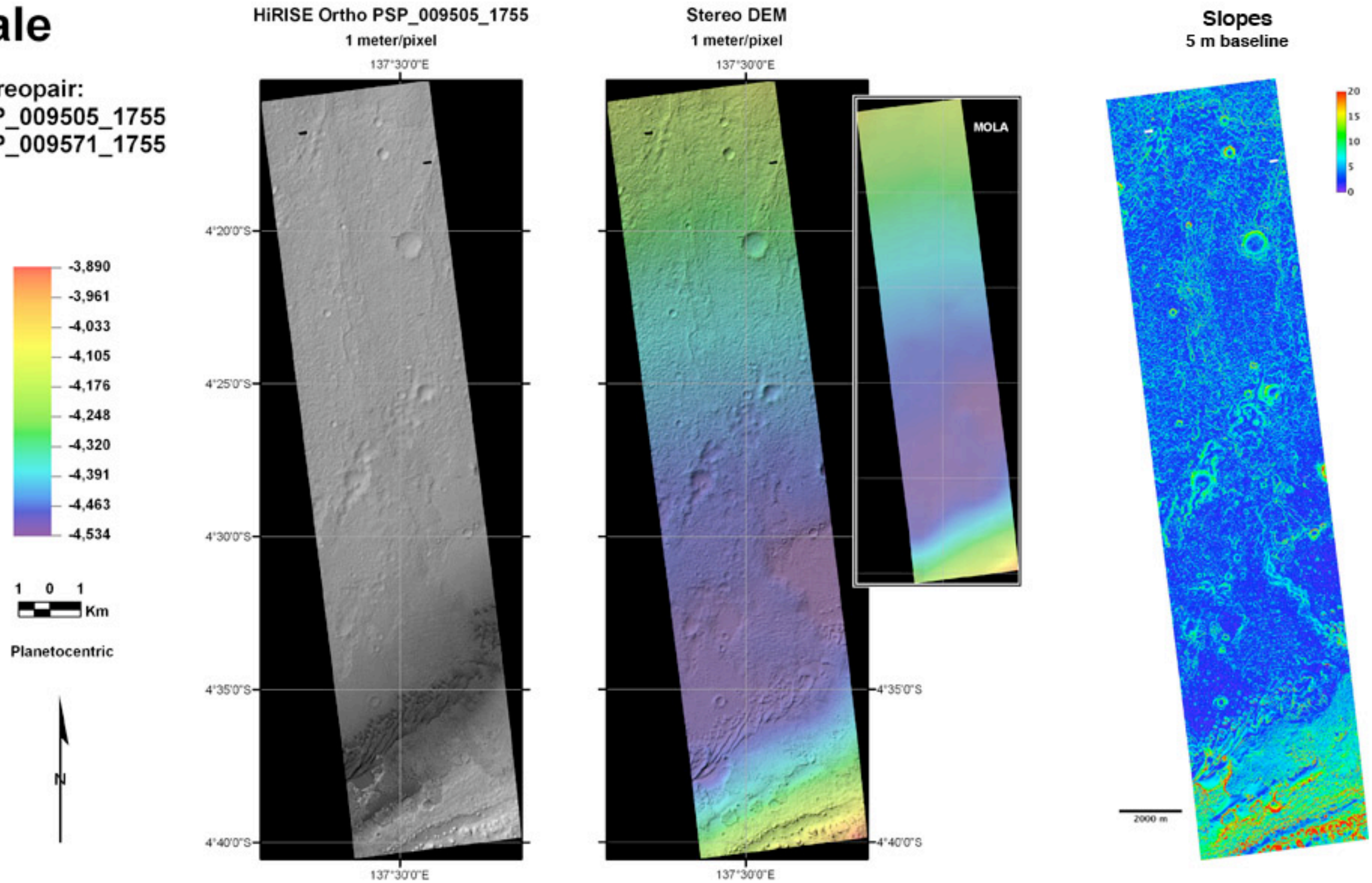
Stereopair:
PSP_010573_1755
PSP_010639_1755





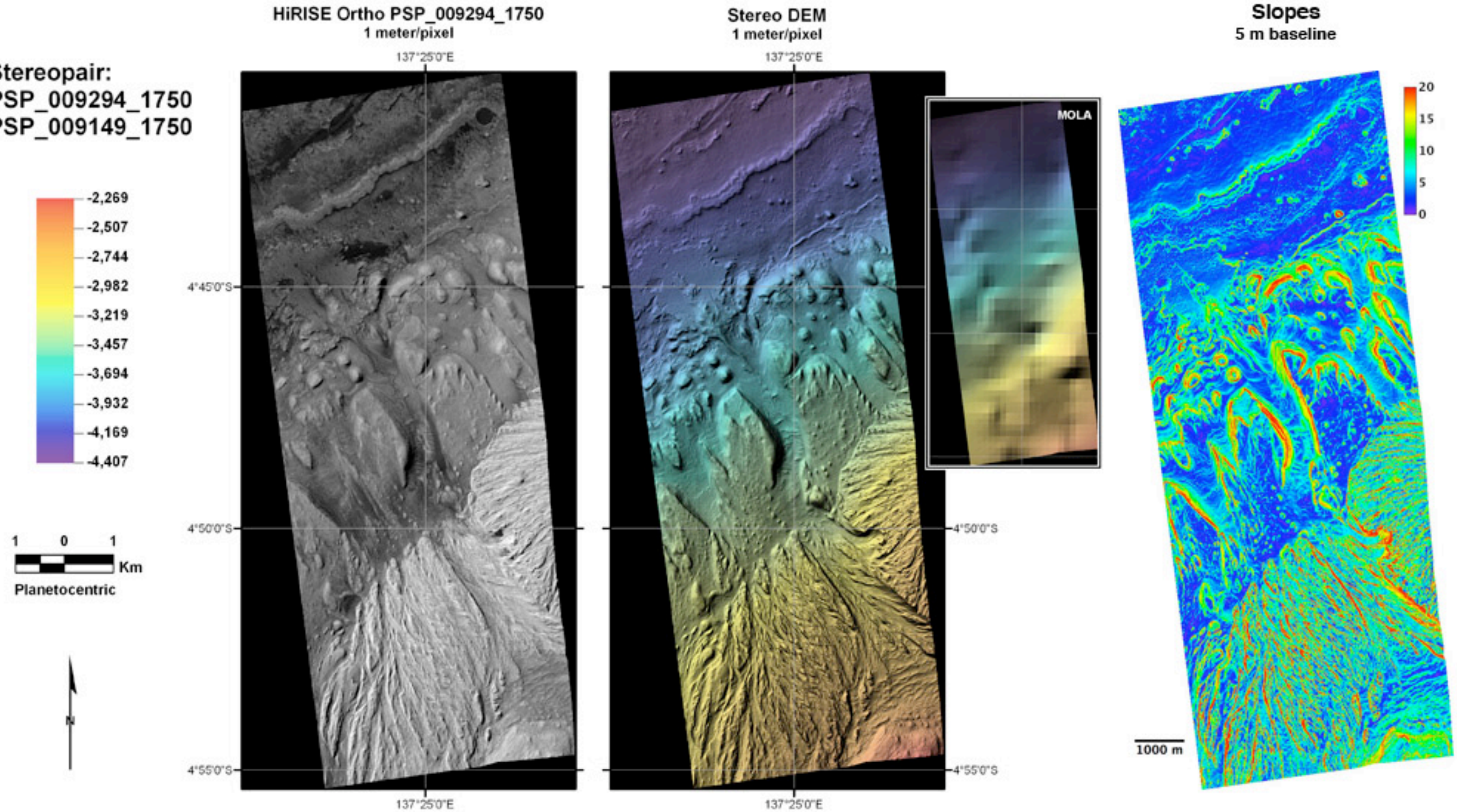
Gale

Stereopair:
PSP_009505_1755
PSP_009571_1755



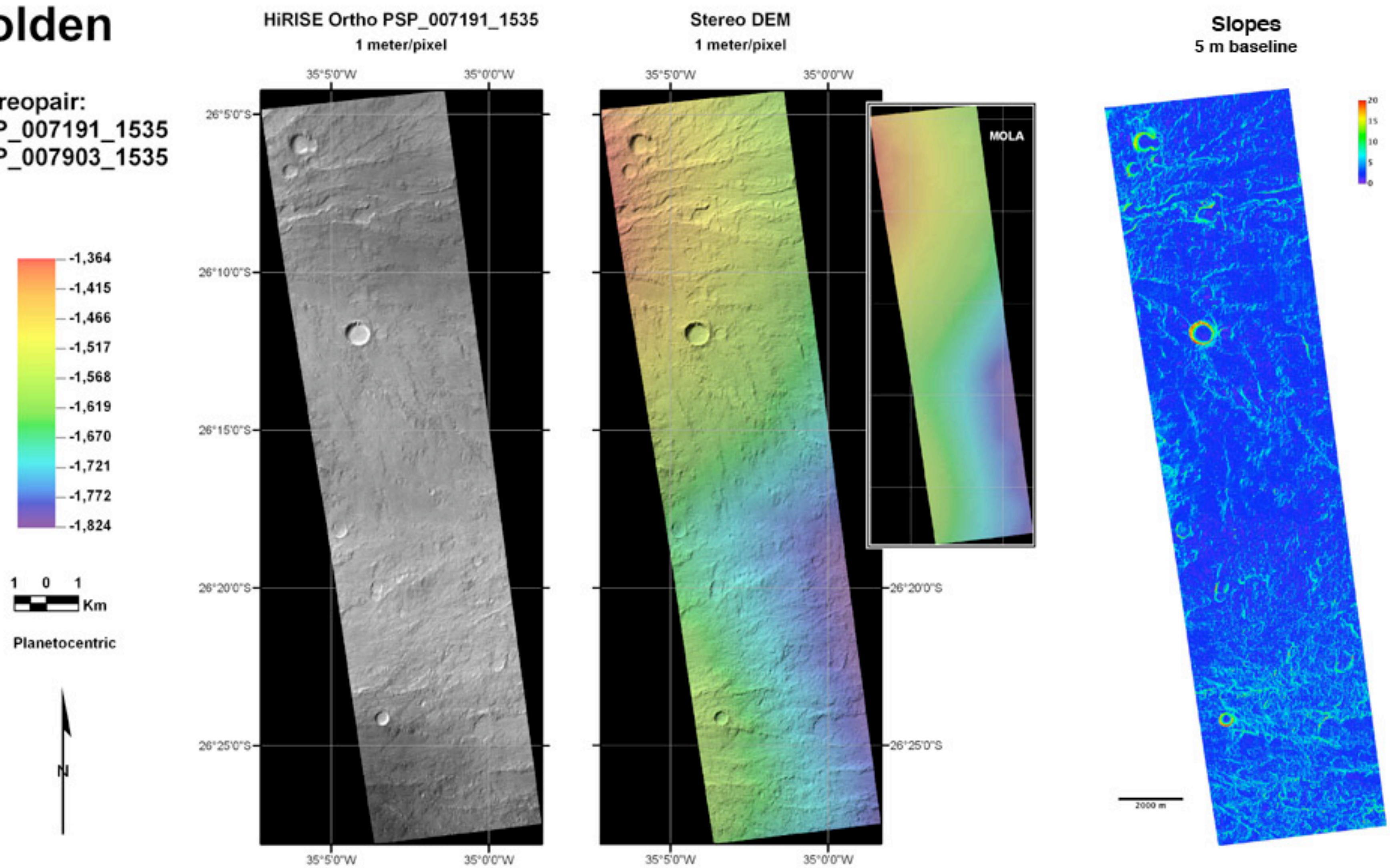
Gale Traverse 1

Stereopair:
PSP_009294_1750
PSP_009149_1750



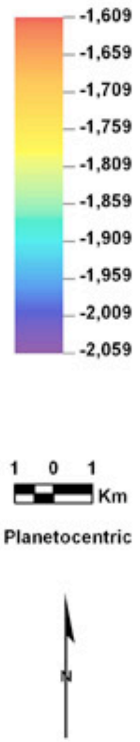
Holden

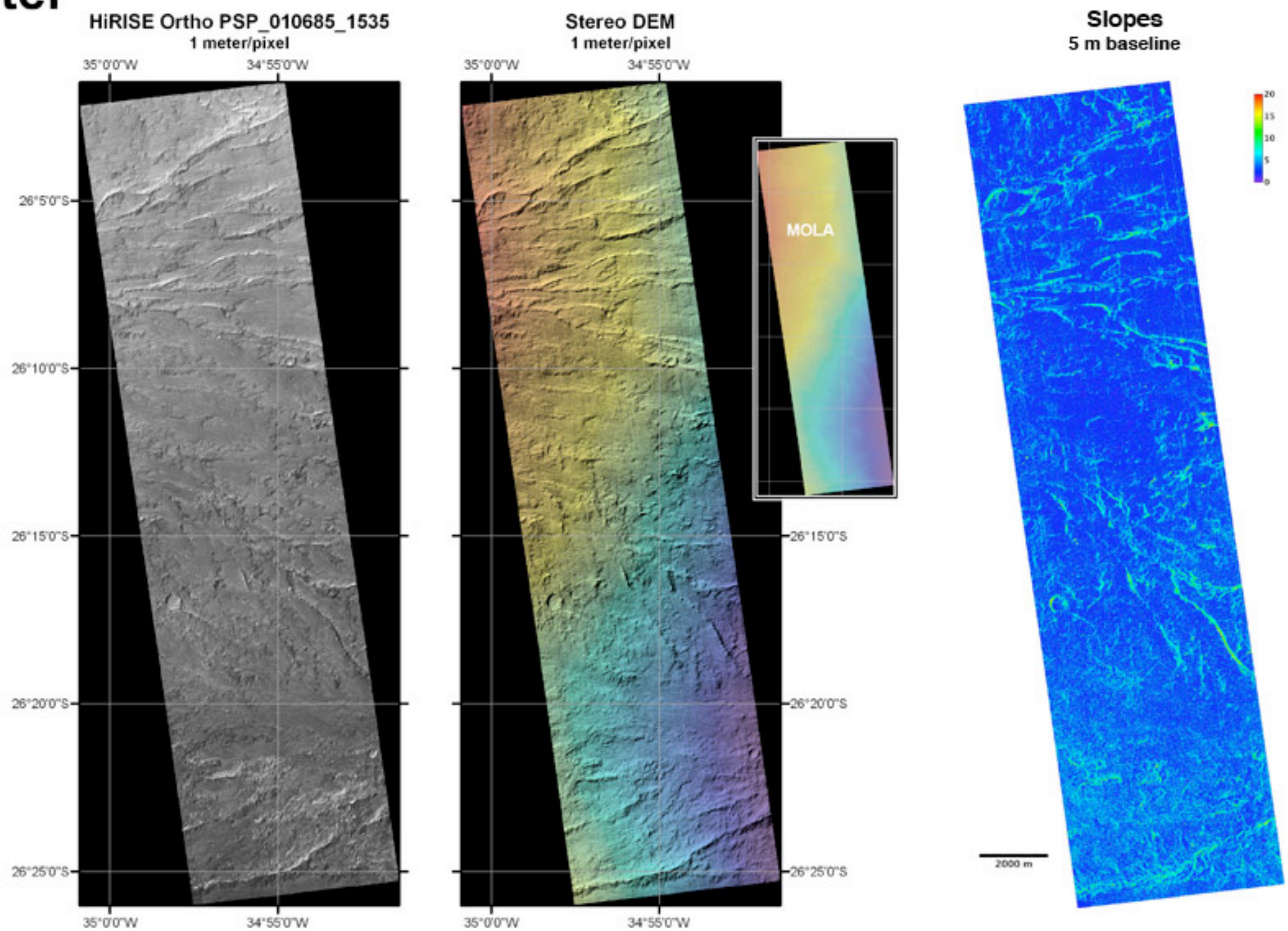
Stereopair:
PSP_007191_1535
PSP_007903_1535



Holden Center

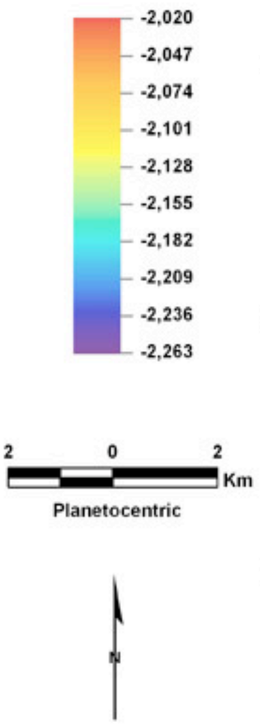
Stereopair:
PSP_010685_1535
PSP_010540_1535

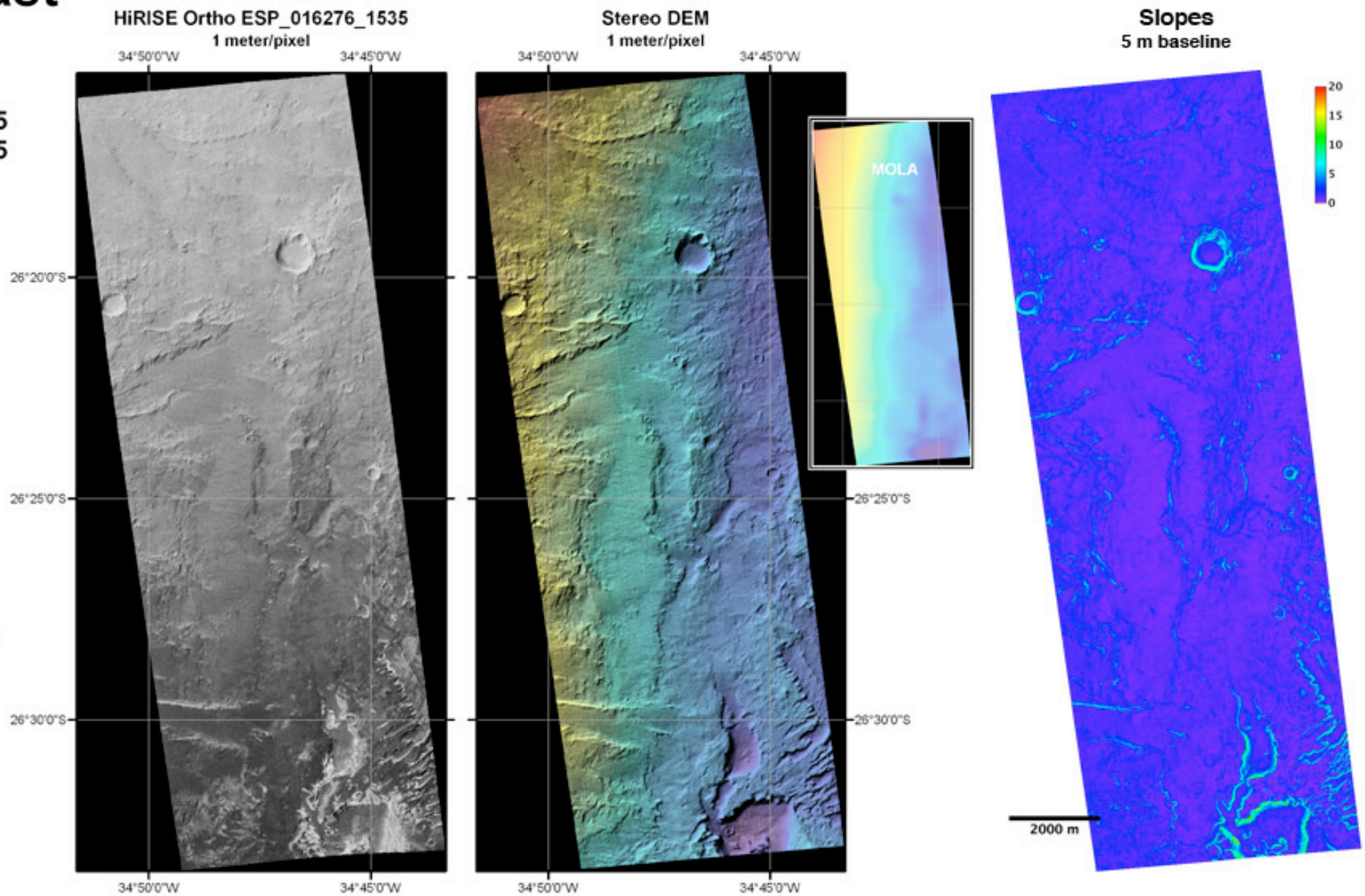




Holden East

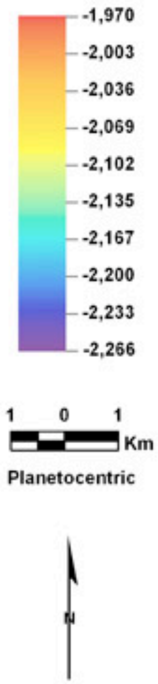
Stereopair:
ESP_016276_1535
ESP_015999_1535

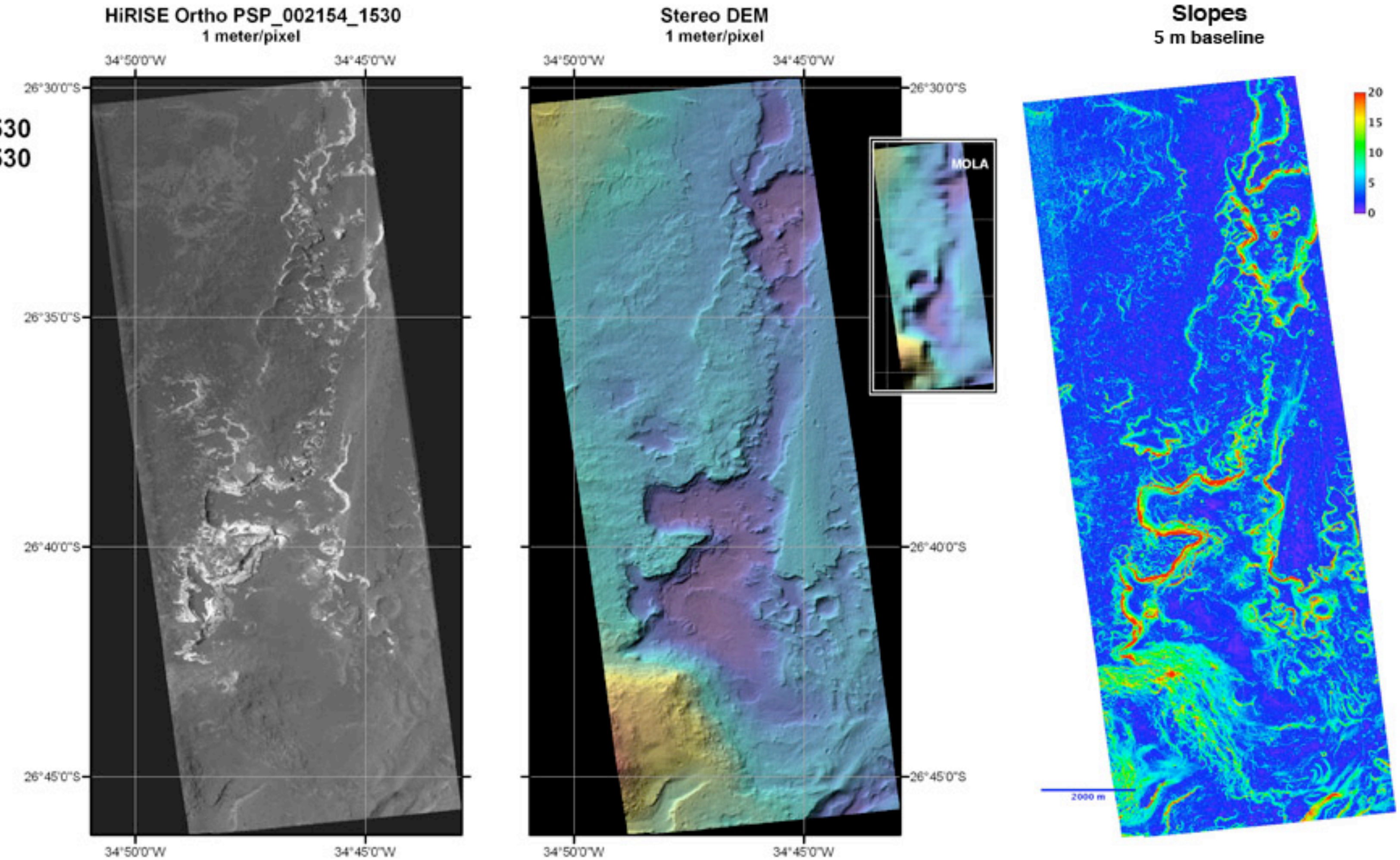




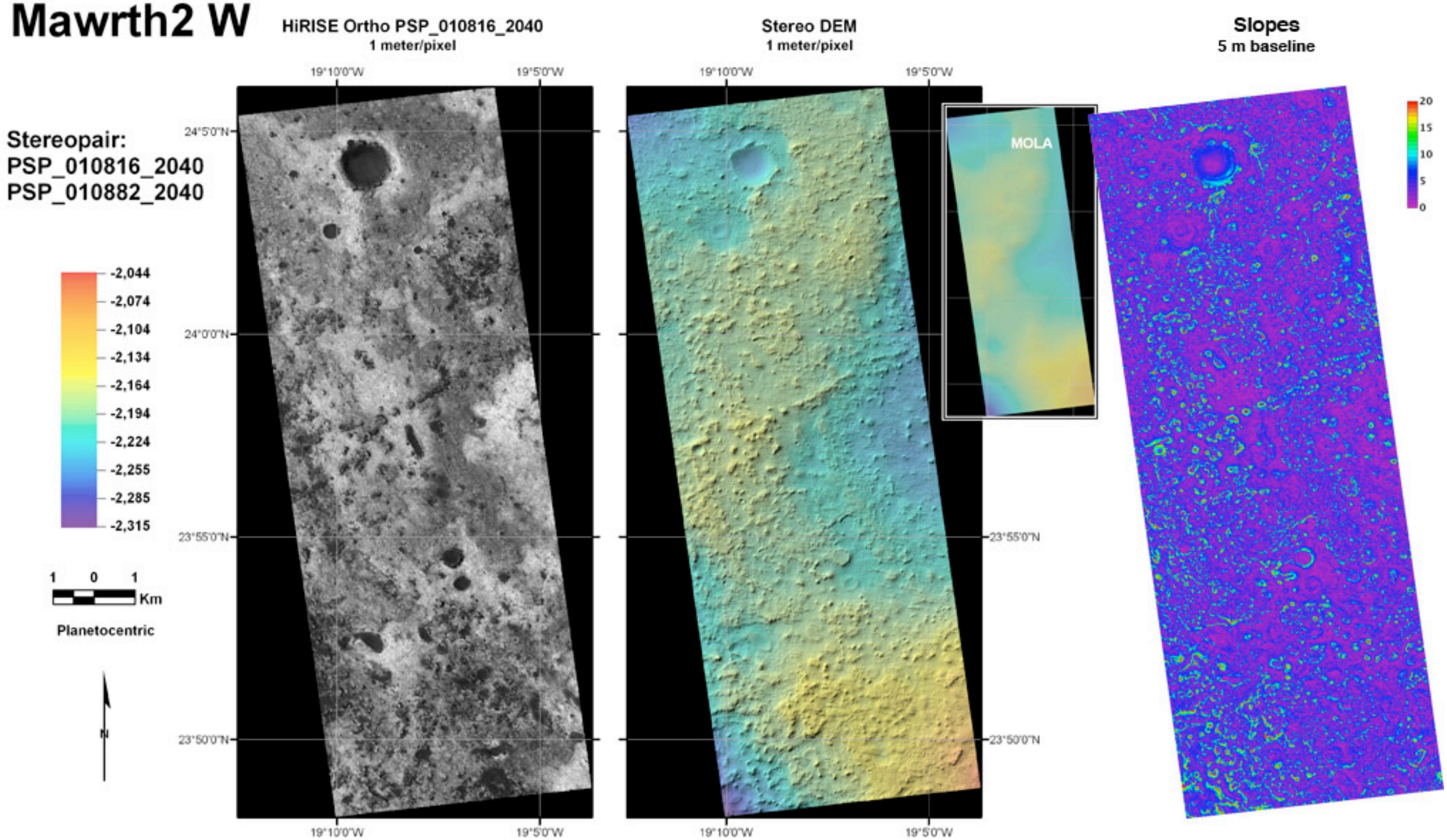
Holden Traverse 1

Stereopair:
PSP_002154_1530
PSP_002088_1530

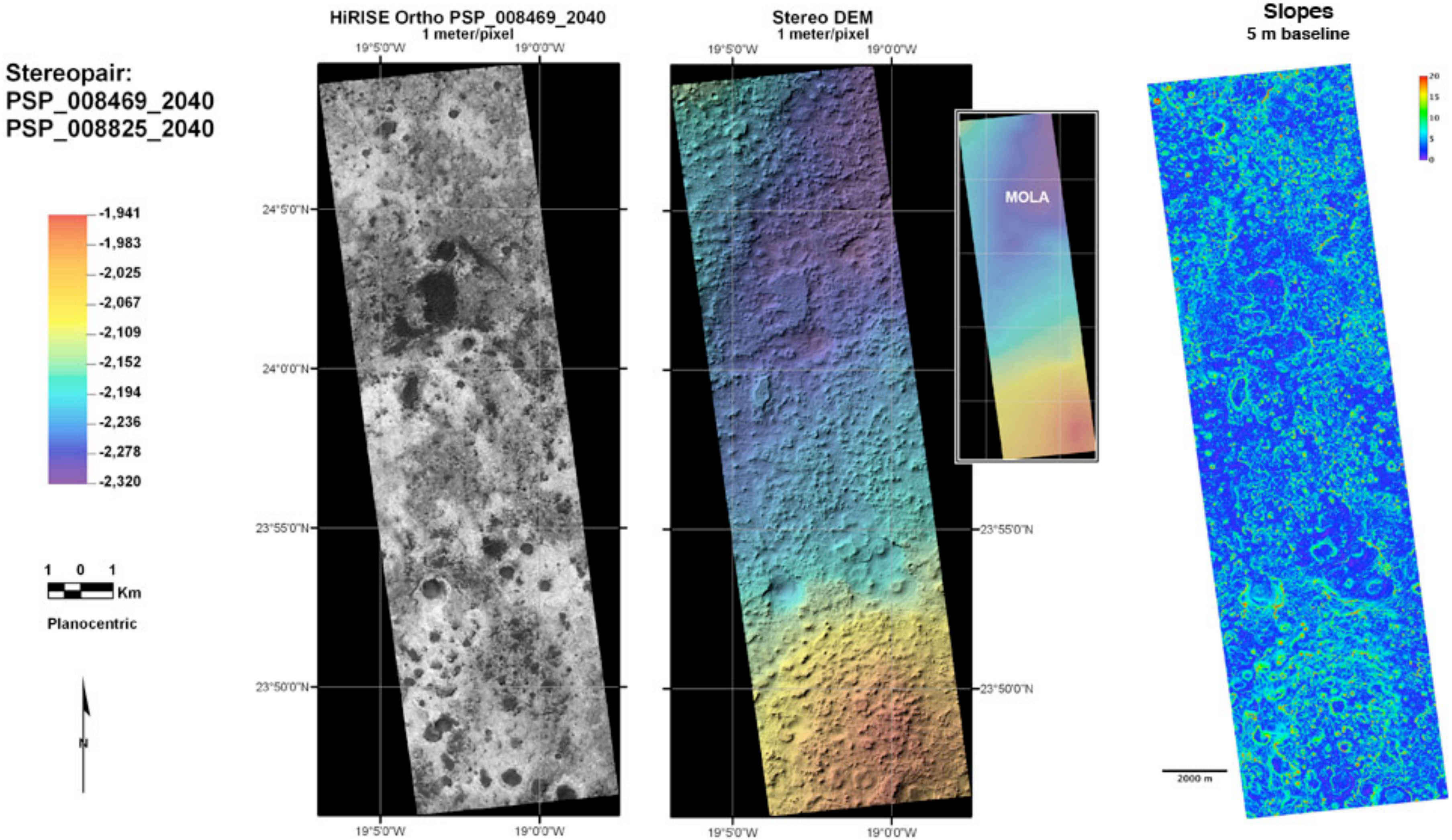




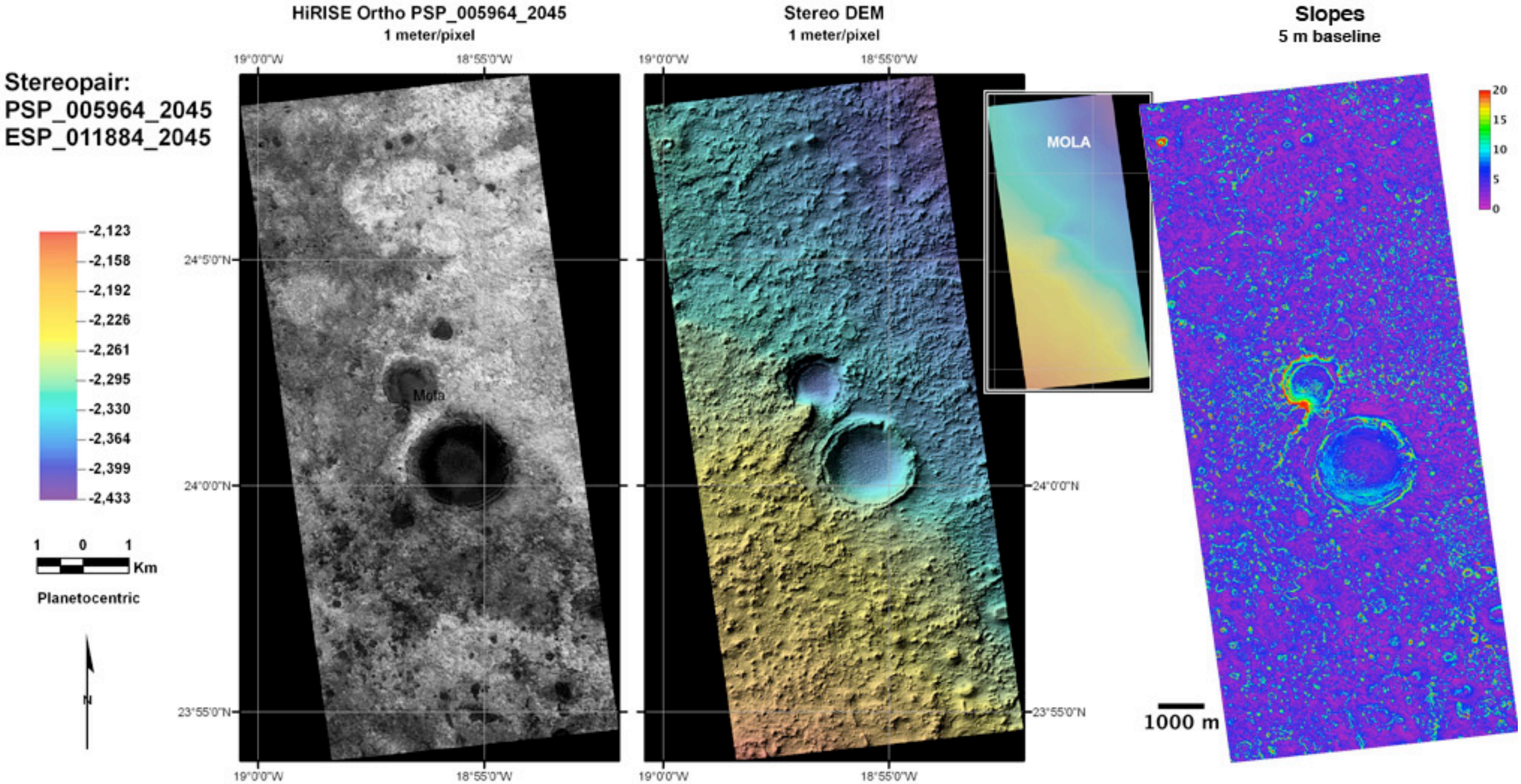
Mawrth2 W


HiRISE Ortho PSP_010816_2040
1 meter/pixel
Stereo DEM
1 meter/pixel
Slopes
5 m baseline
Stereopair:
PSP_010816_2040
PSP_010882_2040
-2,044
-2,074
-2,104
-2,134
-2,164
-2,194
-2,224
-2,255
-2,285
-2,315
1 0 1
Km
Planetocentric
N
MOLA
19°10'0"W
19°5'0"W
24°5'0"N
24°0'0"N
23°55'0"N
23°50'0"N
20
15
10
5
0

Mawrth2 W of Center

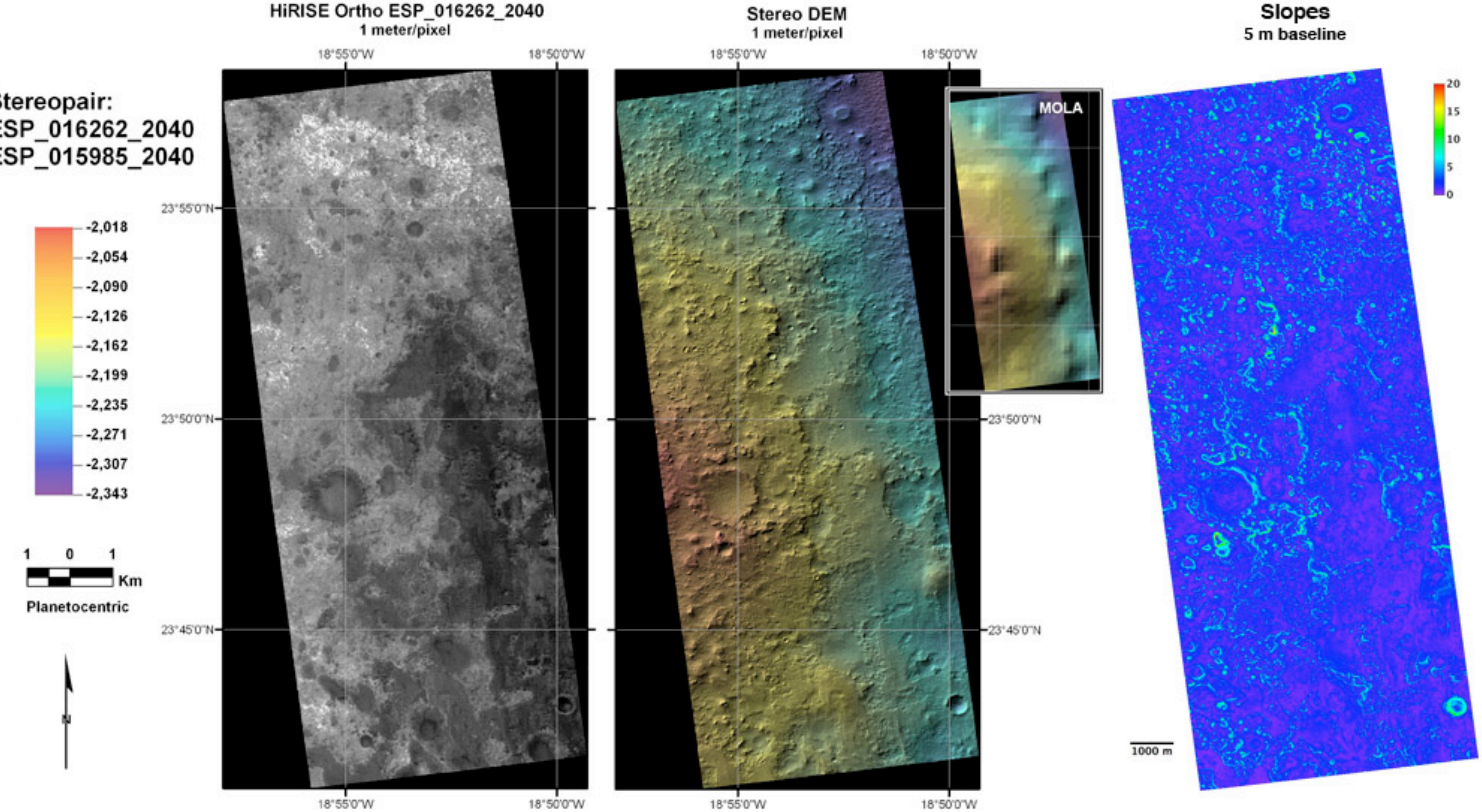


Mawrth2 Center



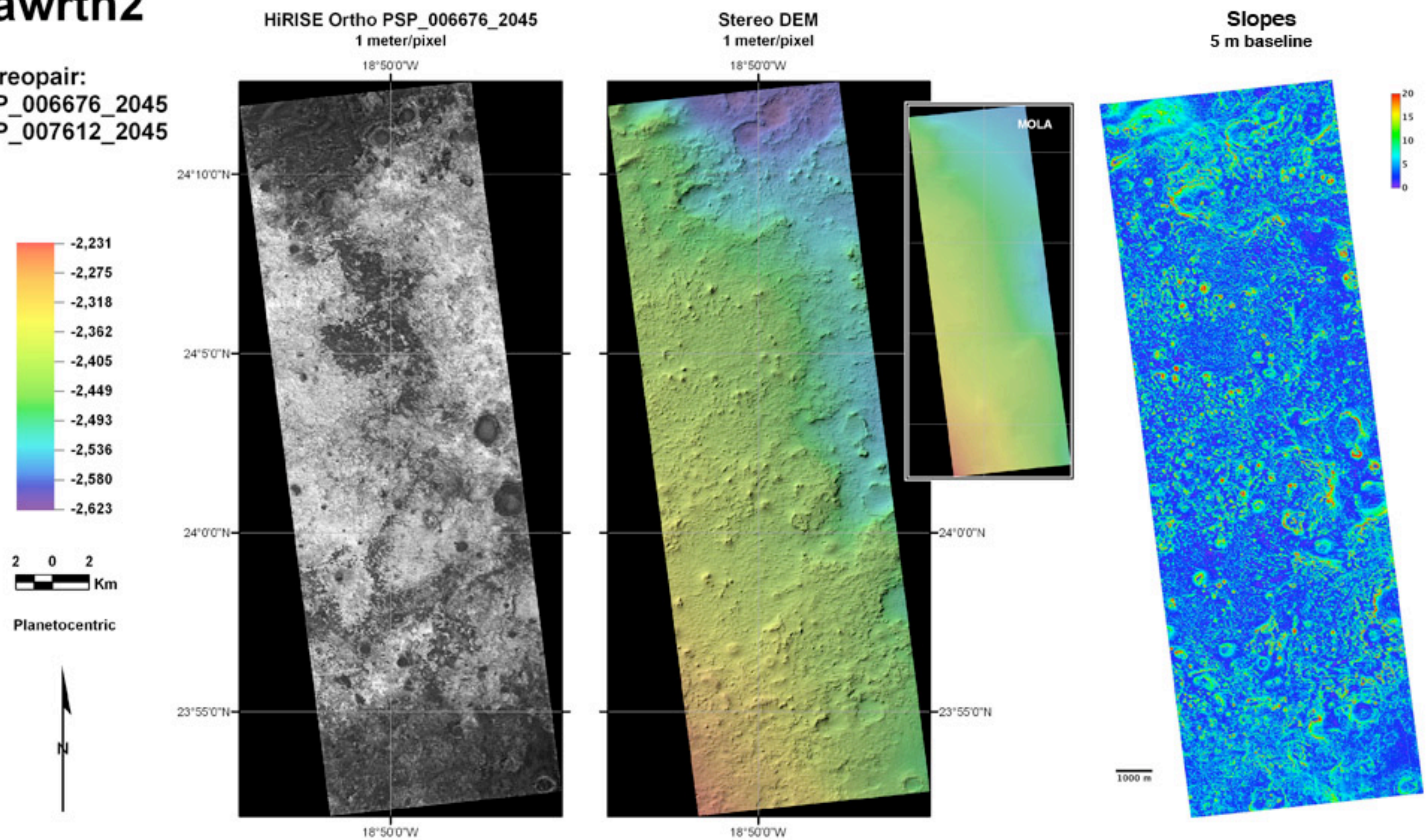
Mawrth 2 South Central

Stereopair:
ESP_016262_2040
ESP_015985_2040

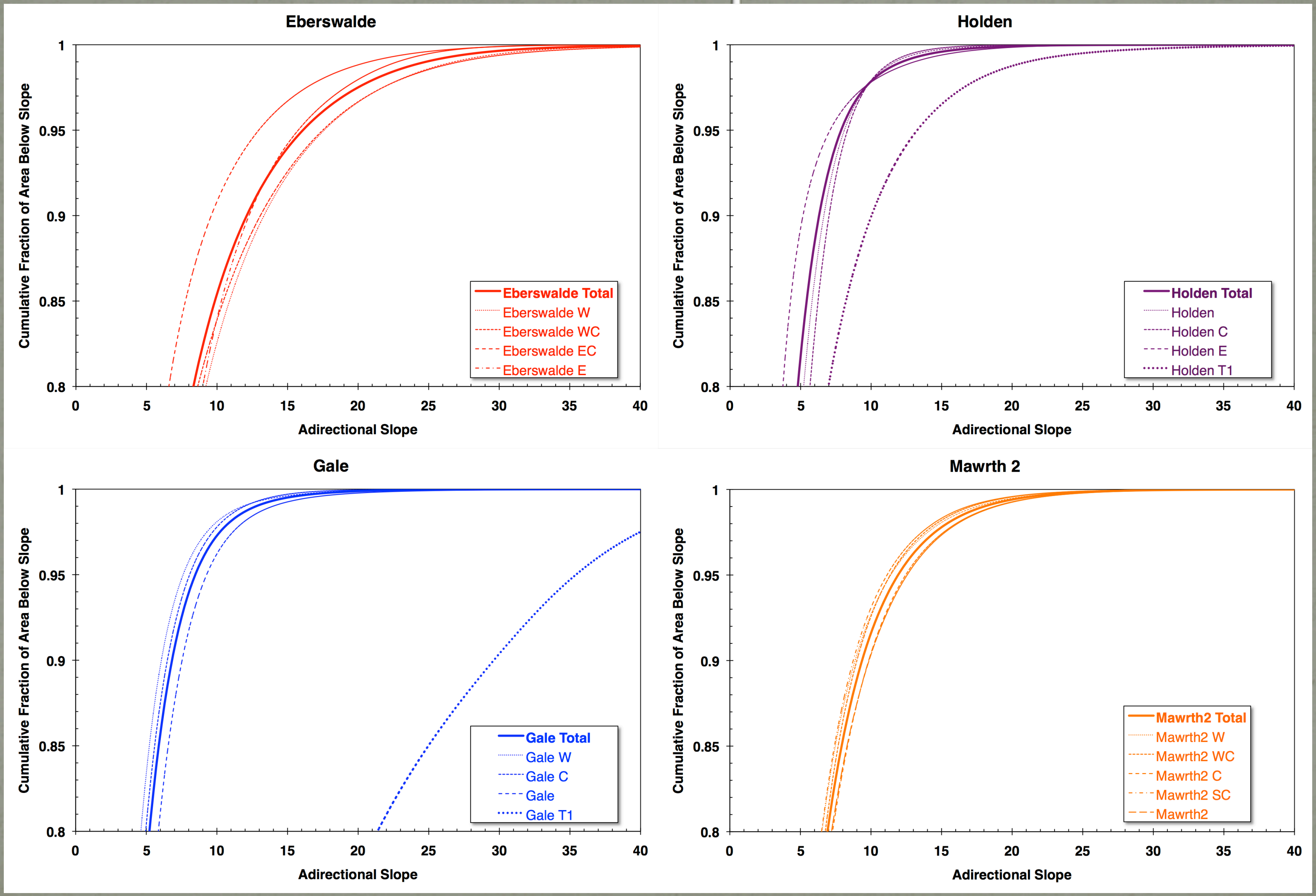


Mawrth2

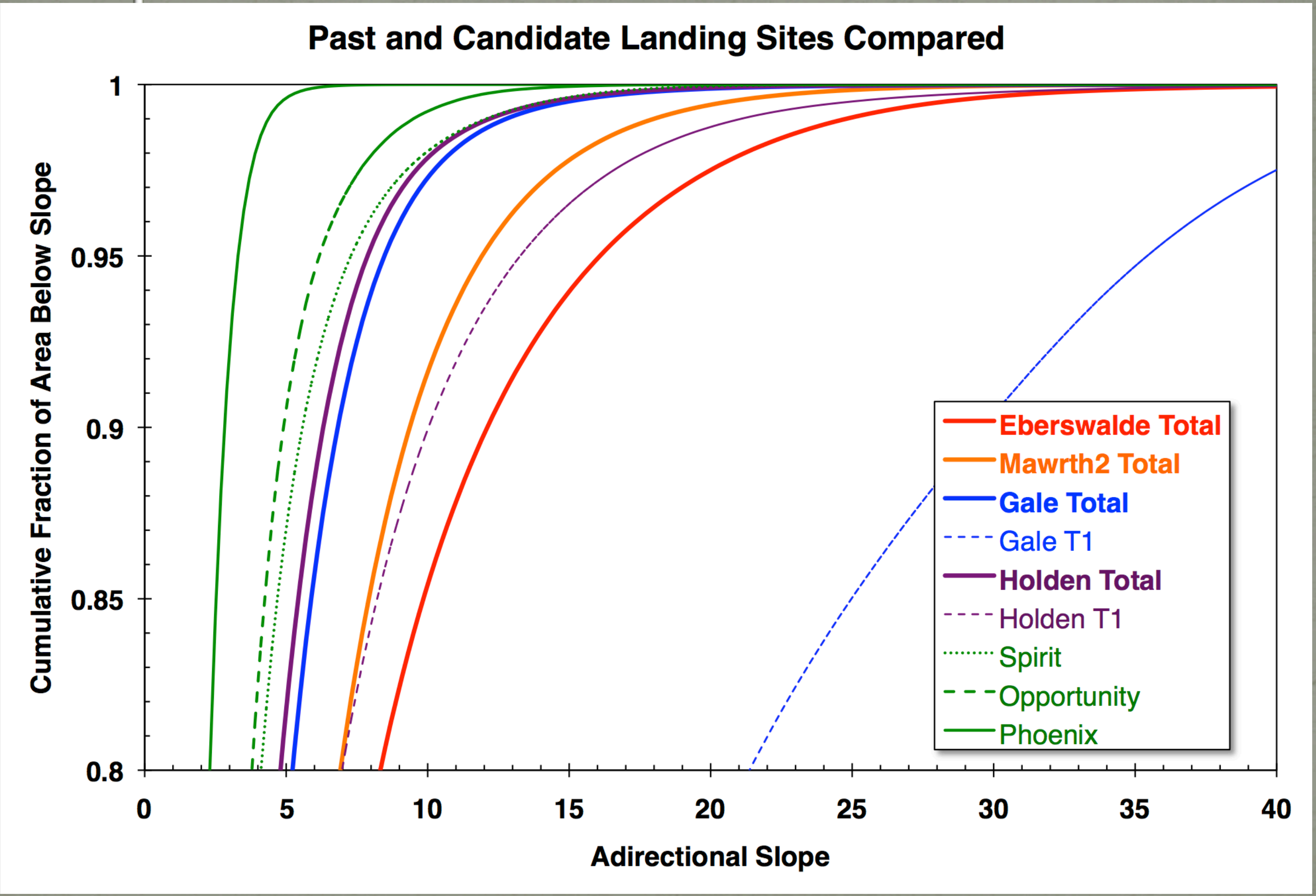
Stereopair:
PSP_006676_2045
PSP_007612_2045



5 m Adirectional Slope Distributions



Comparison with Past LS's



Summary of Slope Statistics

Site/DTM	Fraction of Ellipse	RMS Slope	98th %ile Slope	99th %ile Slope	Slopes > 15°	Slopes > 20°	Slopes > 25°
Eberswalde Total	**84%**	**7.03**	**21.3**	**24.9**	**5.93%**	**2.45%**	**0.94%**
Eberswalde W	17%	8.29	23.1	26.9	7.49%	3.31%	1.38%
Eberswalde WC	26%	6.19	23.3	27.3	7.30%	3.28%	1.43%
Eberswalde EC	21%	6.17	17.5	20.9	3.23%	1.15%	0.38%
Eberswalde E	19%	7.75	20.1	22.9	5.69%	1.99%	0.50%
Mawrth 2 Total	**95%**	**6.00**	**15.5**	**18.1**	**2.15%**	**0.57%**	**0.15%**
Mawrth 2 W	16%	5.72	14.9	17.7	1.88%	0.51%	0.13%
Mawrth 2 WC	25%	5.81	14.7	17.1	1.74%	0.42%	0.10%
Mawrth 2 C	22%	6.27	16.1	18.9	2.53%	0.71%	0.20%
Mawrth 2 SC	8%	5.65	14.5	16.9	1.63%	0.40%	0.10%
Mawrth 2	23%	6.25	16.3	18.9	2.60%	0.72%	0.20%
Gale Total	**62%**	**4.46**	**10.9**	**12.9**	**0.48%**	**0.12%**	**0.04%**
Gale W	17%	4.00	9.9	11.9	0.37%	0.06%	0.00%
Gale C	21%	4.21	10.3	12.1	0.29%	0.04%	0.01%
Gale	23%	4.96	11.9	14.1	0.73%	0.22%	0.09%
Gale T1		*17.16*	*41.3*	*44.9*	*33.48%*	*22.15%*	*14.85%*
Holden Total	**50%**	**4.15**	**10.3**	**12.3**	**0.39%**	**0.08%**	**0.02%**
Holden	9%	4.38	10.1	11.9	0.26%	0.05%	0.01%
Holden C	17%	4.63	10.1	11.5	0.17%	0.01%	0.00%
Holden E	25%	3.70	10.5	13.1	0.58%	0.14%	0.03%
Holden T1		*6.45*	*17.7*	*21.1*	*3.41%*	*1.21%*	*0.49%*
Spirit		**3.73**	**10.1**	**12.1**	**0.36%**	**0.05%**	**0.01%**
Opportunity		**3.27**	**8.1**	**9.5**	**0.06%**	**0.00%**	**0.00%**
Phoenix		**1.85**	**4.1**	**4.5**	**0.00%**	**0.00%**	**0.00%**

Conclusions

- HiRISE stereo mapping is a mature technology
- HiRISE DTMs contain errors but the severe ones can be fixed and the normal ones contribute only ~1° to slope estimates
- Baselines at which slope estimates are needed are no longer at the limit of resolution, so we can really measure these slopes
- DTM coverage of candidate ellipses is very high (50–95%) and still growing
  - See http://hirise.lpl.arizona.edu/dtm/ for DTM data
  - Slopes and DTMs will be hosted on CDP pages at JPL soon
- Slopes at MSL sites range from similar to Gusev to 1.5-2x greater
  - Eberswalde > Mawrth 2 > Gale ≥ Holden = Gusev
- Traverse areas are rougher
  - That's why those sites are go-tos!
  - Acceptable traverse paths exist within the rough areas