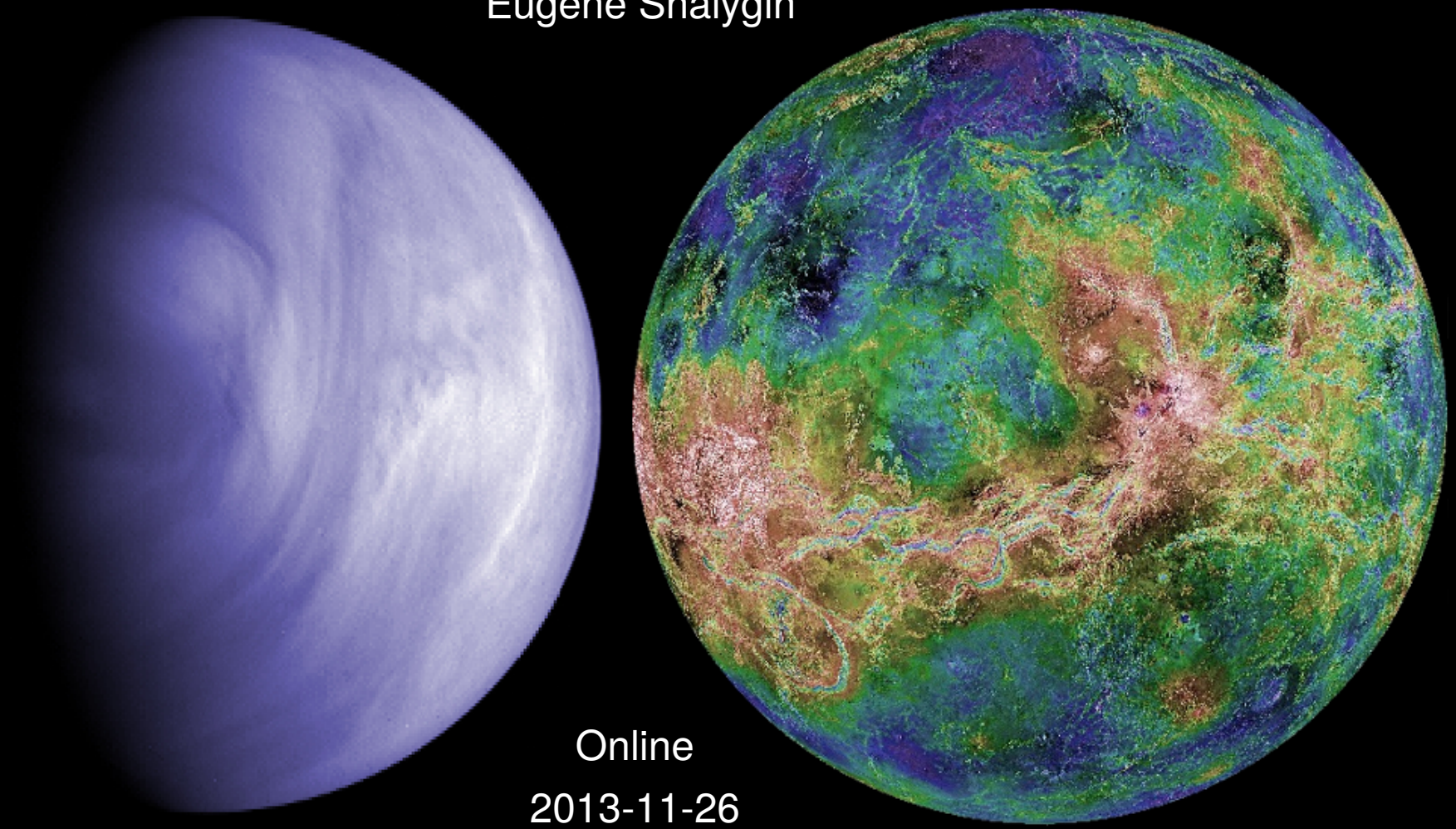
Application of cartographic methods for the Venus Express' Venus Monitoring Camera images

Eugene Shalygin



Online

2013-11-26

Outline

Part I: Introduction

Part II: Preparing the the VMC data for the analysis

Part III: Sensing the atmosphere

Part IV: Sounding the surface

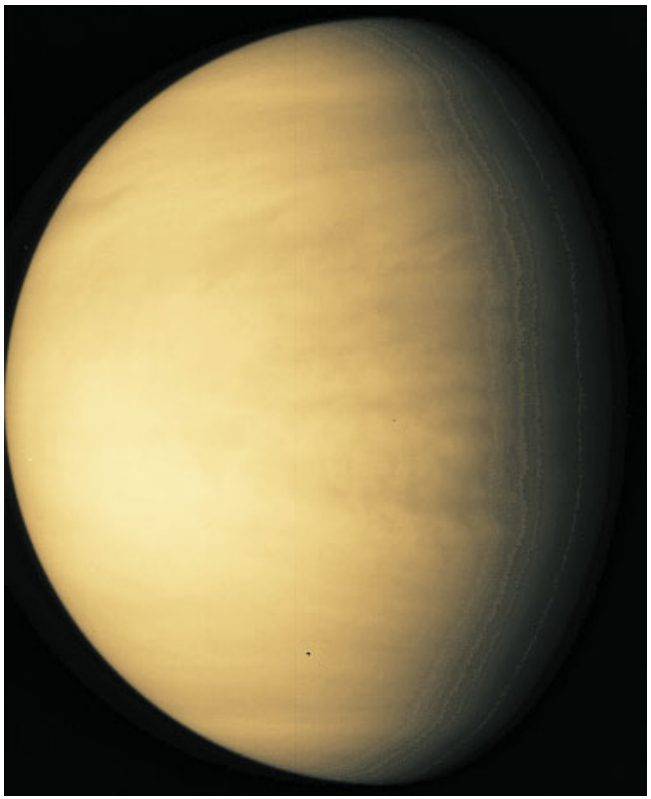
Part V: Supplementary slides

Part I

Introduction

1. Venus at a glance
   - Venus before the space missions
   - Results from the space missions
2. Remote sensing possibilities
   - Venus Monitoring Camera (VMC) experiment
   - Magellan mission
3. Data flow in a space experiment

Venus before the space missions



Venus as it seen by a naked eye

General properties

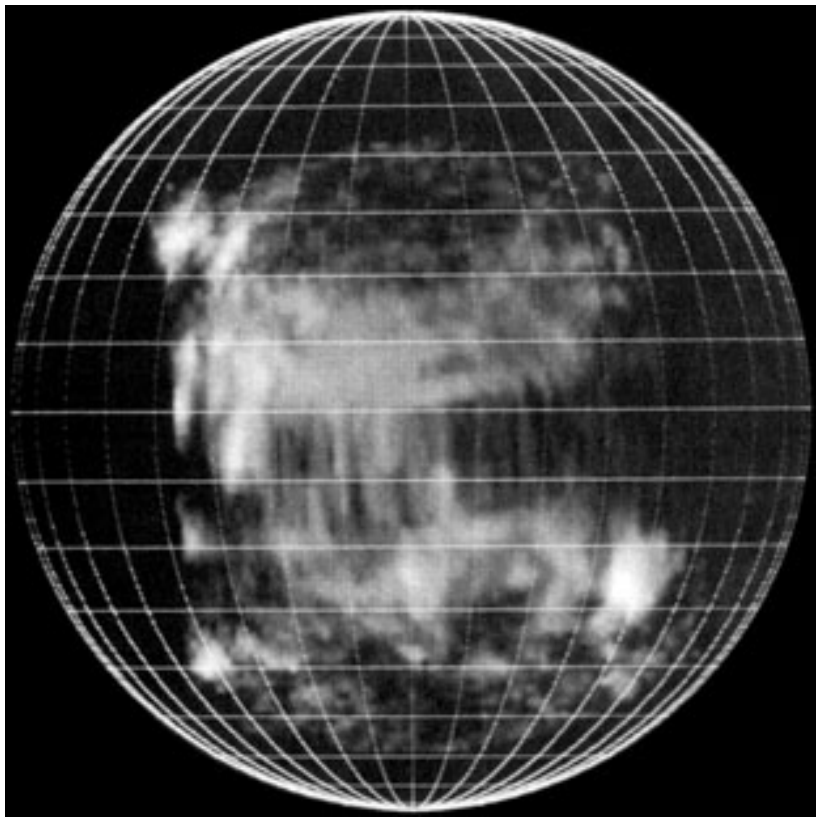
Orbit radius	0.72 ua
Mean body radius	0.95 R_{δ}
Mass	0.81 M_{δ}
Bulk density	0.95 ρ_{δ}
Surface gravity	0.91 of Earth's
Atmosphere	CO_2+N_2

Expectations were that Venus is very similar to Earth, in particular, has generally similar conditions near the surface

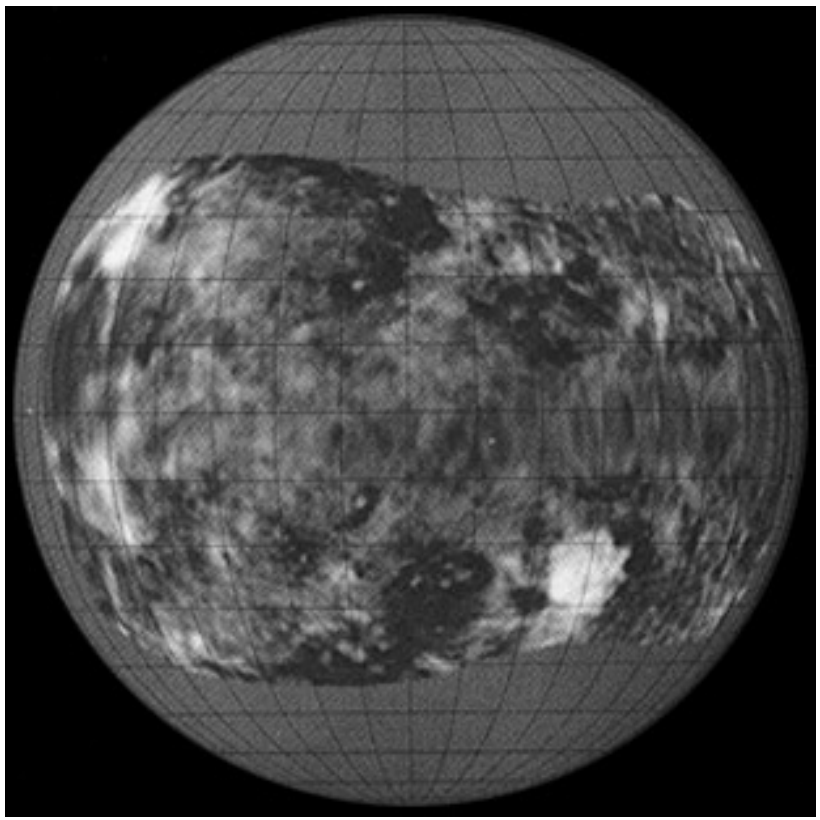
First determinations of the physical conditions

Year	Observations	Finding(s)
1932	Spectroscopy (Adams and Dunham)	Presence of CO_2 in the atmosphere
1940 – 1960	Spectroscopy (various authors)	Pressure at the clouds top level (0.1 – 5 bar)
1956	Radio (Mayer et al.)	Temperature of 600 K at 3.15 cm
1961	Radio (Kuz'min and Solomonovich)	Temperature is 600 K at $\lambda \sim 1$ cm and 300 K at $\lambda \sim 1$ mm
1961 – 1964	Radars at Goldstone, Arecibo, and Ευπατορια	First images of the surface, determination of the rotation period
1962 – 1963	Star occultations (Sagan)	Atmospheric pressure is more than 10 bar
1965	Radio (Clark and Kuz'min)	Emission from the edge of the planet at 3.02 cm is partially polarized
1968	Absolute photometry (Irvine)	$A = 0.77 \pm 0.07$ that gives $T_e = 228$ K
1974 – 1975	Polarimetry (Hansen et al.)	Upper clouds consist of $\sim$ 1 µm droplets of 75 % H_2SO_4
1984	Photometry (Allen and Crawford)	Near infra-red transparency "windows" in the atmosphere

First radar images of the surface



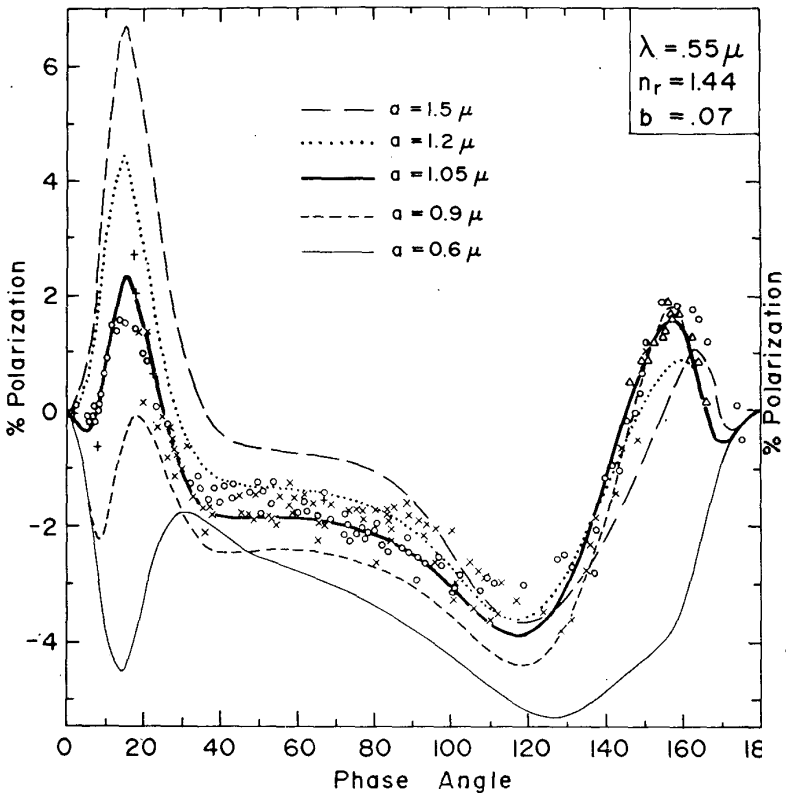
Hayford Antenna (MIT), 1967



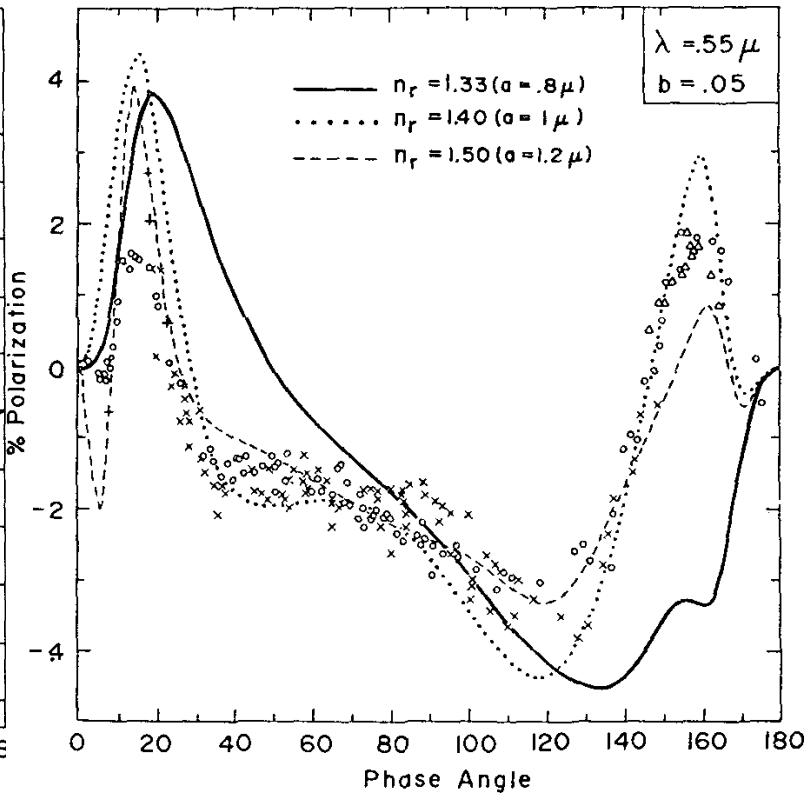
Goldstone Antennas (JPL), 1972

Maps of the radar albedo

Determination of the particles composition



Variations of the effective radius



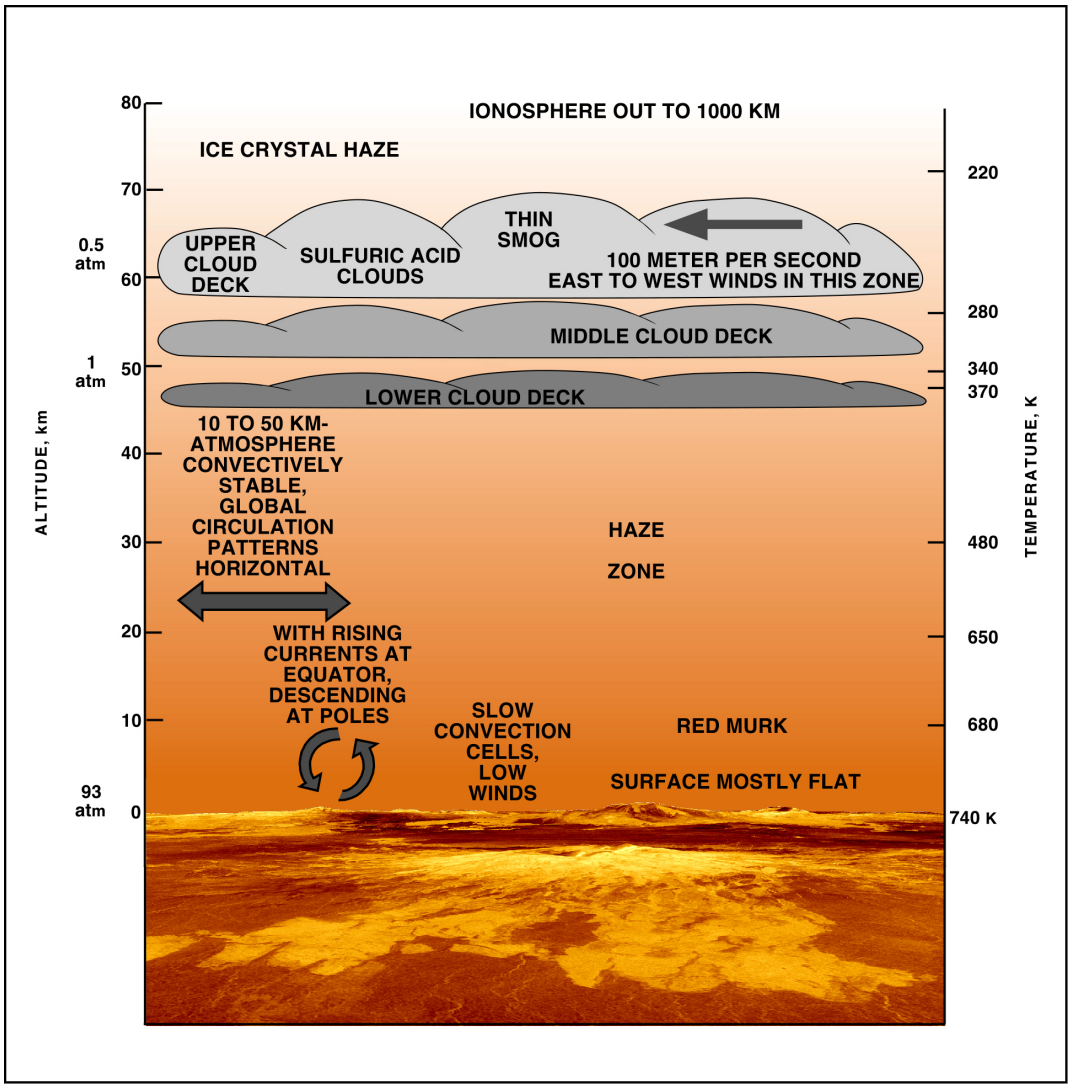
Variations of the refractive index

Observations of the polarization of sunlight reflected by Venus in the visual wavelength region and the theoretical computations for $\lambda = 0.55$ µm

23 successful missions to Venus

Venus Express	**2005**	**EU/ESA**	**Orbiter**
Galileo	1990	USA/NASA	Flyby on the route to Jupiter
Magellan	1990	USA/NASA	Radar orbiter
Vega 1	1985	USSR	Baloon, soft landing, geochemistry
Vega 2	1985	USSR	Baloon, soft landing, geoghemistry
Venera 15	1983	USSR	Orbiter, radar mapping
Venera 16	1983	USSR	Orbiter, radar mapping
Venera 13	1982	USSR	Entry probe, soft landing, geochemistry
Venera 14	1982	USSR	Entry probe, soft landing, geochemistry
Pioneer Venus Orbiter	1978	USA/NASA	Radar mapping
Pioneer Venus Entry	1978	USA/NASA	Entry probes
Venera 11	1978	USSR	Entry probe, soft landing
Venera 12	1978	USSR	Entry probe, soft landing
Venera 9	1975	USSR	Soft landing, TV panorama, K, U, Th
Venera 10	1975	USSR	Soft landing, TV panorama, K, U, Th
Mariner 10	1974	USA/NASA	Flyby
Venera 8	1972	USSR	Soft landing, K, U, Th
Venera 7	1970	USSR	Soft landing
Venera 5	1969	USSR	Entry probe
Venera 6	1969	USSR	Entry probe
Venera 4	1967	USSR	Entry probe
Mariner 5	1967	USA/NASA	Flyby
Mariner 2	1962	USA/NASA	Flyby

Atmosphere structure



Bulk properties

Total mass	4.8×10^{20} kg
	$(0.96\times10^{-4}M_{\varphi})$
P_{surface}	93 bar
ρ_{surface}	65 kg/m^3
T_{surface}	737 K (464 °C)

Composition

CO_2	96.5 %
N_2	3.5 %

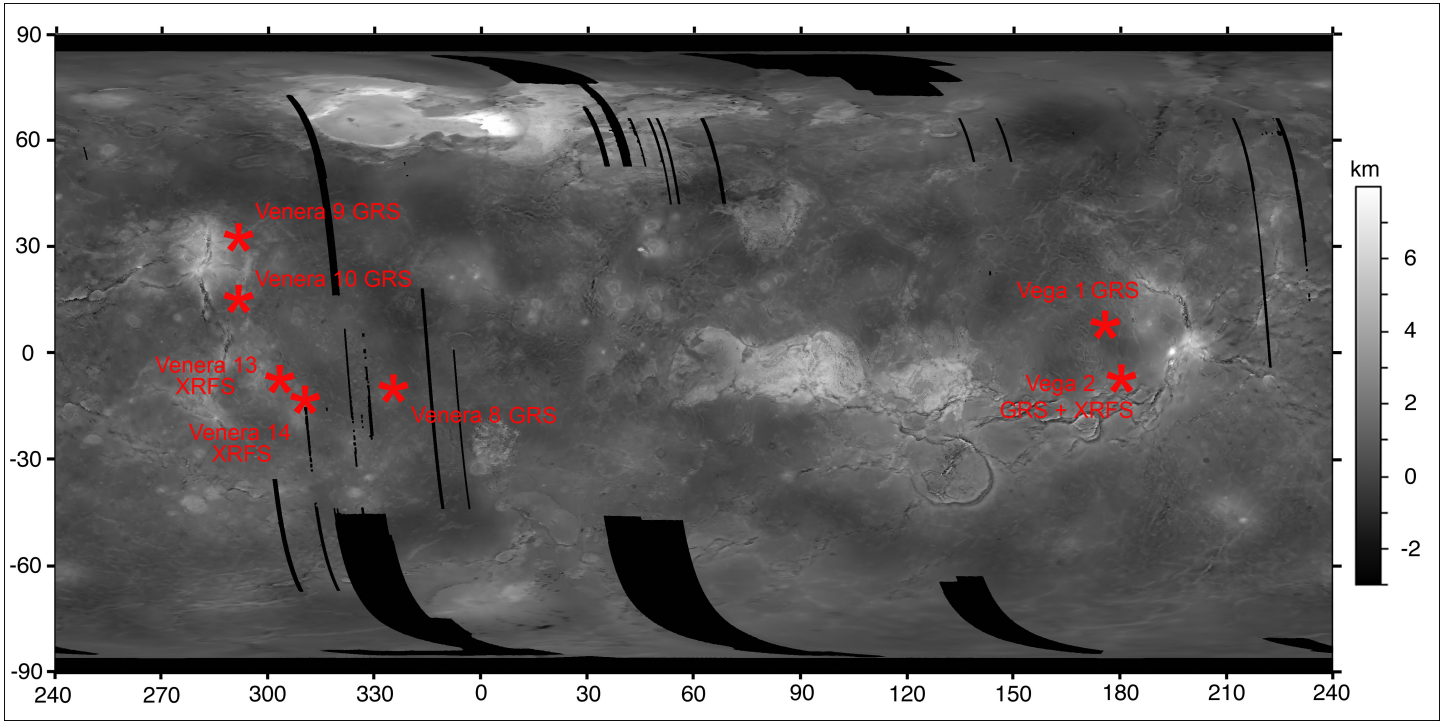
Clouds

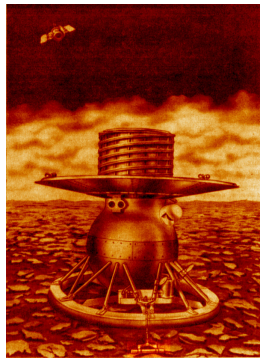
Total τ	20 – 40

Three cloud decks

Altitude	45 – 75 km
Composition	H_2SO_4 droplets

Venera and Vega *in situ* measurements



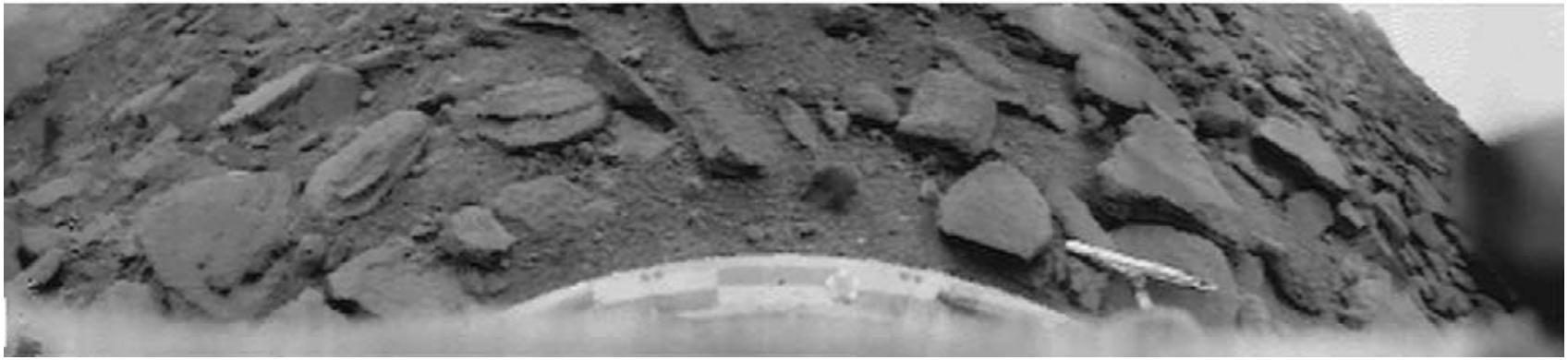


GRS — Gamma Ray Spectrometer

XRFS — X-Ray Fluorescence Spectrometer

Spectrometers showed basaltic composition of the soils

Surface TV-panoramas



Venera-9, inside the large continent of Beta Regio, on 22 October 1975

Venera-14, near the eastern flank of Phoebe Regio, on 5 March 1982

Panoramas of the surface of Venus obtained by Venera-9 and Venera-14

Remote sensing of the Venus atmosphere

Earth-based

- Any analyser of the electro-magnetic waves could be used.
- Very limited coverage in terms of phase angles.
- Very limited coverage in terms of surface regions.
- Transparency “windows” in Earth and Venus atmospheres do not always coincide.

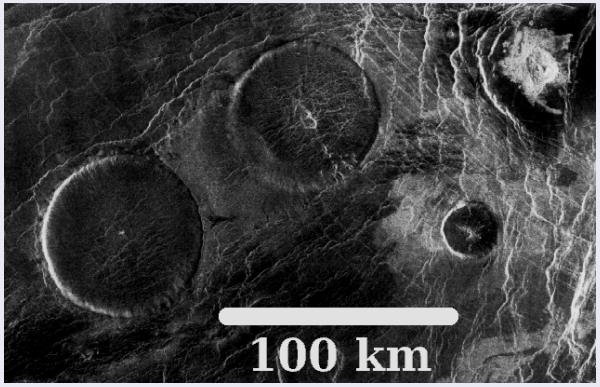
From the space

- Almost the whole range of phase angles is accessible from orbit.
- Much higher resolution can be achieved in optical range.
- Whole surface is accessible.
- Usually tight constrains on used instruments.
- Instruments are inaccessible after the launch.

Remote sensing of the Venus surface

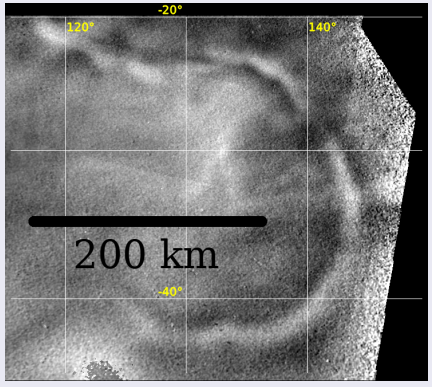
Microwave

- Transparent atmosphere
- No blurring
- Emission is formed or reflected by thick layer
- Low orbit is needed
- Low sensitivity to surface temperature
- Panoramic detectors do not exist

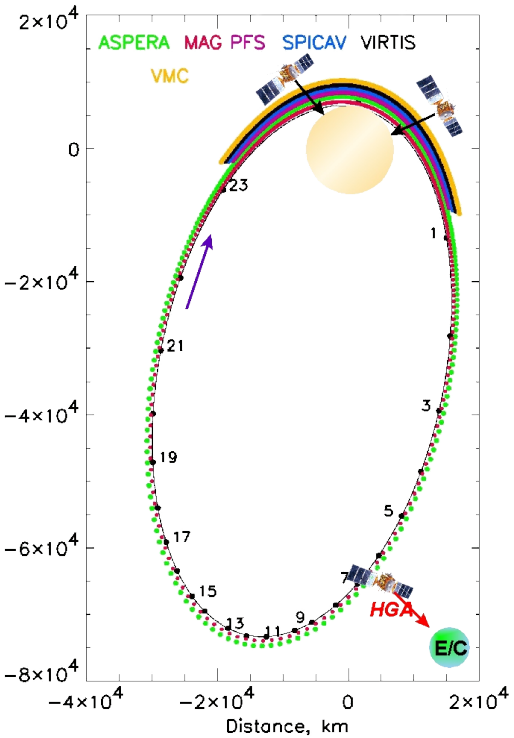


Near infra-red

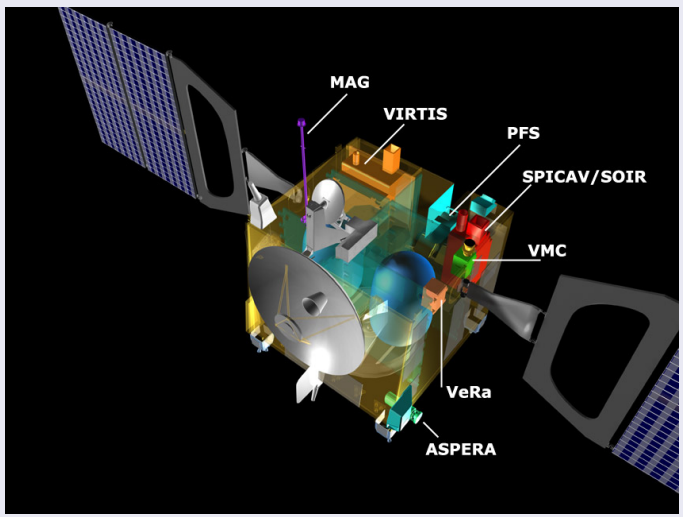
- Sensitive to mineralogical properties
- Sensitive to surface temperature
- Detector can be much more simple
- Resolution is limited to ~ 50 km
- Observations are possible at night-side only
- Stray light limits observations geometry even further



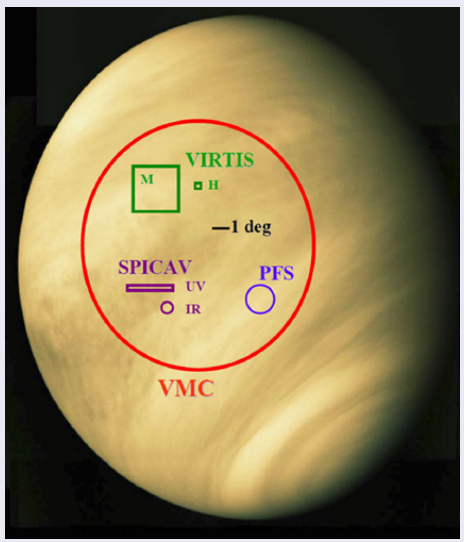
Venus Express



VEX payload



Fields of view

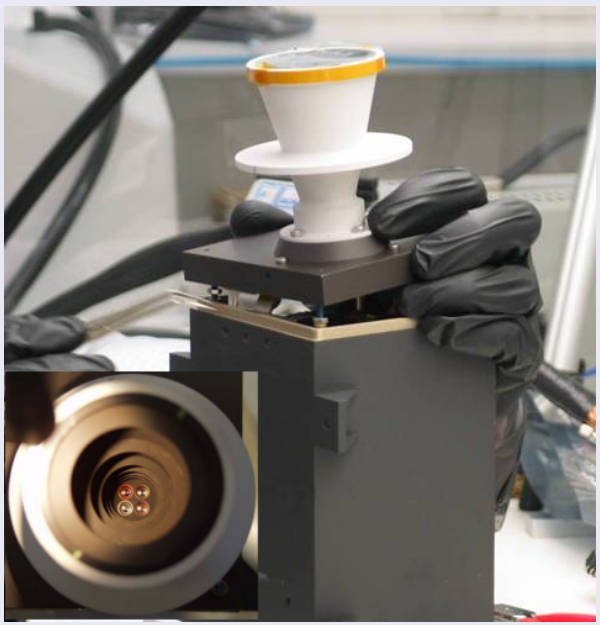


Highly elliptical polar orbit

- Orbital period is 24 hours
- Altitudes: $\sim$ 200 km in periapsis, $\sim$ 66 000 km in apoapsis

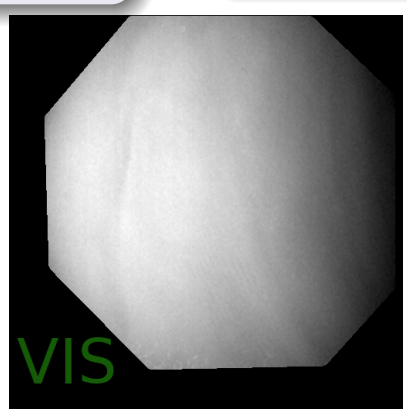
Venus Monitoring Camera

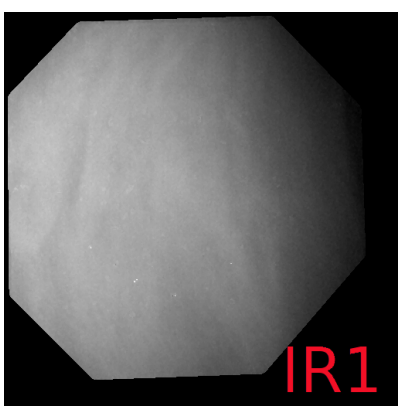
Optics

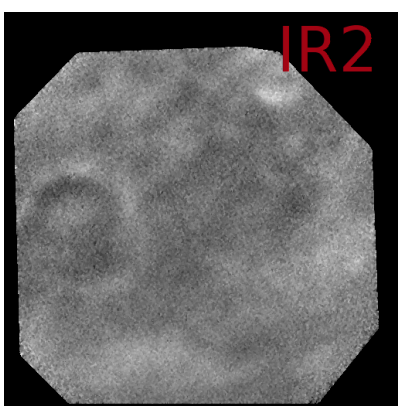


Characteristics

Total field of view	$\approx 17.5°$ (0.3 rad)
Image scale	≈ 0.74 mrad/px
Filters	
UV	365 / 40 nm
VIS	513 / 50 nm
NIR1	965 / 40 nm
NIR2	1000 / 40 nm
F-number	UV: 7; VIS, NIR1, NIR2: 5







Main VMC science goals

UV Distribution and nature of the unknown UV absorber. Atmospheric dynamics at the cloud tops.

VIS Mapping O_2 night-glow and its variability.

NIR1 Properties of the particles in the main cloud deck.

NIR2 Thermal mapping of the surface in the 1 µm transparency "window" on the night side

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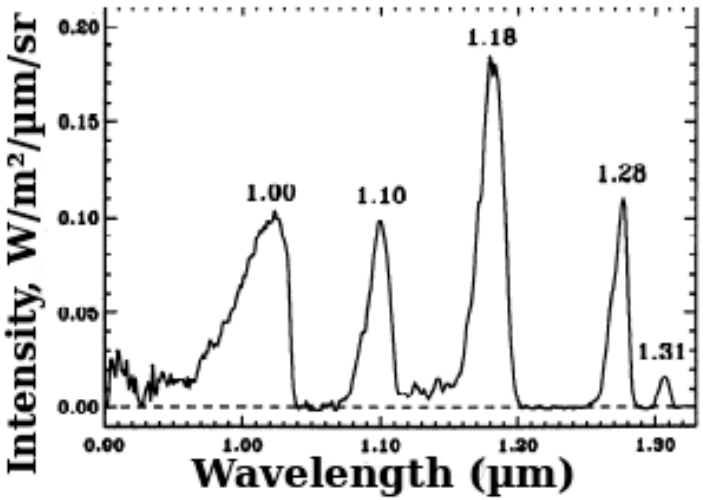
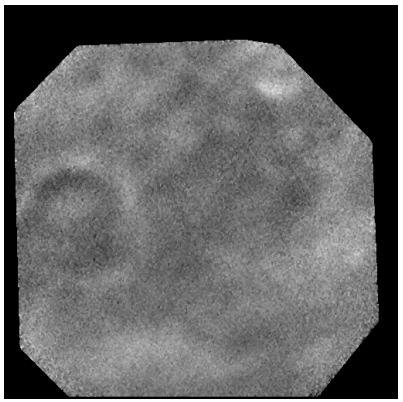
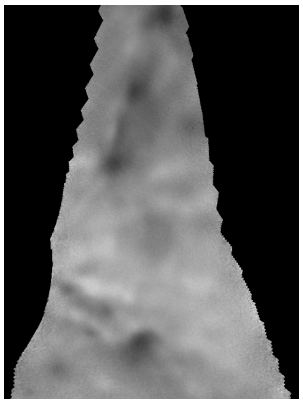
Surface through the atmosphere



Windows in Venus atmosphere. VMC uses 1.01 μm transparency window



Sith Corona from orbit 1376

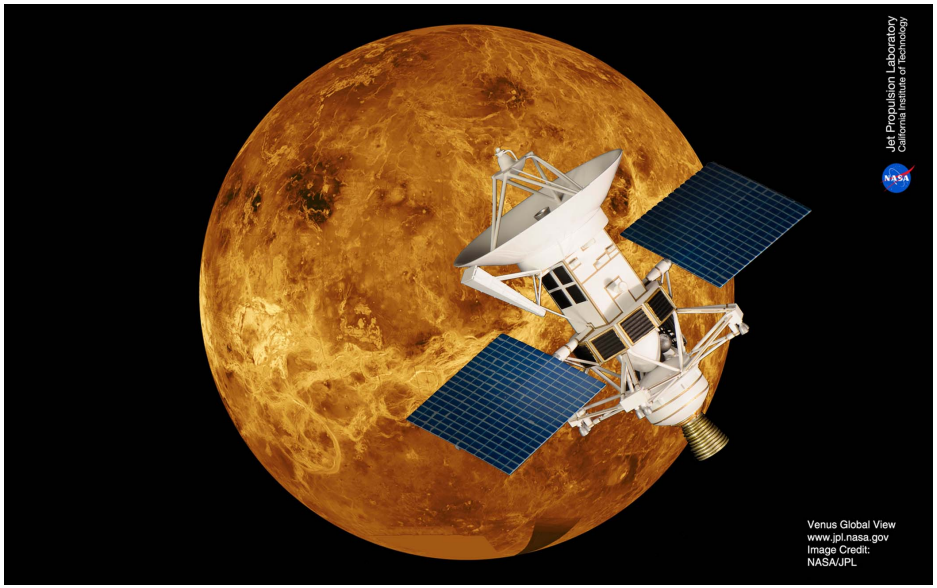


Mosaic for orbit 0679

Venus surface through 1.01 μm window as seen by VMC

Windows in near infra-red part of spectra can be used to register thermal emission of the surface on the night side.
Emission in 1.01 μm window contains $\approx 95\%$ radiation from surface and the rest from the atmosphere. However, these 95% scatter on clouds with optical thickness $20-40$ that reduces level of details significantly.

Magellan Venus Radar Mapping Mission



Launch date	May 4, 1989, by NASA.
Orbital insertion	August 10, 1990.
Decay date	October 13, 1994.

- Radar operated in 3 modes: synthetic aperture radar (SAR), altimetry (ALT), and radiometry (RAD).
- During the mission SAR and altimeter have mapped $\approx 98\,\%$ of the surface.
- Topography data obtained with vertical accuracy of $80\,\text{m}$ and spatial of $\approx 4\,\text{km}$.
- Resolution of the SAR is $0.1 - 0.25\,\text{km}$.

MGN GxDR datasets

- The Global Topography Data Record (GTDR), Global Emissivity Data Record (GEDR), Global Slope Data Record (GSDR), and Global Reflectivity Data Record (GREDR).
- Each of them consists of frames in Mercator or Sinusoidal projection for the latitudes $66°\text{S} - 66°\text{N}$ and in Stereographic for the latitudes higher than $32°$.

One can take a look at GxDR data at www.mapaplanet.org

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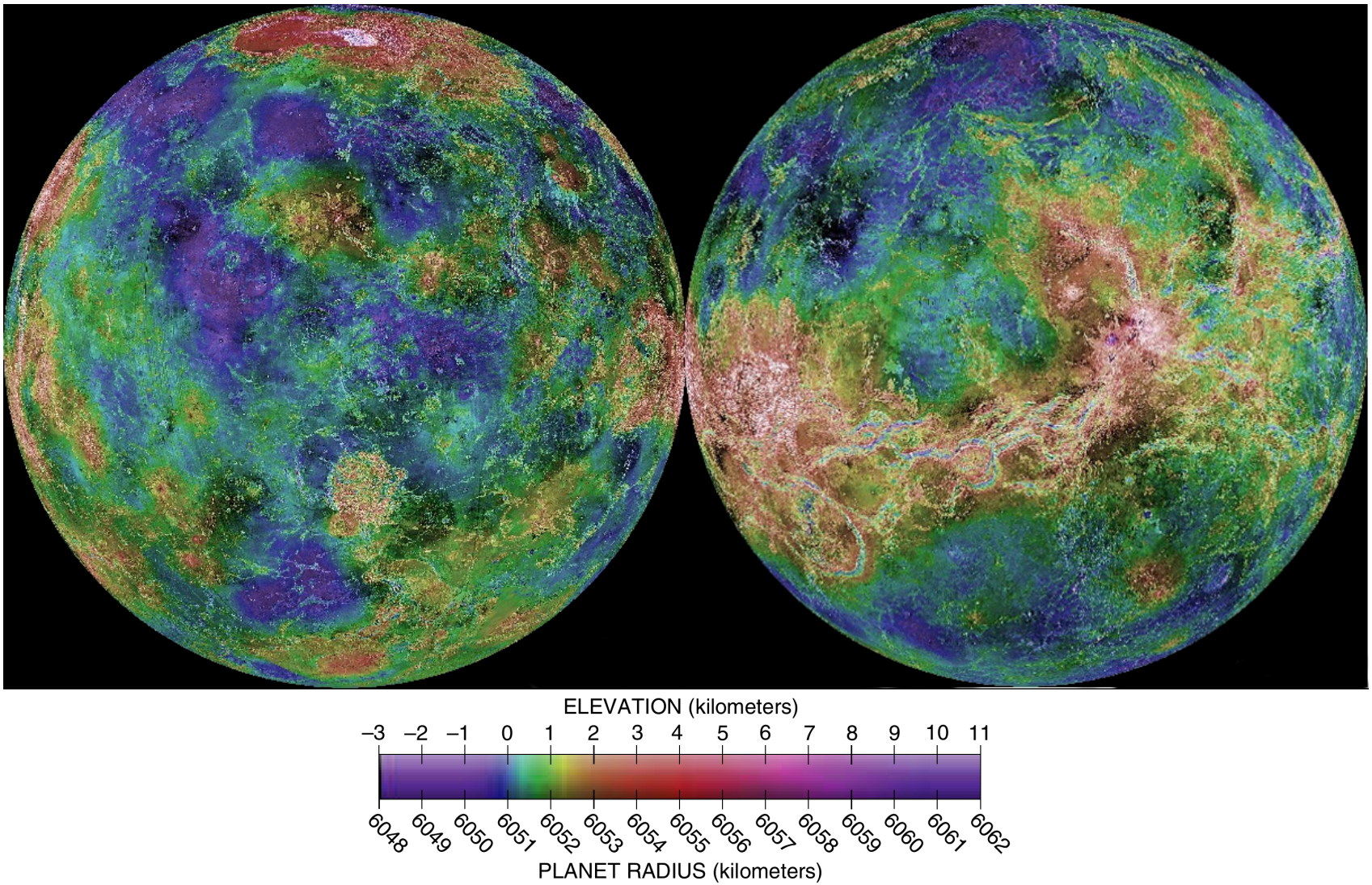
- In order to use these data together with data from an orbital experiment, both of them must be transformed into the same projection, possibly making new mosaics.

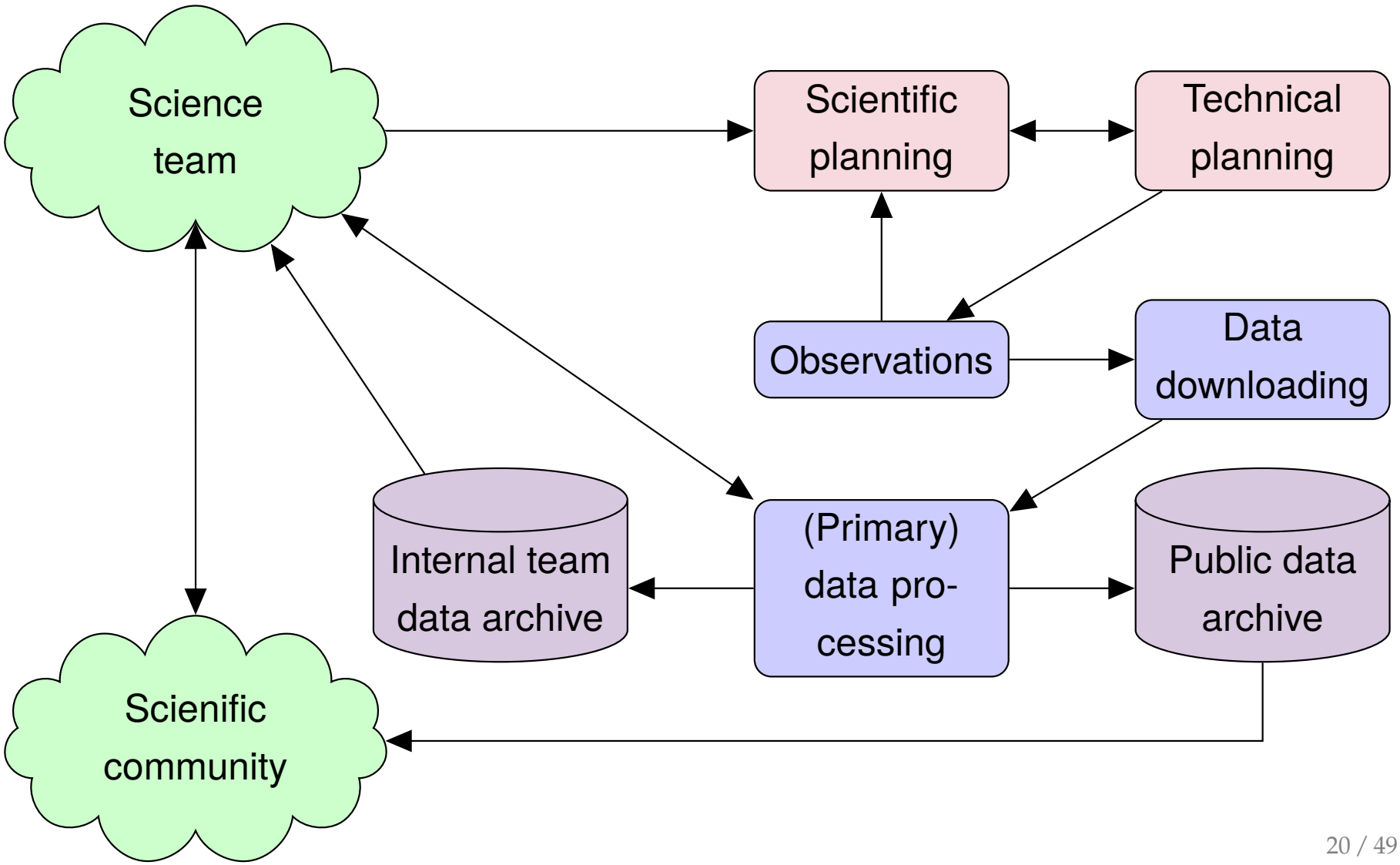
One can take a look at GxDR data at www.mapaplanet.org

Topography map of Venus created from the Magellan radar data

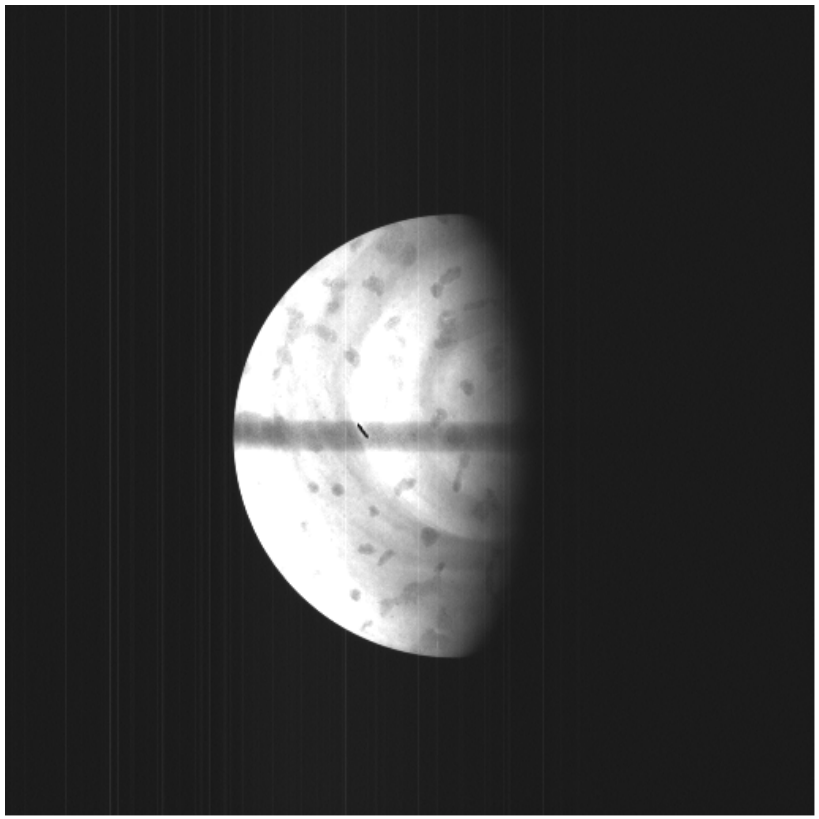


Magellan altimetry maps, centered at 0° and 180°E longitude

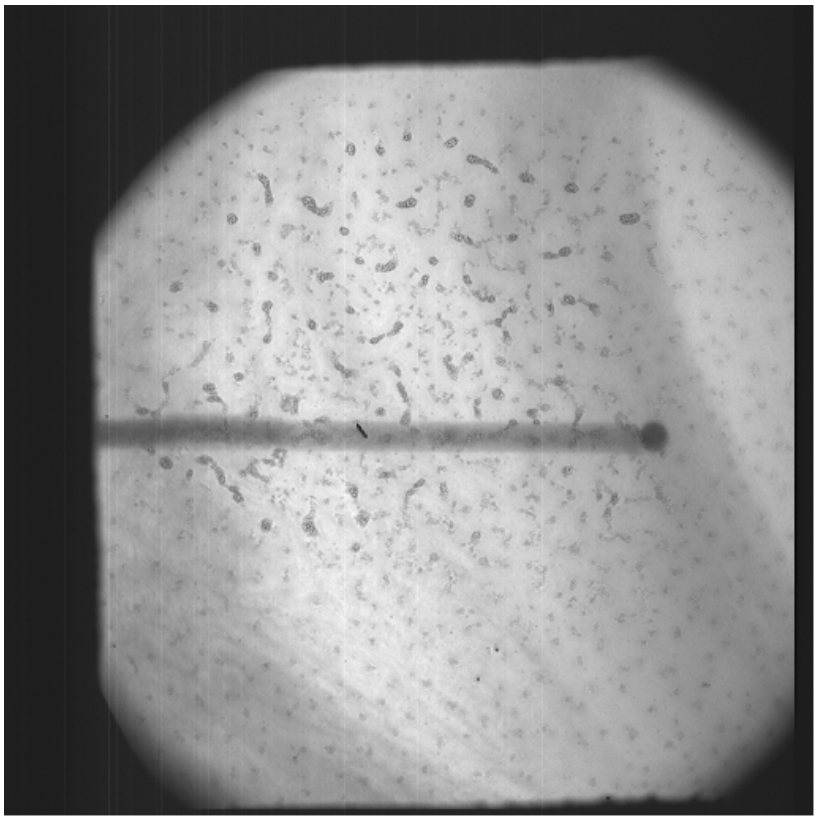
Data flow in a typical ESA' space experiment



Raw VMC data



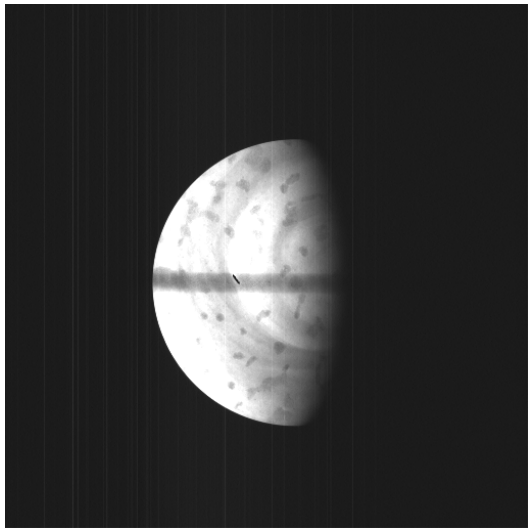
UV, Orbit #470, image #10

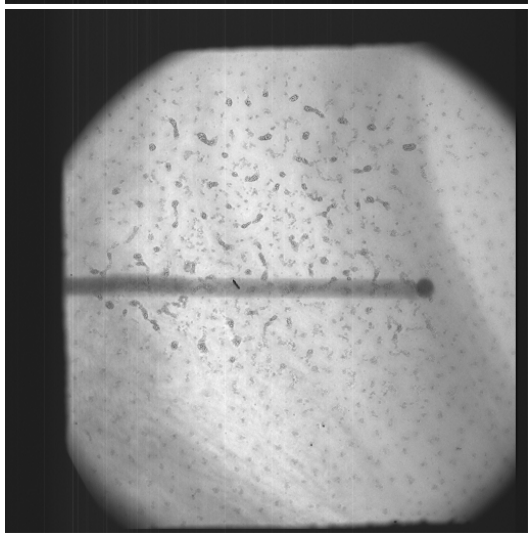


UV, Orbit #2032, image #44

Primary processing (UV)

12 and 15 ms exposure





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Primary processing (UV)

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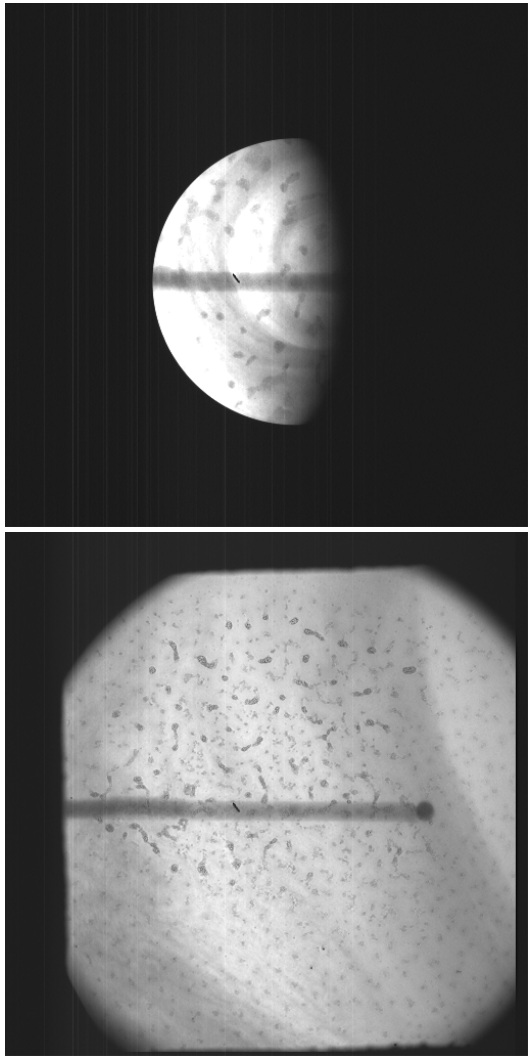
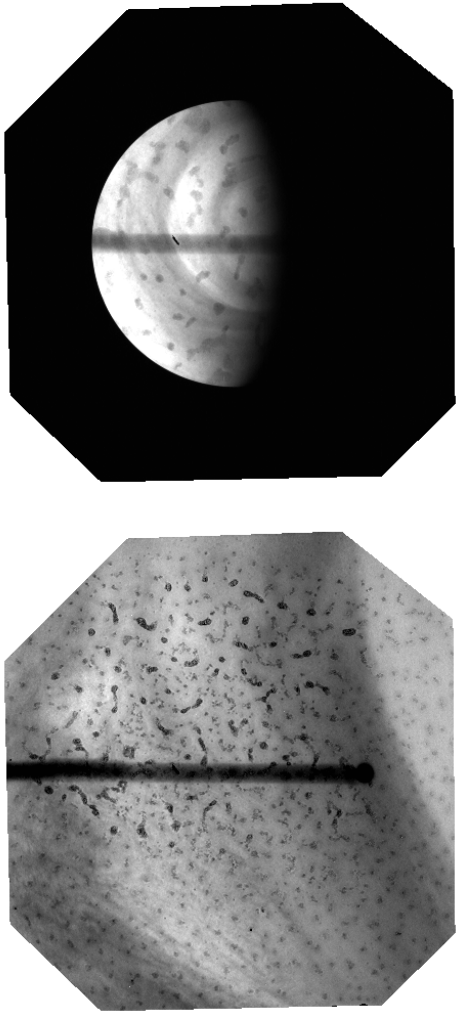
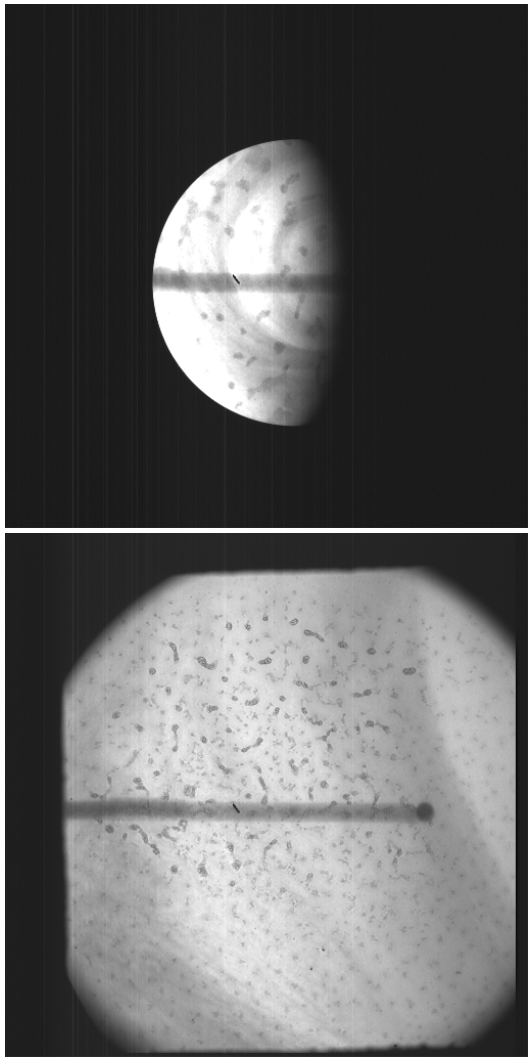




1 2

Primary processing (UV)

12 and 15 ms exposure



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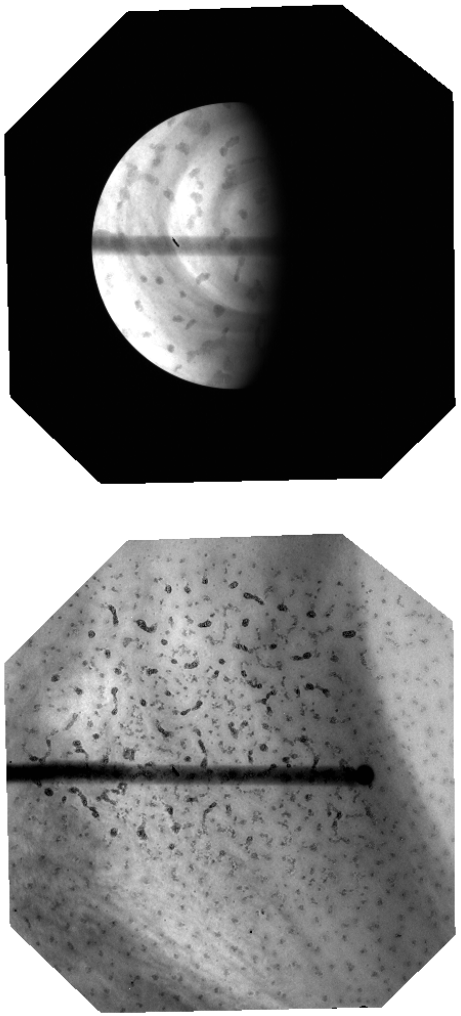

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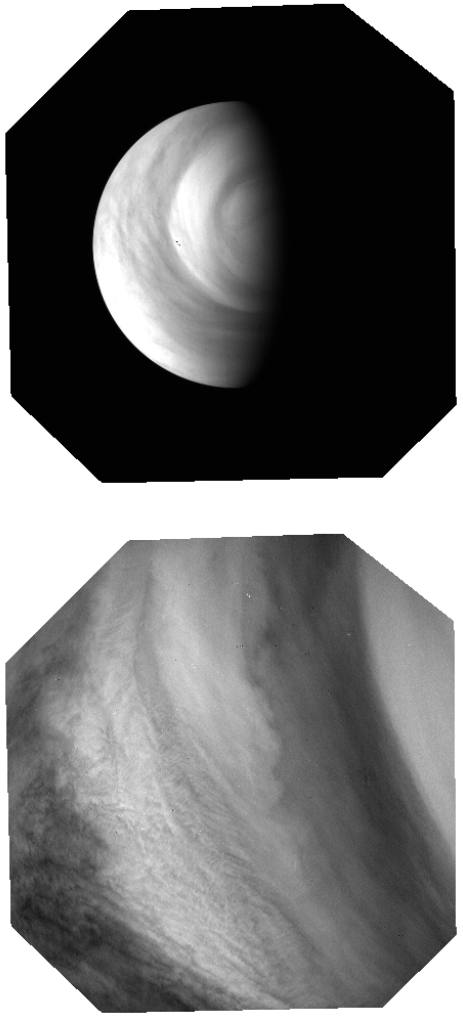
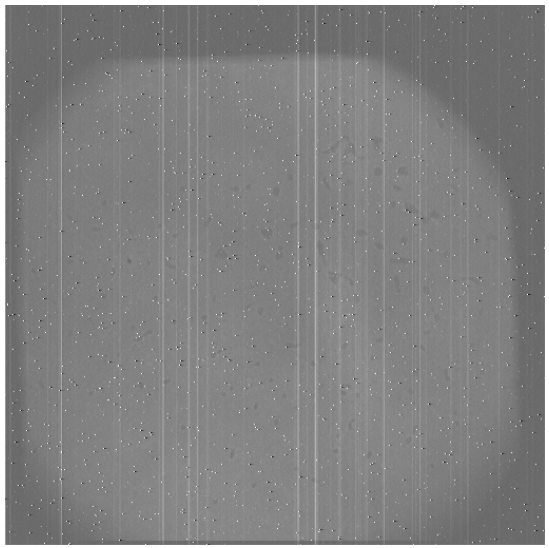


3

Primary processing (NIR2)

30 seconds exposure!



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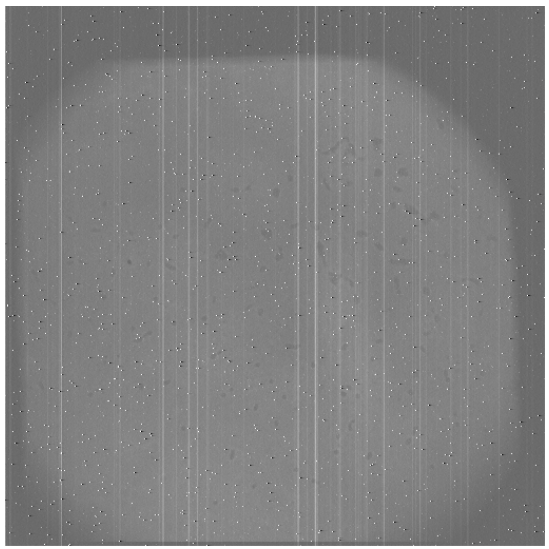
Primary processing (NIR2)

30 seconds exposure!



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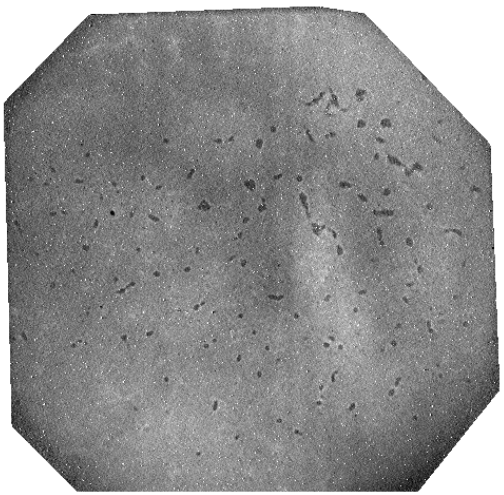

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Primary processing (NIR2)

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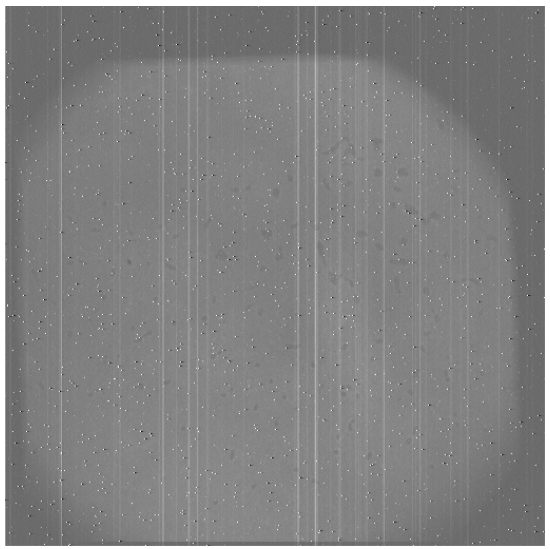
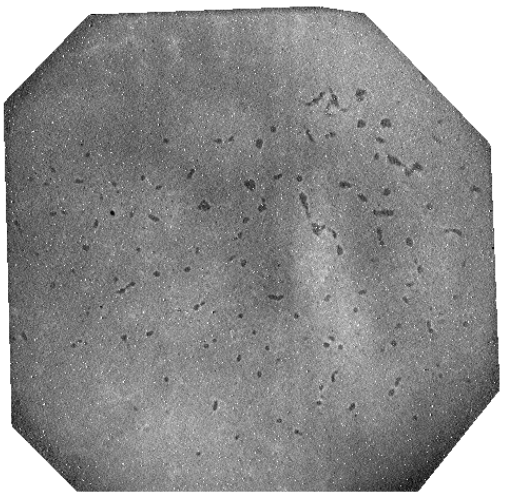
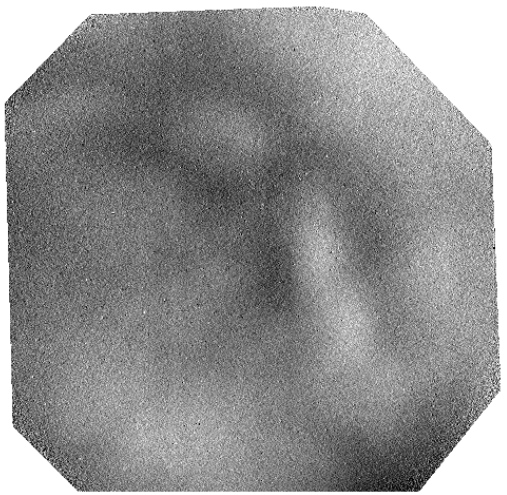


1



2



3

Part II

Preparing the the VMC data for the analysis

4 Motivation

5 The SPICE toolkit

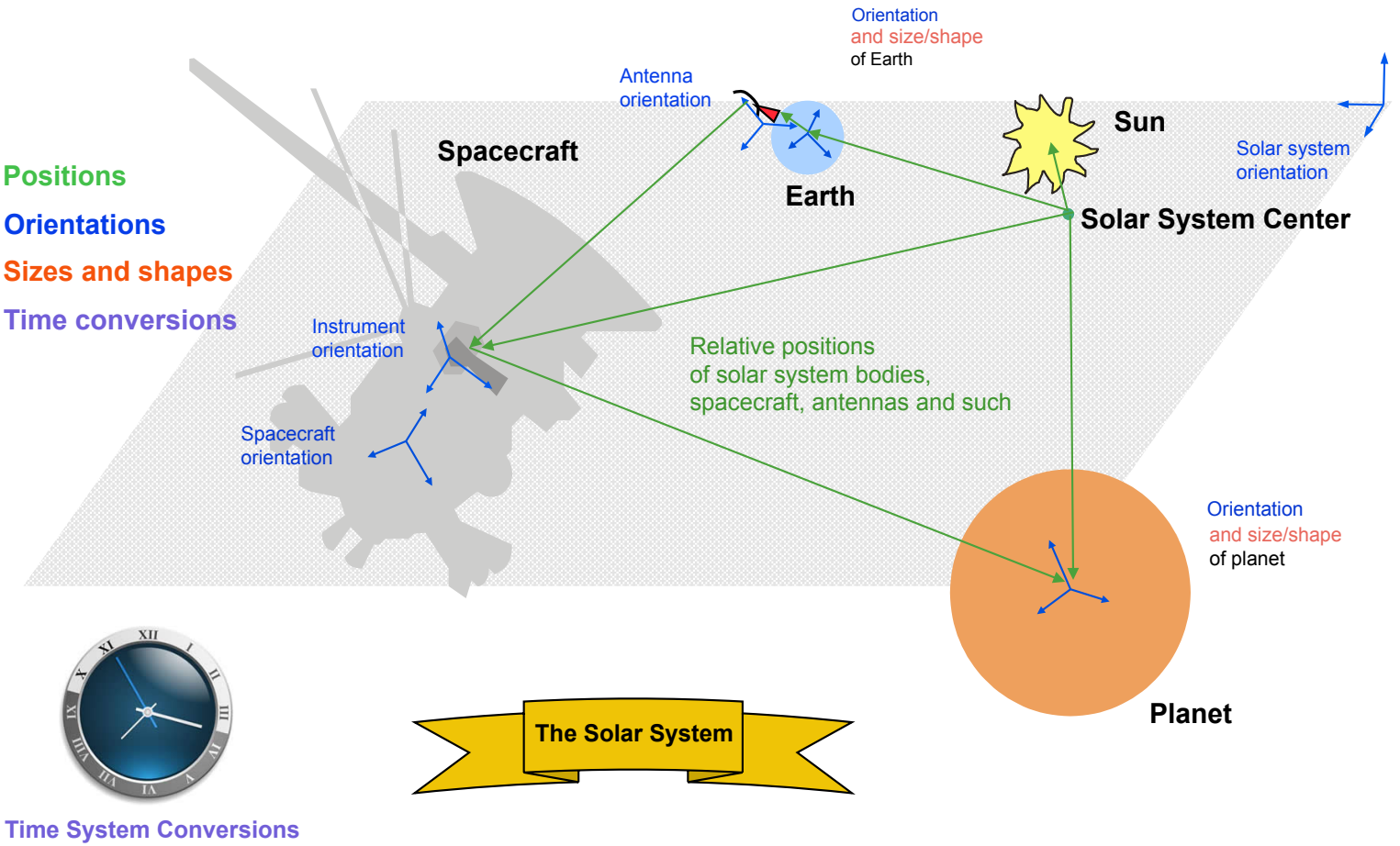
6 Pre-calculating the navigation data

Why can't the images be analysed straight away?

1. For photometrical tasks photometrical coordinates have to be added.
2. Moreover, local solar time (LST), latitude and longitude are often needed also (and the last ones are crucial for surface studies).
3. To date VMC obtained more than $250\,000$ images $\Rightarrow$ data selection is needed basing on various parameters.
4. Images of the clouds are taken from various distances $\Rightarrow$ accounting for varying pixel size is needed.
5. SNR for the surface images is only ≈ 4 $\Rightarrow$ averaging (mosaicking) is needed.

enumeration can be continued

Solar System Geometry



Credits to of Navigation and Ancillary Information Facility (NAIF)

The NAIF' SPICE Toolkit

Geometry and event data for space missions

The principle components of the SPICE system are SPICE Toolkit software and SPICE data files — often called "kernels."

- The software is freely available from the NAIF web-site.
- Common SPICE data files (the ones describing the solar system) are available from the same web-site.
- Mission-specific data files (that deal with the given spacecraft and the instrument(s) are available from the mission team (usually they can be obtained from NASA PDS/ESA PSA).

What can one get from the toolkit?

1. General information about the target.
2. General information about the instrument.
3. For a given time position and attitude of the given planet in a given frame.
4. For a given time position and attitude of the given instrument in a given frame.

The SPICE data files

What the mission-specific files look like? They contain:

- Long-long sequences of attitude of the spacecraft.
- Sequences of attitude of the instruments (if applicable).
- Description of the instrument in form of comments in the files.
- Spacecraft geometry.

Position and orientation of the spacecraft are often stored in binary format, while the rest of the data is in ASCII text files.

SPICE advantages and shortcomings

- Is not ready-to-use system, but an API. Or this is actually an *advantage?*
- Standard system used for both the planning and analysis of the experiments. Evolution of the system is very slow.
- Available for C, FORTRAN, IDL, and Matlab. API is very primitive.
- Can compute all the navigation parameters needed for analysis of space experiments results. Could be overcomplicated in a simple use-case.
- SPICE API is *stateless* $\Rightarrow$ the same calculations are repeated over and over. Errors are not accumulated.

SPICE advantages and shortcomings

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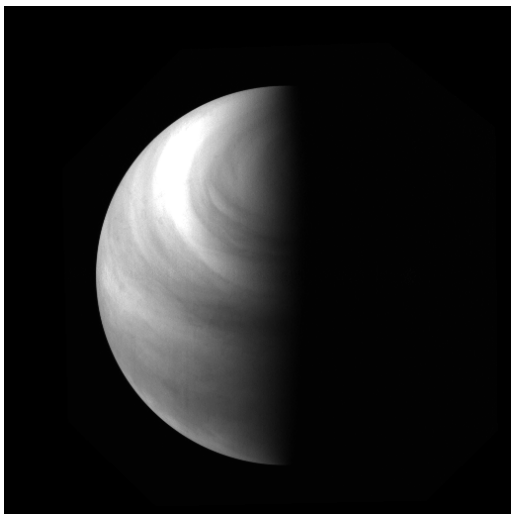
For practical use the SPICE system must be surrounded by higher level layer

Required and optional parameters

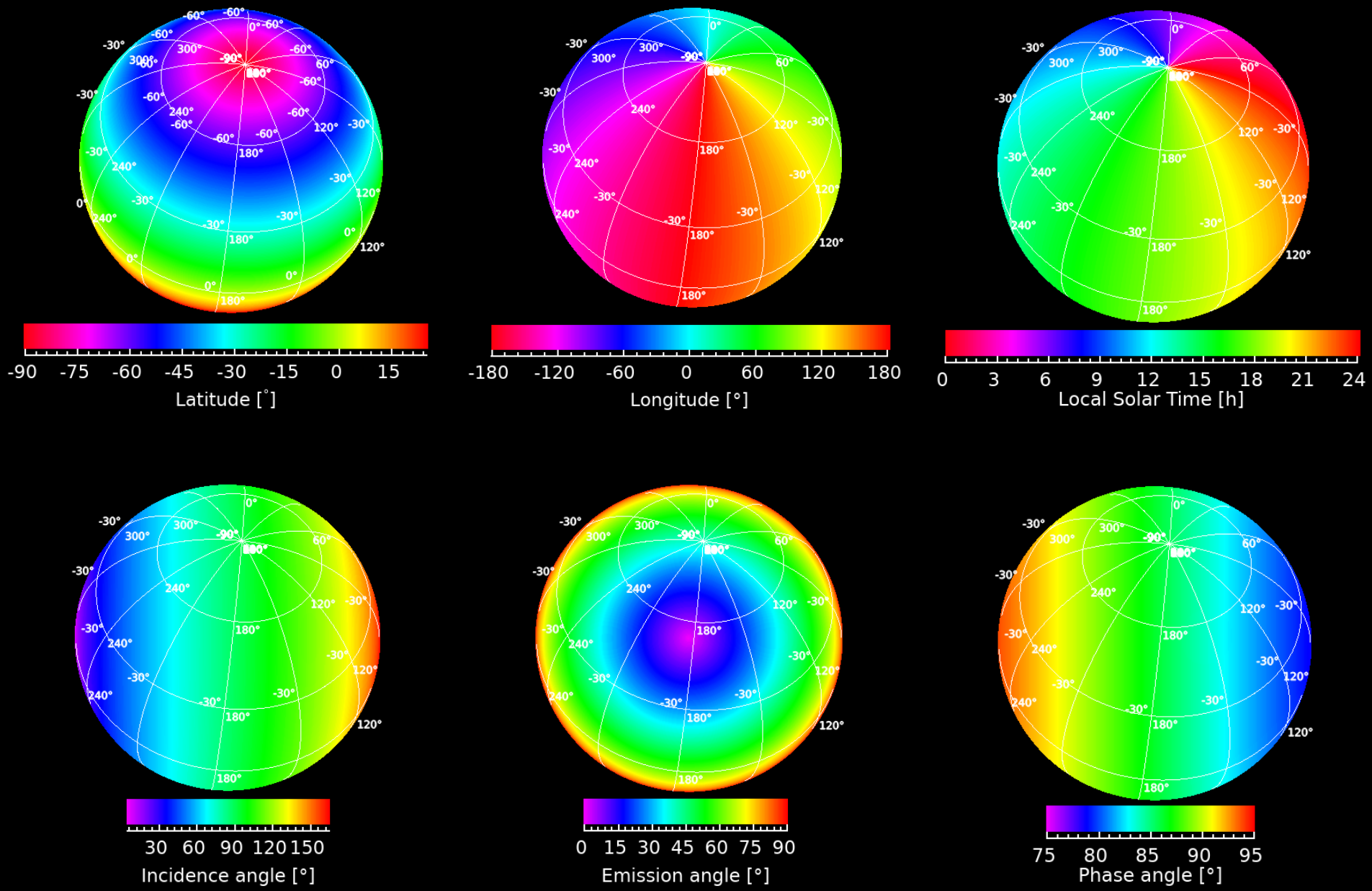


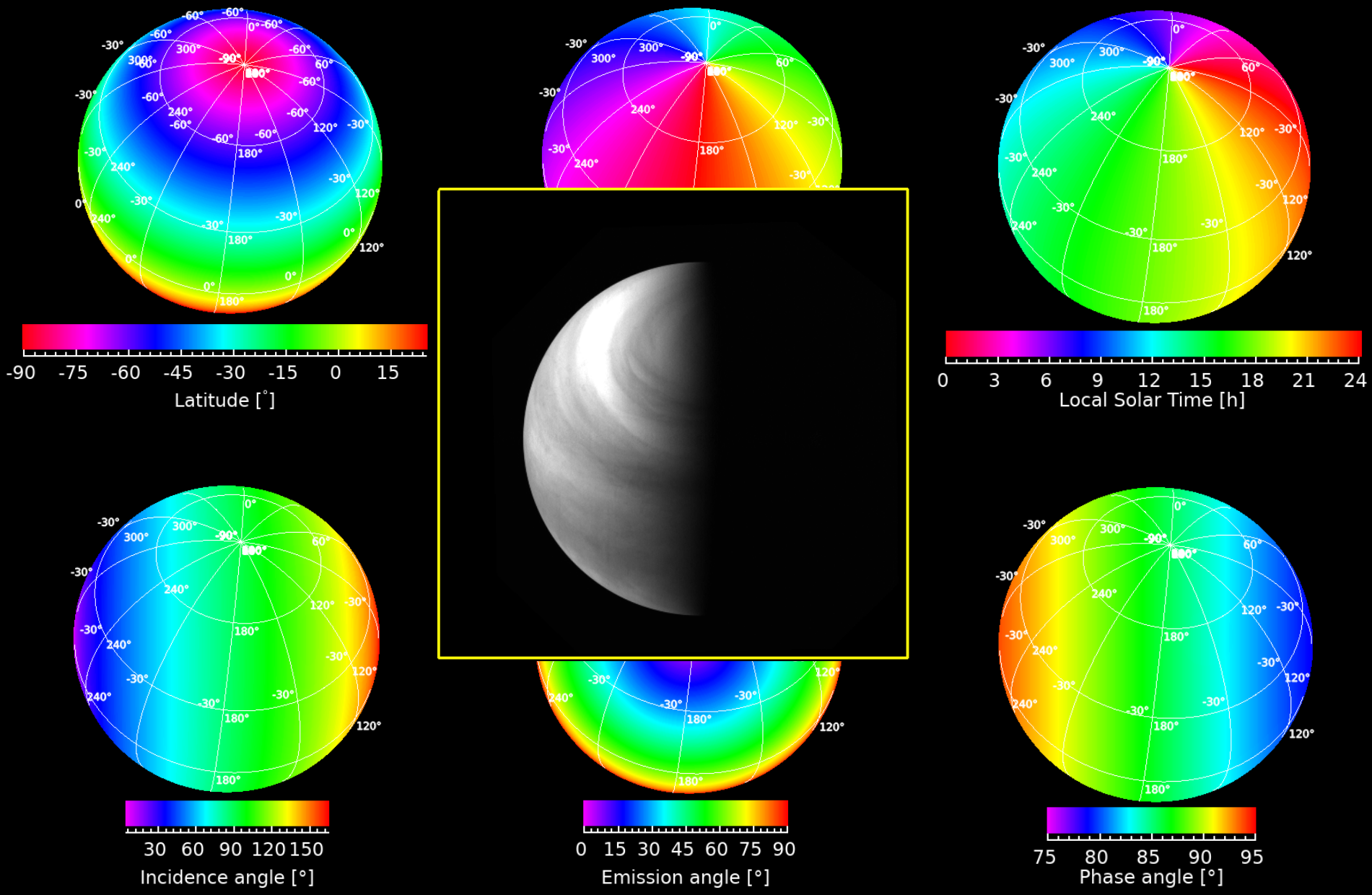
Required

1. Planetocentric co-ordinates φ, λ (or another equal pair).
2. Photometric angles ι,ε,α (or another equal triplet).
3. Distance from the camera to the planet.

Optional

1. Co-ordinates of Sun in the planet frame.
2. Co-ordinates of the camera in the planet frame.
3. Local solar time.


-90 -75 -60 -45 -30 -15 0 15
Latitude [°]
-180 -120 -60 0 60 120 180
Longitude [°]
0 3 6 9 12 15 18 21 24
Local Solar Time [h]
30 60 90 120 150
Incidence angle [°]
0 15 30 45 60 75 90
Emission angle [°]
75 80 85 90 95
Phase angle [°]


-90 -75 -60 -45 -30 -15 0 15
Latitude [°]
0 3 6 9 12 15 18 21 24
Local Solar Time [h]
30 60 90 120 150
Incidence angle [°]
0 15 30 45 60 75 90
Emission angle [°]
75 80 85 90 95
Phase angle [°]

Pre-calculated navigation database

Data

Images of:

- maps of longitude, latitude, local solar time, incidence, emergence, and phase angles.

Index

ASCII table with:

1. minimal and maximal values of all the above listed parameters.
2. Orbital parameters such as distance to the planet, time after periapsis, *etc*.
3. Camera-specific info such as exposure time, CCD temperature, minimal and maximal DNs.

Queries to the database

Input

1. Condition for any of the parameters mentioned above.
2. Some additional conditions such as pixel coordinates, saturated values, orbit and image numbers.
3. List of values to return.
4. Format of the results.

Output

- List of VMC images whose pixels satisfy query conditions.
- List of VMC pixels with their values and corresponding parameters that suit the query.
- Part of the index file with the relevant records.

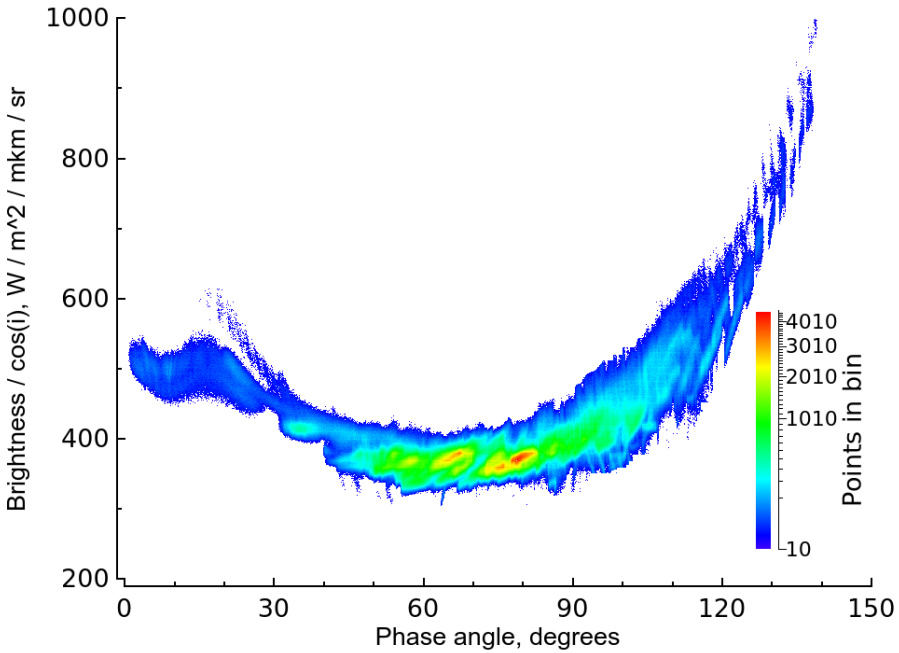
Part III

Sensing the atmosphere

7 Phase function

8 Looking for brightness variations

Phase function of the Venus clouds in NIR1

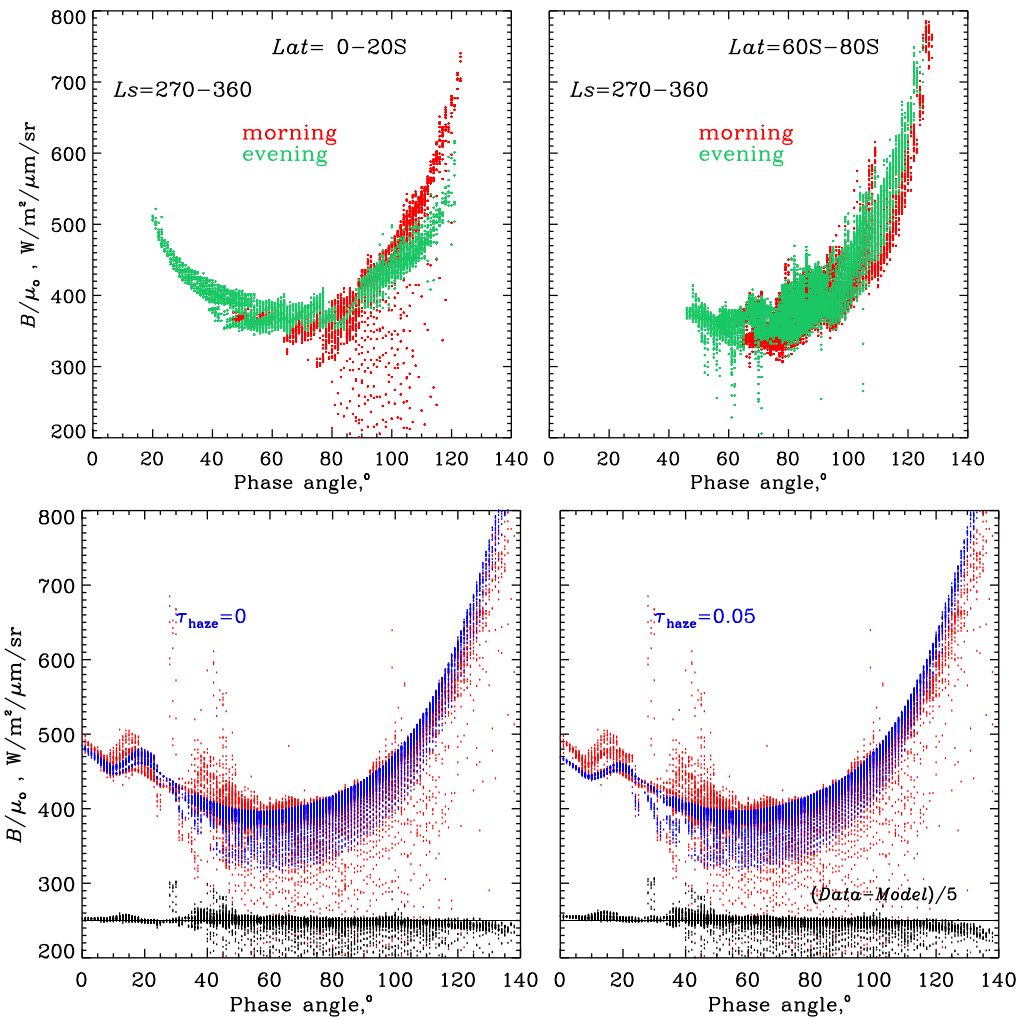


Phase function for $\iota \approx 70°$

Result of query to the database with parameters (more than 13×10^6 points):

- $68° < \iota < 72°$.
- $5°S < \varphi < 5°N$.
- Day-side ($\varepsilon < 85°$).
- Orbit numbers $60 - 2352$.

Example of modelling the data



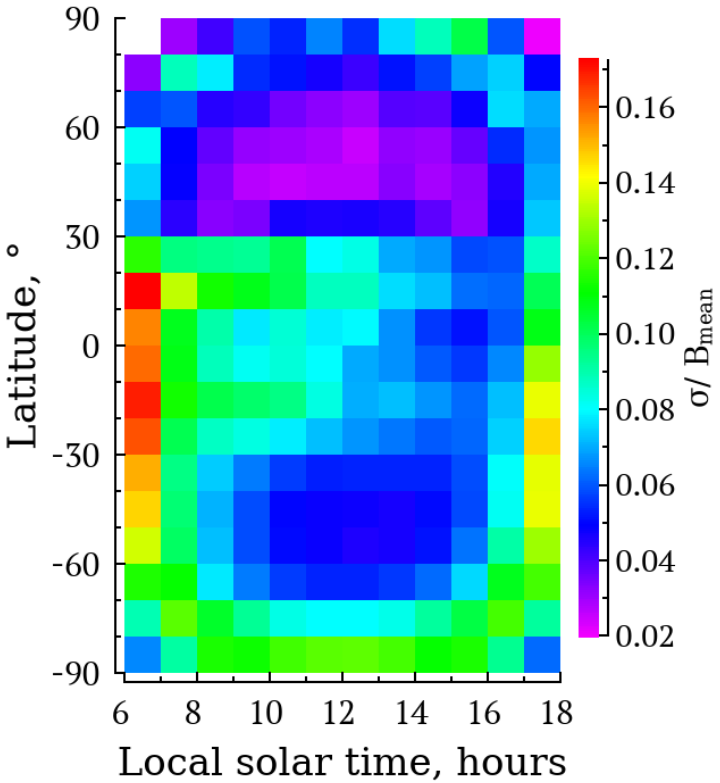
Difference between morning and evening

- Orbit numbers 1497 − 1552.

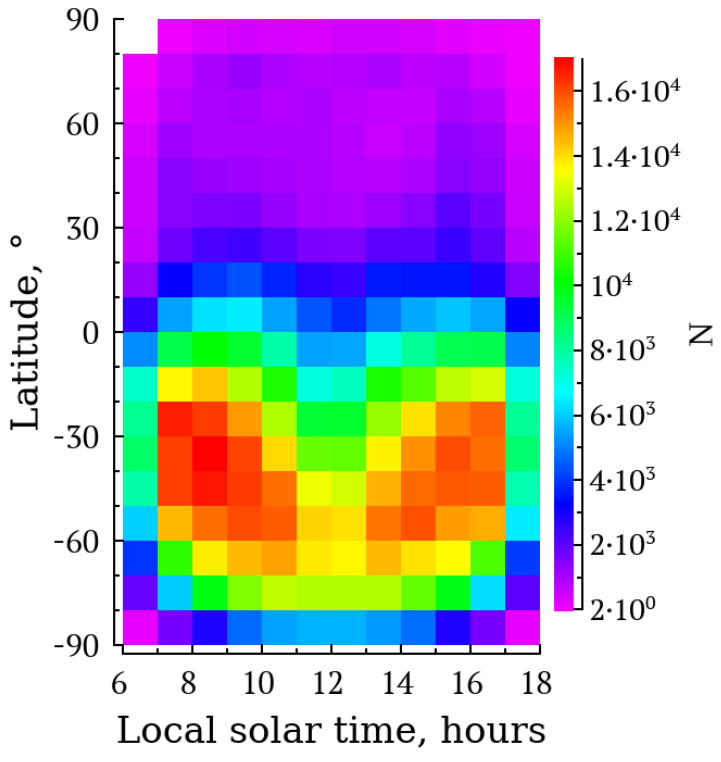
Model with data comparison

- Orbit numbers 60 − 2352.
- Every point is at different emission angle.

Brightness deviations



Deviations of brightness



Number of VMC pixels

Part IV

Sounding the surface

9 Motivation

10 VMC mosaics

11 MGN mosaics

12 Emissivity retrievals
- Modelling the surface thermal emission
- Determining the model parameters

13 Targets for near-infra-red (NIR) sounding

What sounding in NIR can provide?

Prizes

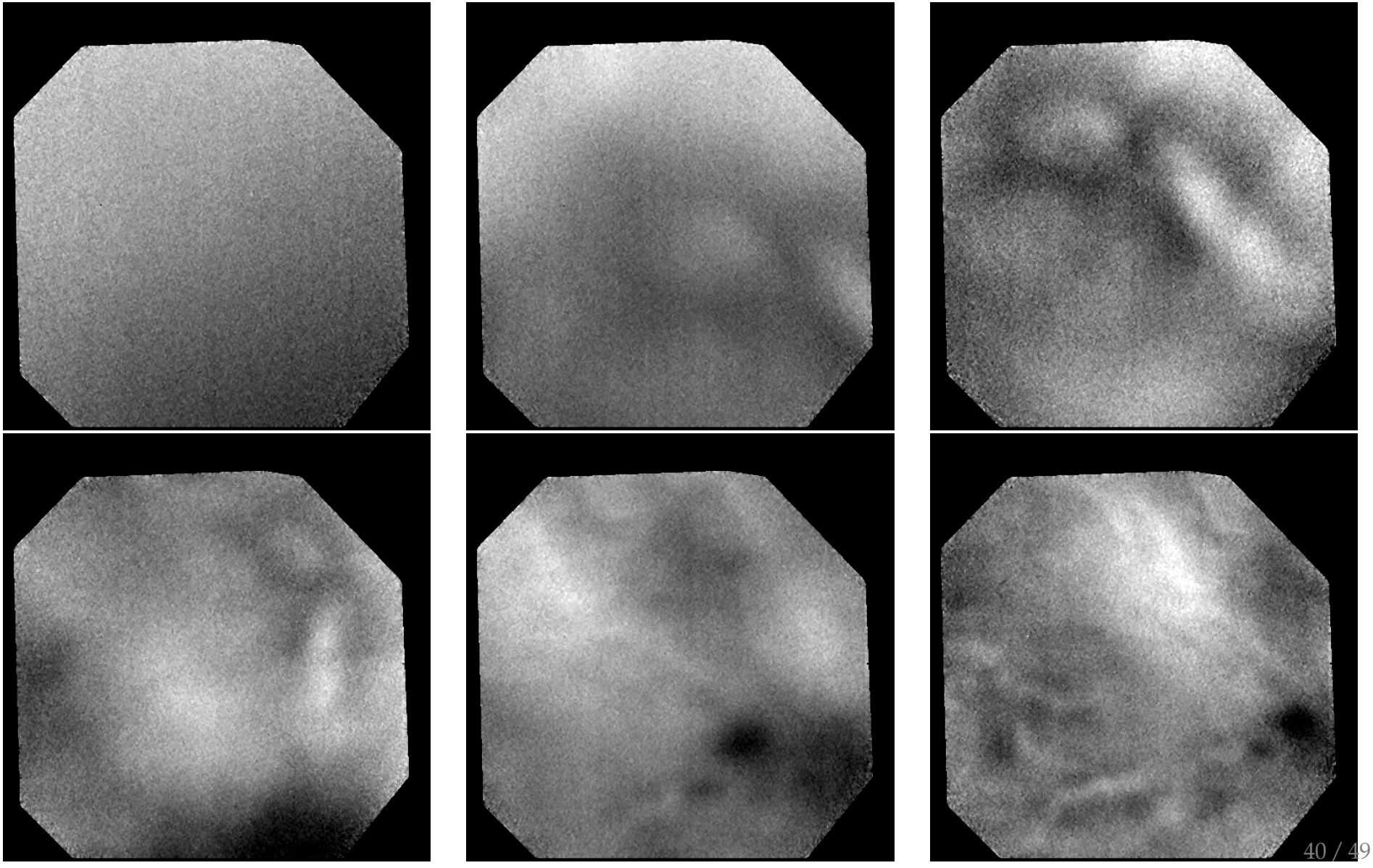
1. Significant part of the surface can be observed.
2. NIR emissivity/reflectivity is sensitive to mineralogical composition.

Complications

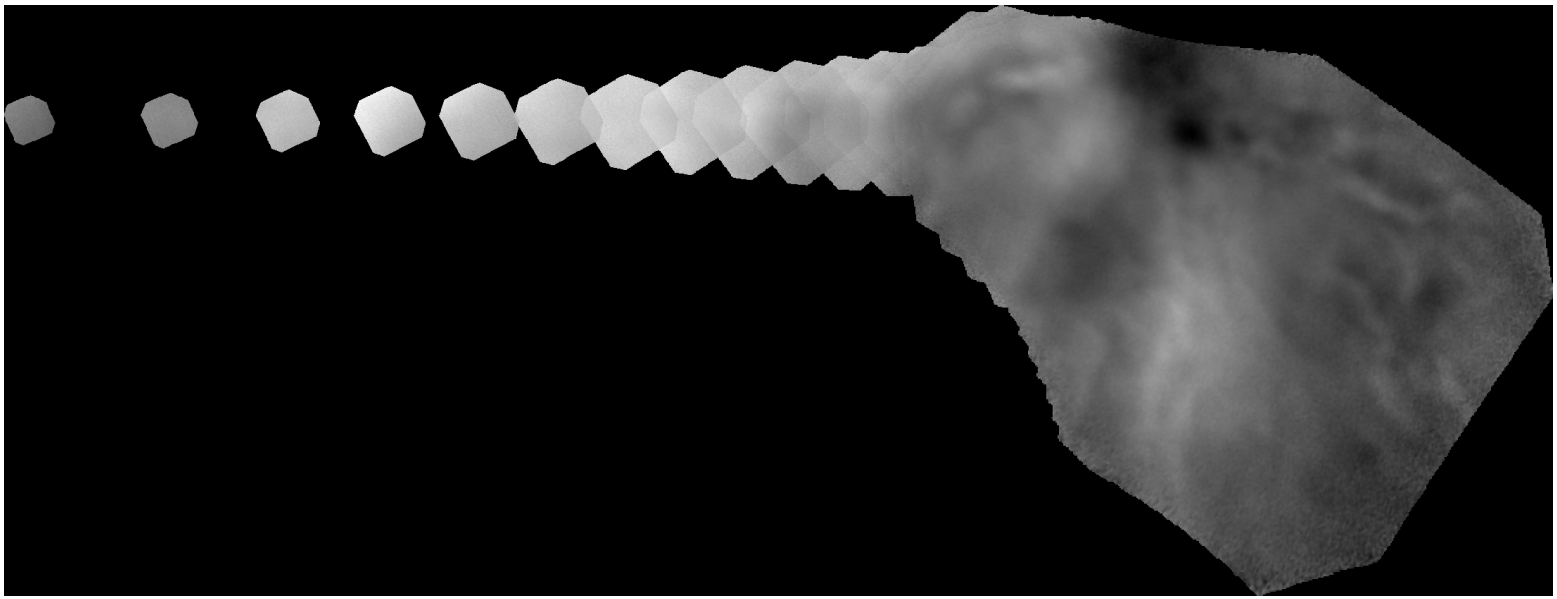
1. NIR flux strongly depends on temperature.
2. Surface temperature depends on altitude (lapse is -8.1 K/km, altitude variations are up to 12 km.
3. Clouds optical thickness might vary significantly from point to point and one spectral channel of VMC is not enough to deduce retrieve the optical thickness and the flux simultaneously.
4. Value of gaseous absorption is unknown and can not be determined theoretically (so far).

VMC mosaics

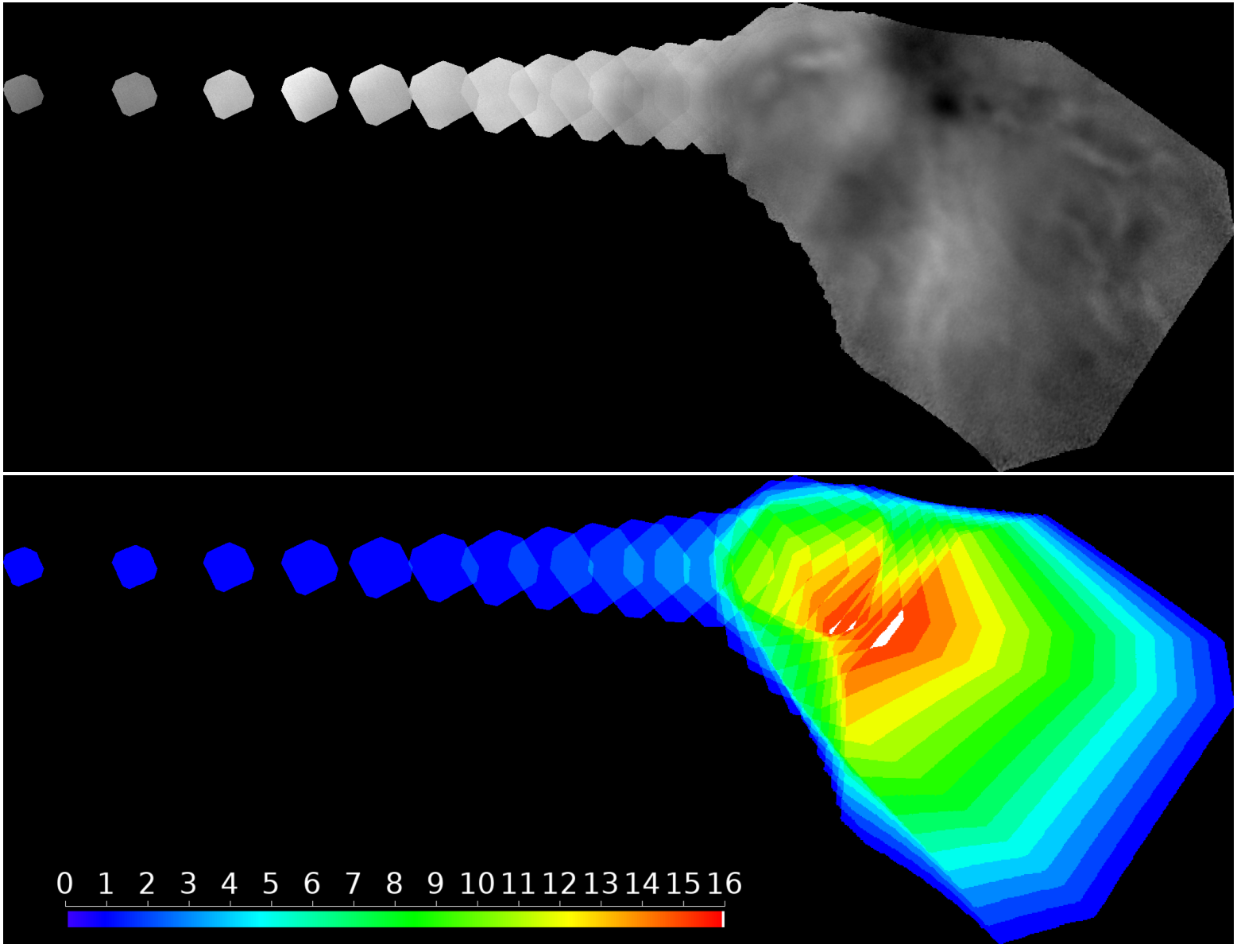
Combining the images greatly increases SNR



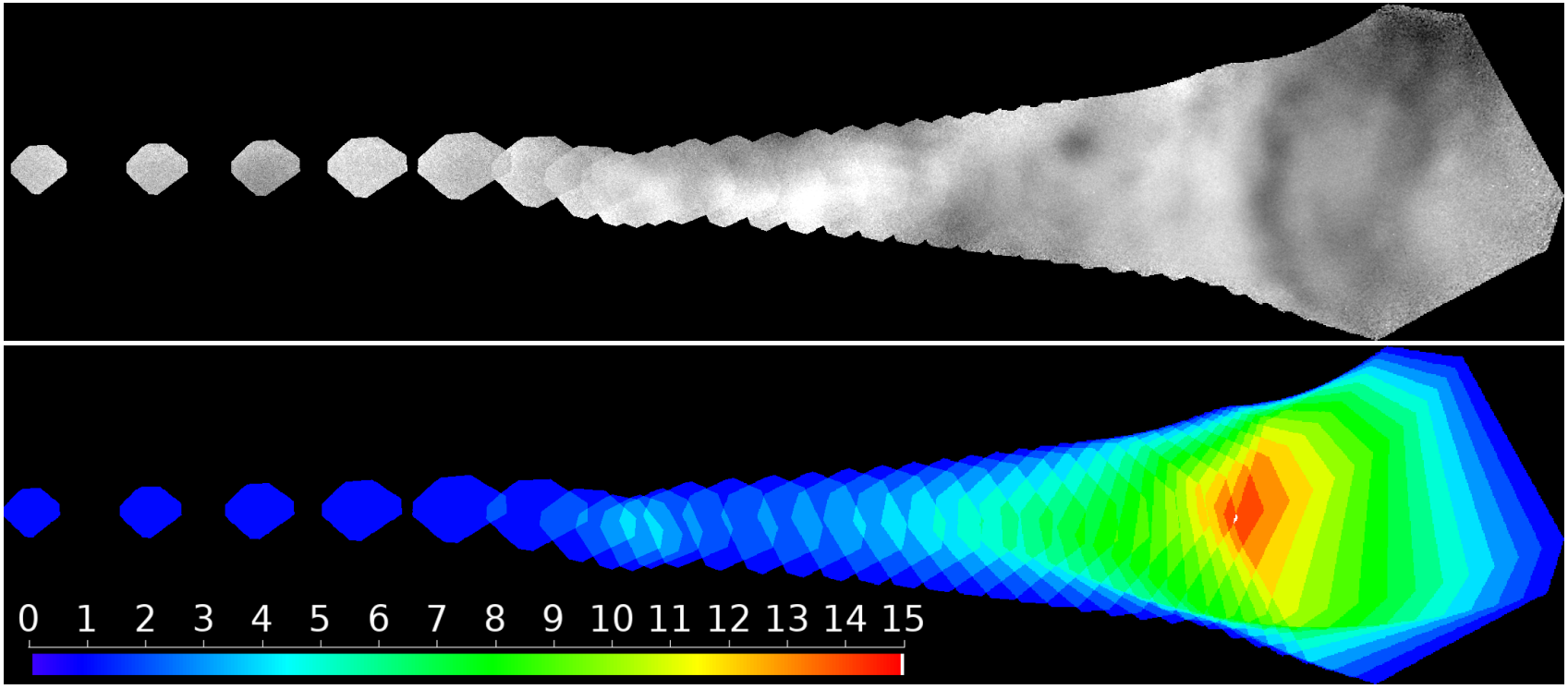
VMC mosaics



VMC mosaics



VMC mosaics



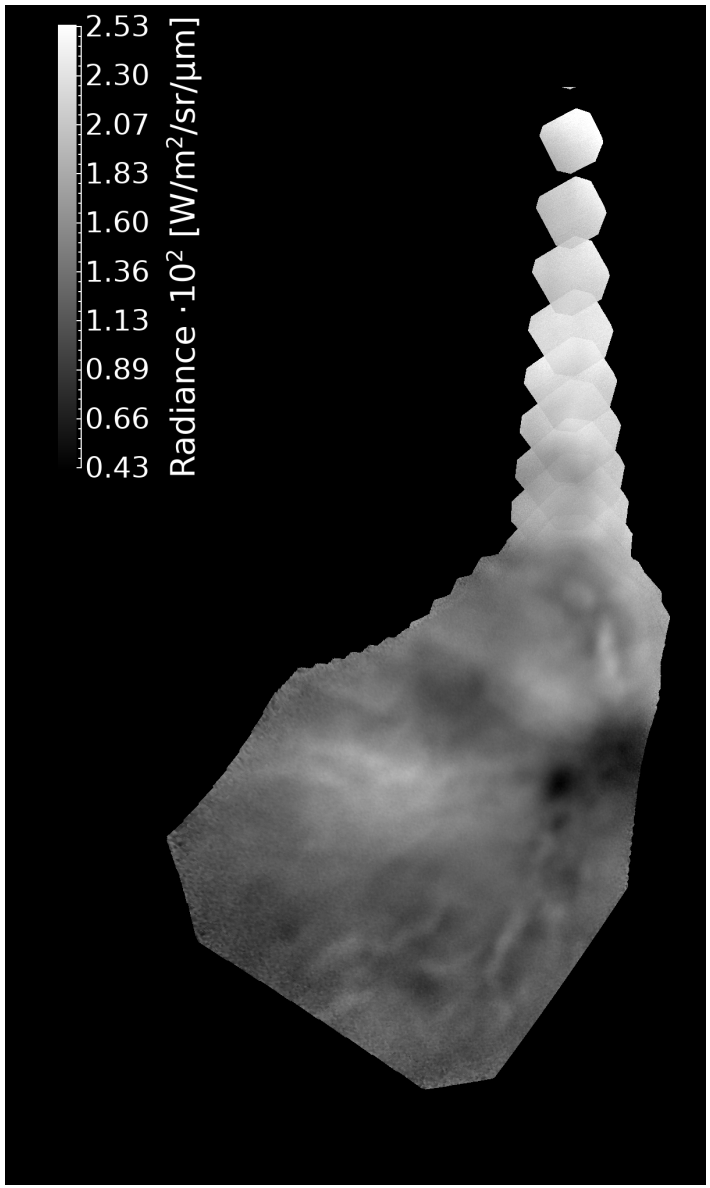
Magellan Radar mosaics

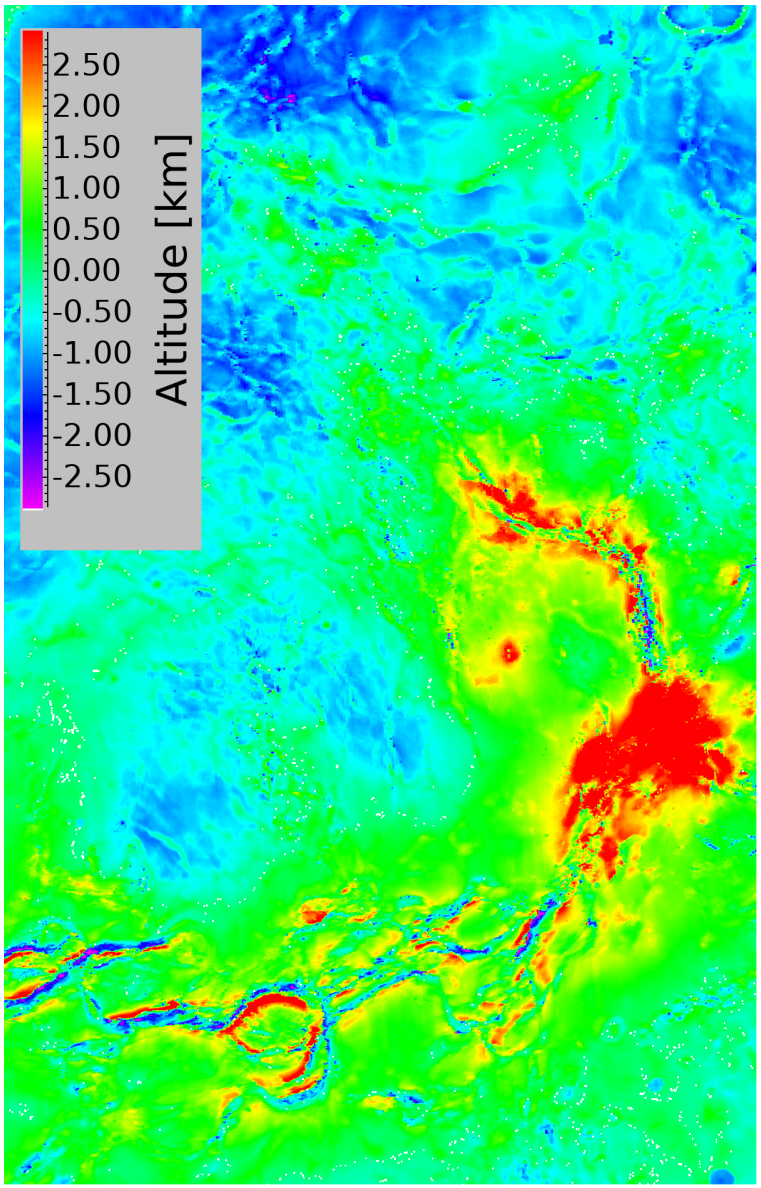
To retrieve the emissivity we need at least the topography map for each VMC mosaic.

To produce the map we:

1. Determine the projection of the VMC mosaic and its parameters.
2. Select MGN frames that intersect with the region of VMC mosaic.
3. Transform MGN frames into the projection of the VMC mosaic.
4. Average transformed MGN frames.

Example of MGN topography mosaic





Modelling the observations

An image at the top of the atmosphere can be expressed by the formula:

$$I(x,y) = k\frac{a(x,y)t(x,y)\varepsilon(x,y)}{1-(r(x,y)[1-\varepsilon(x,y)])} \cdot \iint B[T_s(x',y')] \cdot F(x-x',y-y')dx'dy'$$

x, y	coordinates of point on the surface, I — flux on top of the atmosphere
a	correction for absorption in gas
r and t	reflectance and transmittance coefficients of the atmosphere
ε	emissivity of surface
T_s	temperature of surface
B	Planck function
F	Point Spread Function of the atmosphere in upward direction
k	calibration coefficient

Assumptions

- Clouds thickness and emissivity variations are negligible on the scale of PSF.
- Scattering sideways in clouds beyond PSF scale is negligible.
- Reflectance from the surface is Lambertian.

Emissivity retrieval

Synthetic image

Consider a model image of the observed area assuming constant emissivity ε_0:

$$M(x,y) = k\frac{a(x,y)t(x,y)\varepsilon_0}{1-(r(x,y)[1-\varepsilon_0])} \cdot \iint B[T_s(x',y')] \cdot F(x-x',y-y')dx'dy'$$

Emissivity map:

$$\varepsilon(x,y) = \frac{R(x,y)\varepsilon_0(1-r(x,y))}{1+r(x,y)\left[\varepsilon_0(1-R(x,y))-1\right]},$$

where

$$R(x,y) = \frac{VMC(x,y)}{M(x,y)}.$$

Determination of model parameters

An image at the top of the atmosphere can be expressed by the formula:

$$M(x,y) = k\frac{a(x,y)t(x,y)\varepsilon_0}{1-(r(x,y)[1-\varepsilon_0])} \cdot \iint B[T_s(x',y')] \cdot F(x-x',y-y')dx'dy'$$

k	calibration coefficient
a	correction for absorption in gas, $a = k_a e^{bh}$, $h(x,y)$ — altitude
r and t	reflection and transmission coefficients of the atmosphere
ε_0	base emissivity
T_s	temperature of surface
F	point spread function

Determination of model parameters

An image at the top of the atmosphere can be expressed by the formula:

$$M(x,y) = k\frac{a(x,y)t(x,y)\varepsilon_0}{1-(r(x,y)[1-\varepsilon_0])} \cdot \iint B[T_s(x',y')] \cdot F(x-x',y-y')dx'dy'$$

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r and t	reflection and transmission coefficients of the atmosphere
ε_0	base emissivity
T_s	temperature of surface
F	point spread function

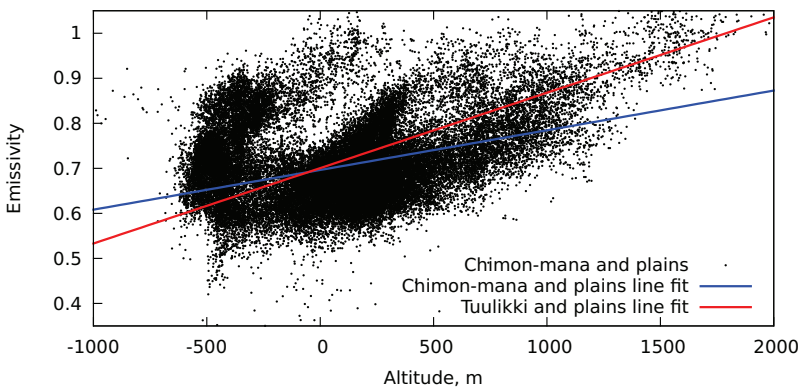
To get rid of k, we assume that at some point (or regions) real (mean real) ε is equal to ε_0.

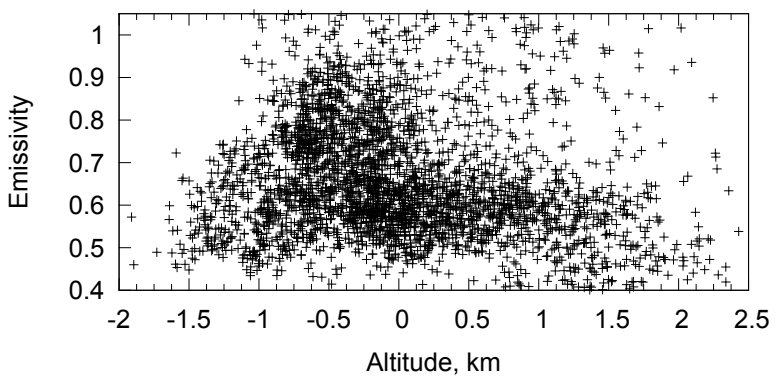
Determination of model parameters

An image at the top of the atmosphere can be expressed by the formula:

$$M(x,y) = k\frac{a(x,y)t(x,y)\varepsilon_0}{1-(r(x,y)[1-\varepsilon_0])} \cdot \iint B[T_s(x',y')] \cdot F(x-x',y-y')dx'dy'$$

- k calibration coefficient
- a correction for absorption in gas, $a = k_a e^{bh}$, $h(x,y)$ — altitude
- r and t reflection and transmission coefficients of the atmosphere
- ε_0 base emissivity
- T_s temperature of surface
- F point spread function





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ε_0	base emissivity
T_s	temperature of surface
F	point spread function

t, r, and F were calculated by Monte-Carlo simulations of light scattering in atmosphere assuming VIRA model of the atmosphere. Cascading reflection from clouds and surface was calculated using two-streams approximation and single-layer atmosphere basing on obtained t and r values.

Determination of model parameters

An image at the top of the atmosphere can be expressed by the formula:

$$M(x,y) = k\frac{a(x,y)t(x,y)\varepsilon_0}{1-(r(x,y)[1-\varepsilon_0])} \cdot \iint B[T_s(x',y')] \cdot F(x-x',y-y')dx'dy'$$

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T_s	temperature of surface
F	point spread function

Regional plains assumed to be of basaltic composition with constant emissivity.

Determination of model parameters

An image at the top of the atmosphere can be expressed by the formula:

$$M(x,y) = k\frac{a(x,y)t(x,y)\varepsilon_0}{1-(r(x,y)[1-\varepsilon_0])} \cdot \iint B[T_s(x',y')] \cdot F(x-x',y-y')dx'dy'$$

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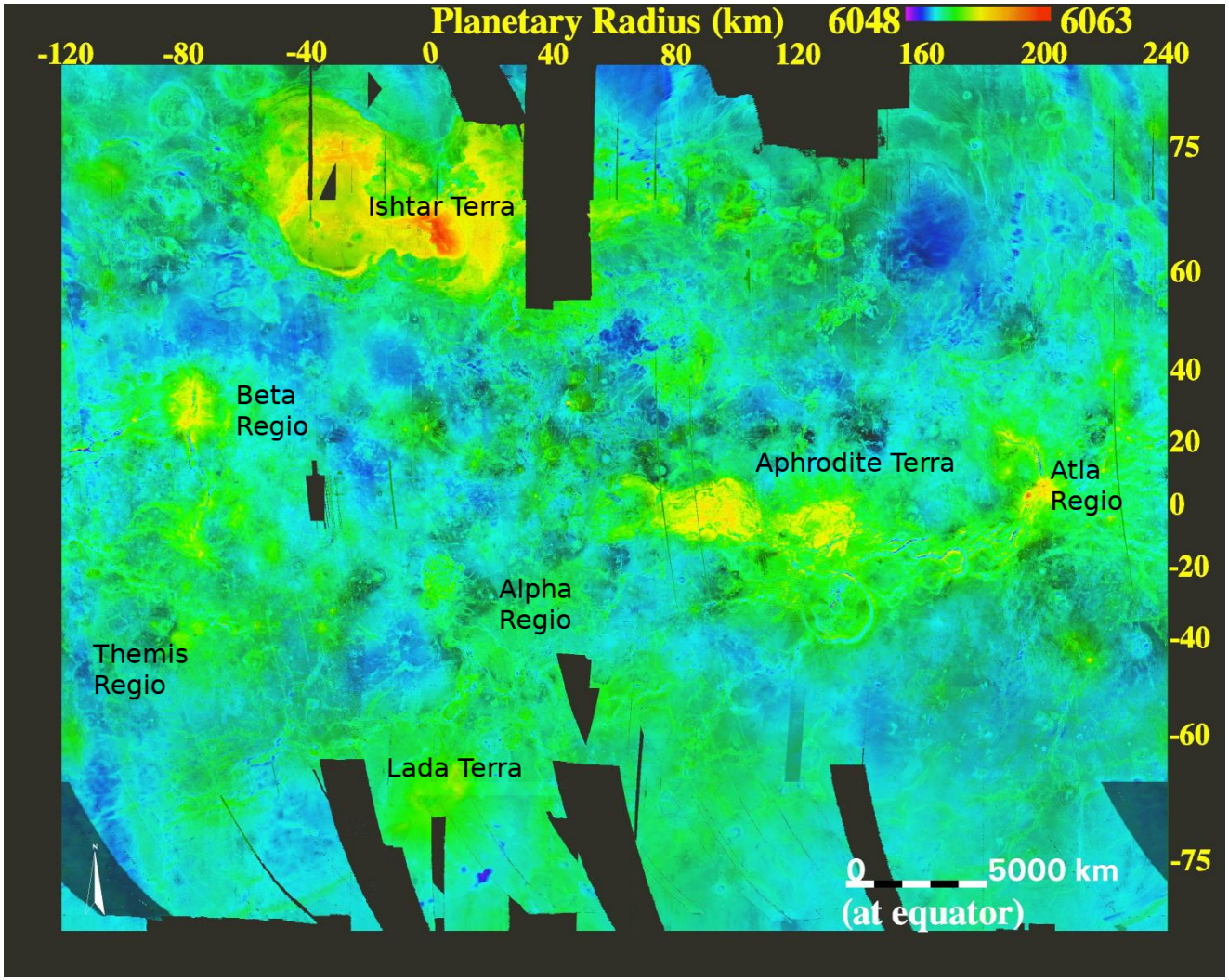
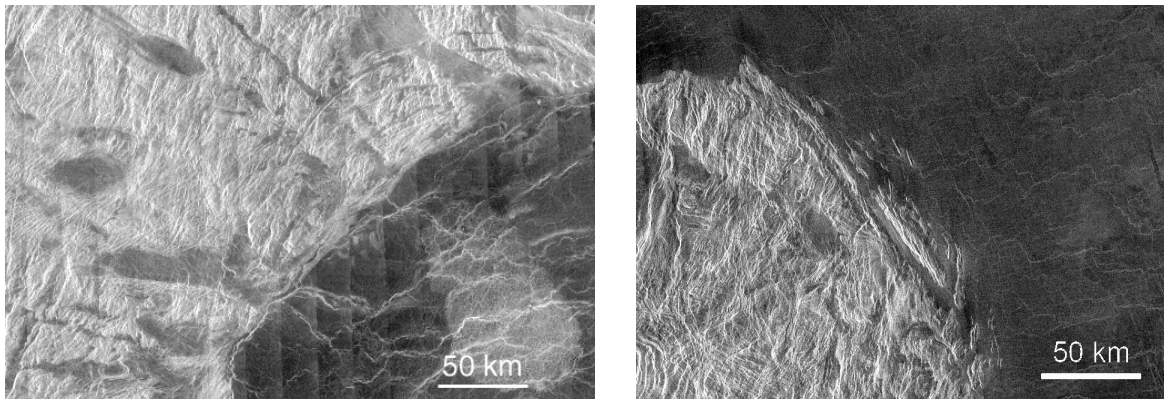
r and t	reflection and transmission coefficients of the atmosphere
ε_0	base emissivity
T_s	temperature of surface
F	point spread function

Temperature lapse was assumed to be adiabatic one (-8.1 K/km).

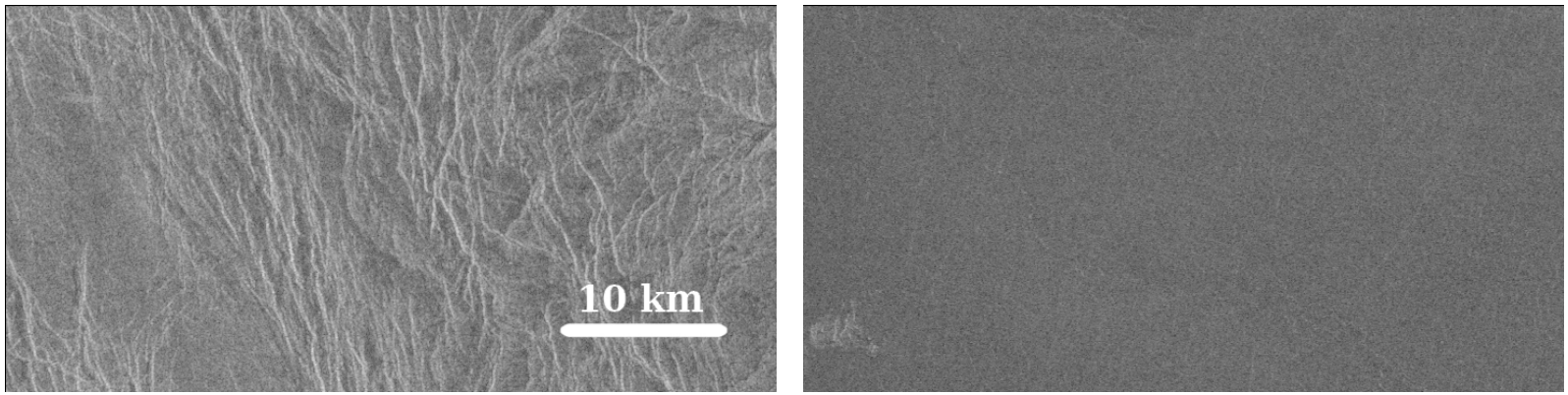
Magellan topography data on top of SAR



Examples of tesserae terrain



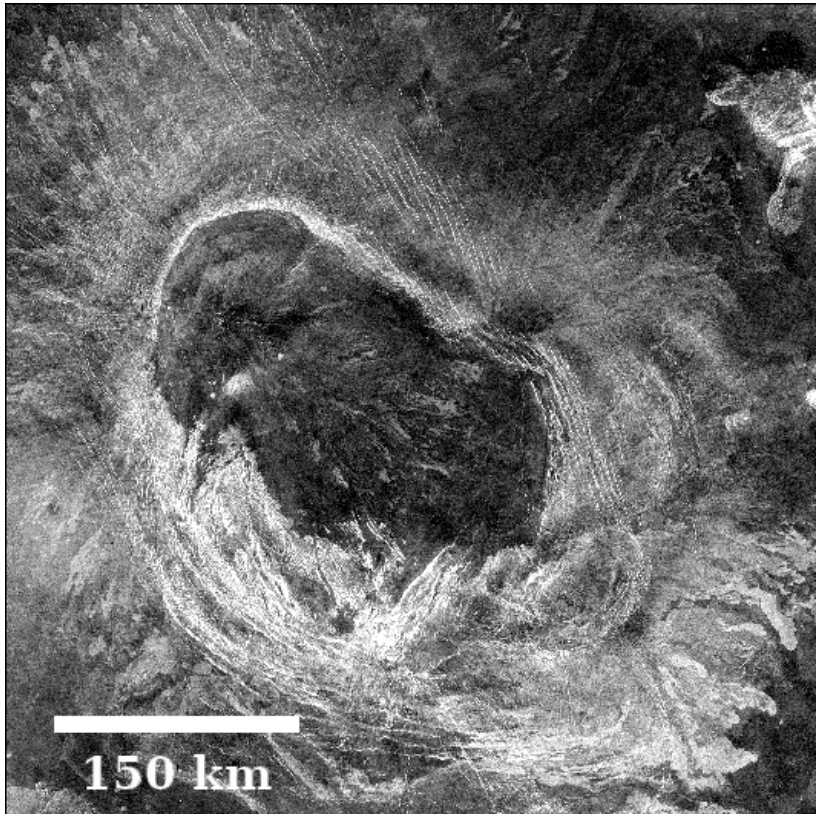
Magellan SAR images of teserae terrains



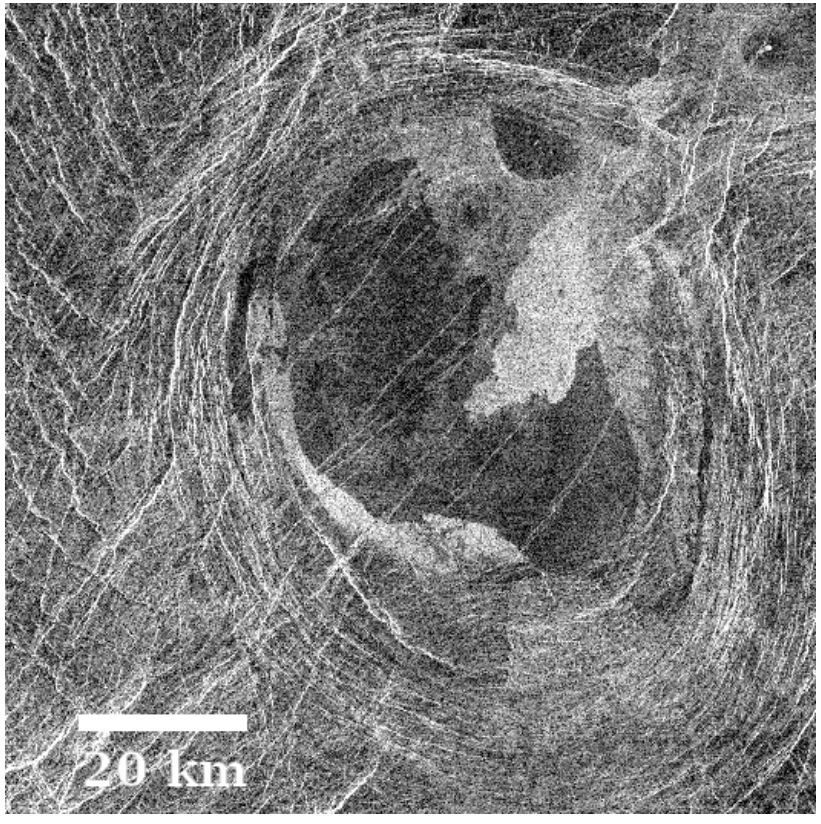
tesserae plains

Tesserae terrain with comparison to plains

Coronae examples



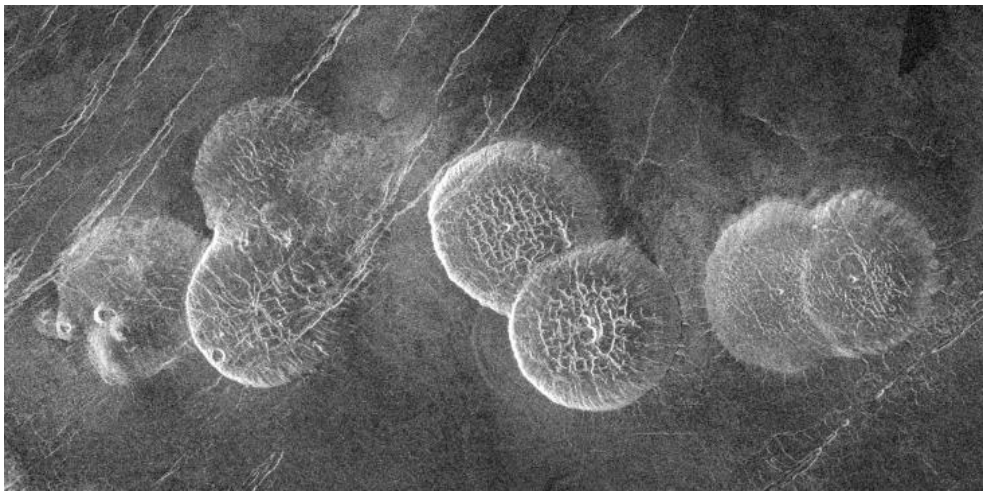
Aruru corona, 9°N, 262°E



Small corona at 2.2°N, 219°E

Magellan SAR images of the coronae

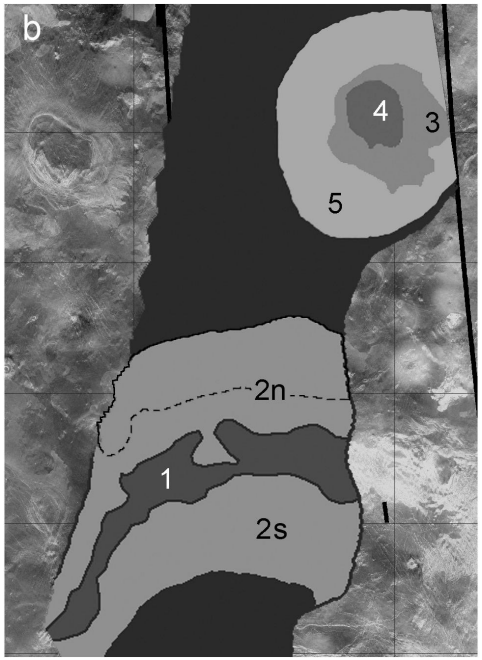
Steep-side domes



Magellan SAR, Venus, tens of km in size

Lava dome, Earth, Alaska

Emissivities comparison



Unit types:

1. Chimon-mana
2. Plains around Chimon-mana
3. Tuulikki major body
4. Tuulikki summit
5. Plains around Tuulikki

Comparison of emissivities of different surface types

Unit A / Unit B	e ± std. dev.		Difference at 0.05 level
	Unit A	Unit B	
1 / 2	0.55±0.37	0.56±0.31	No
1 / 2n	0.55±0.37	0.64±0.24	Yes
1 / 2s	0.55±0.37	0.47±0.35	No
2n / 2s	0.64±0.24	0.47±0.35	Yes
1 / 2nn	0.55±0.37	0.76±0.15	Yes
1 / 2ns	0.55±0.37	0.50±0.27	No
2nn /2ns	0.76±0.15	0.50±0.27	Yes
2n /2nn	0.64±0.24	0.76±0.15	Yes
2n / 2ns	0.64±0.24	0.50±0.27	Yes
3 / 4	0.63±0.07	0.55±0.04	Yes
3 / 5	0.63±0.07	0.53±0.45	Yes
4 / 5	0.55±0.04	0.53±0.45	No
2n / 5	0.64±0.24	0.53±0.45	Yes
2s / 5	0.47±0.35	0.53±0.45	No
2nn / 5	0.76±0.15	0.53±0.45	Yes
2ns / 5	0.50±0.27	0.53±0.45	No

Thank you

Thank you for your attention!

Part V

*

14 Orbits selection
- Ratios
- VMC coverage

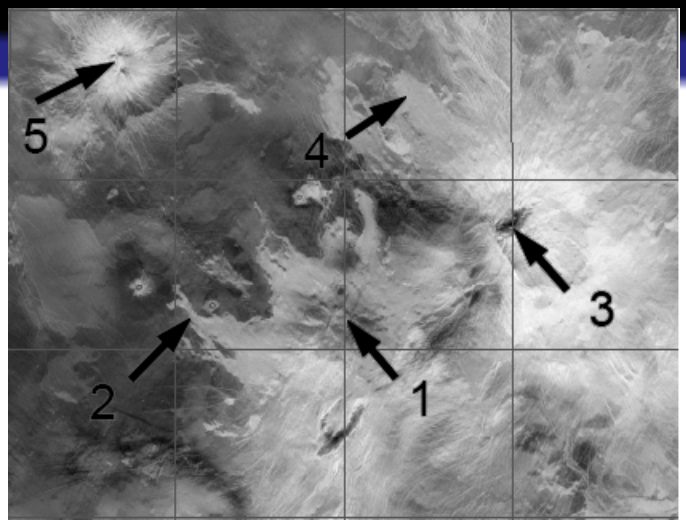
15 Remote sensing possibilities

16 Parabolas

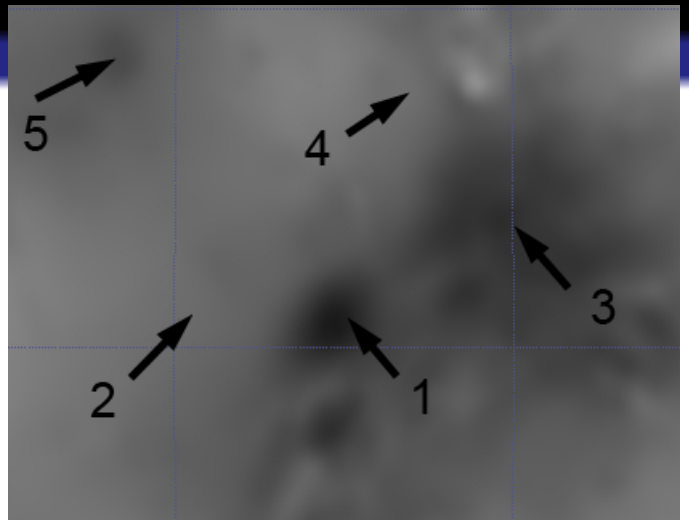
17 Tectonics

18 MC model

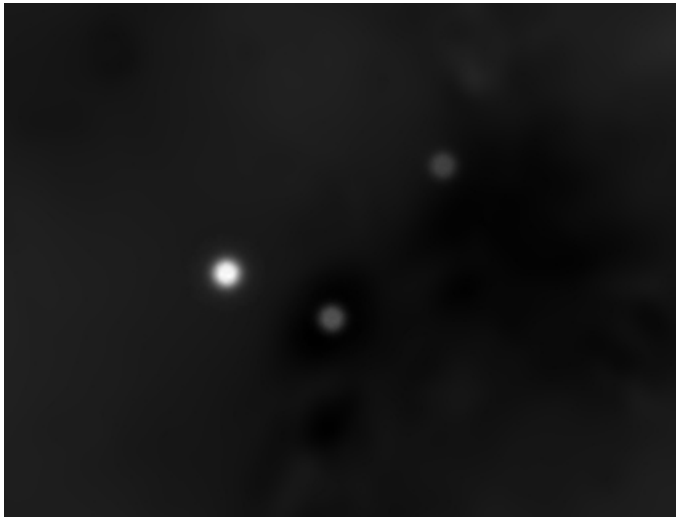
Supplementary slides

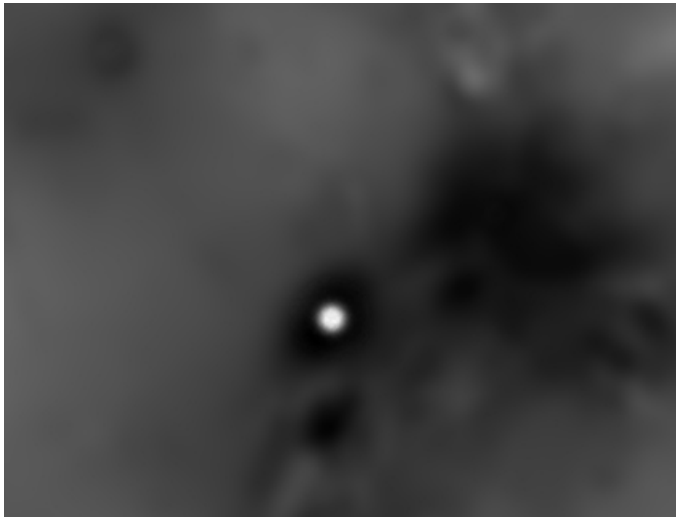


Localities (SAR)



Localities (VMC)



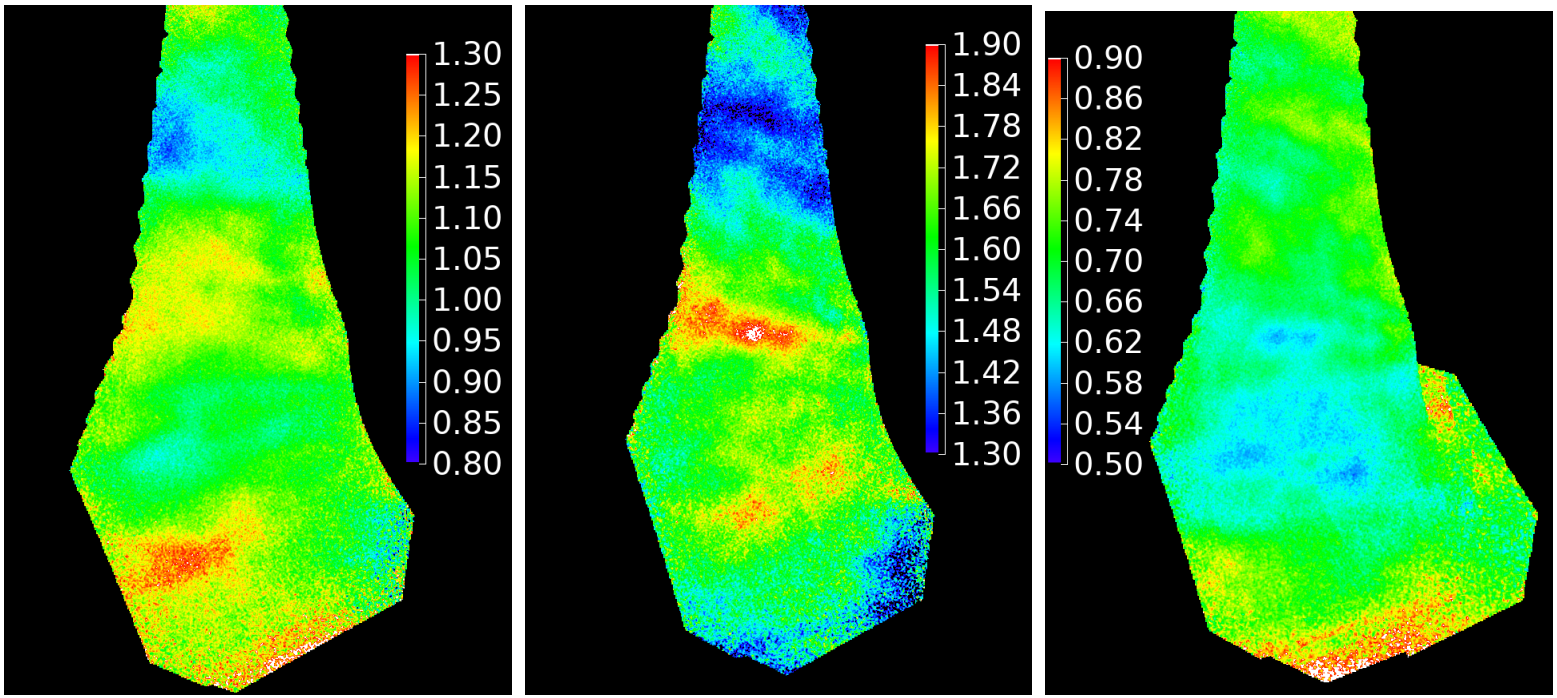


Model of the five lava eruptions with lava Hypothetical eruption on the Maat Mons surface areas 10, 100, 10, 1 and 1 km^2 summit (also 10 km^2)

Maat flank,

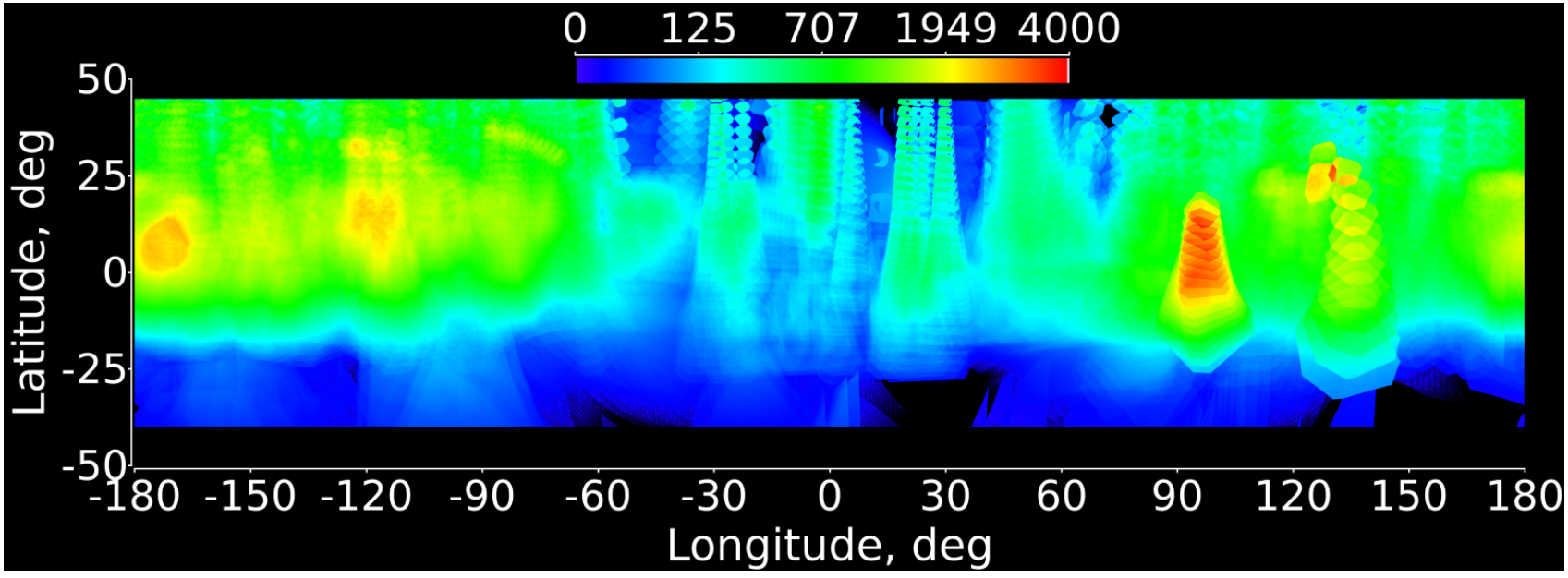
1. For an area of interest, VMC orbits without strong cloud opacity variations are selected. A single orbit is considered in the further steps.
2. VMC images are transformed from DNs into absolute brightness units.
3. Mosaic (in Mercator projection) is made from individual VMC images.
4. For the region, covered by VMC mosaic, an MGN topography mosaic in the same projection as VMC mosaic is made.
5. MGN topography mosaic is transformed into map of brightness as described above, assuming constant surface emissivity.
6. VMC and MGN-based mosaics are compared. Comparison is performed using a blink comparator. If at this step mosaics do not match each other, then imaging time of individual VMC images is adjusted and steps 3 – 6 are repeated.
7. Several reference locations, where surface is supposed to be of basaltic composition, are selected.
8. Map of emissivity is retrieved.
9. The emissivity map is transformed into a required projection for geological investigation.

Orbits selection



470 over 471 470 over 472 472 over 471

Examples of mosaic ratios



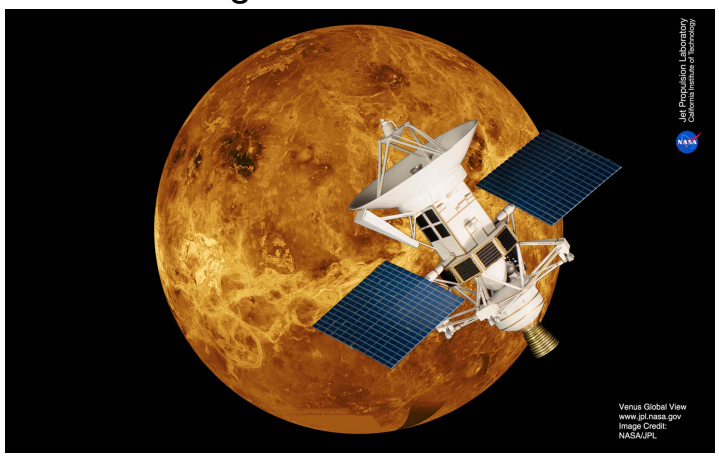
Map of surface coverage by VMC observations from orbits $0-2030$. The map shows number of VMC pixels (non-linear scale) in $0.1^\circ \times 0.1^\circ$ bins

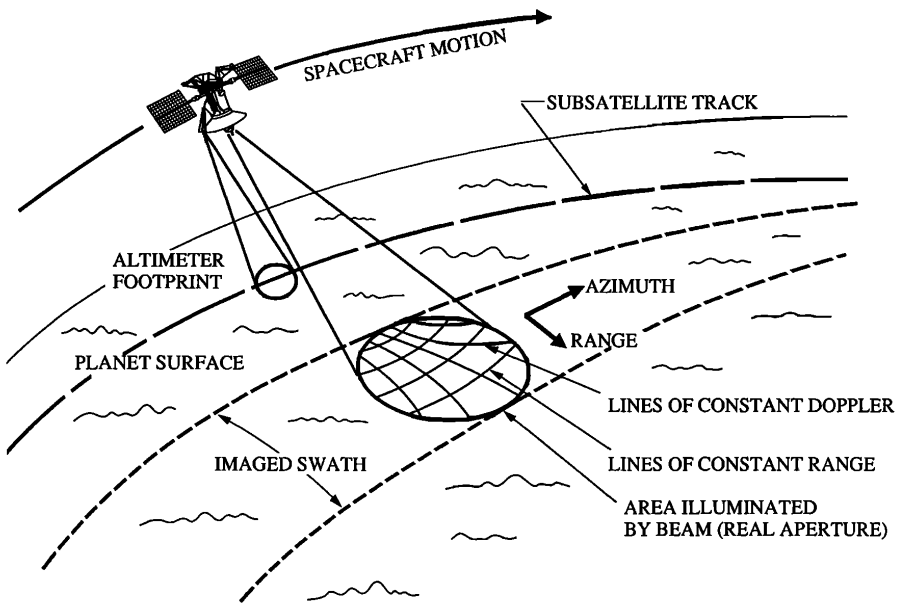
Remote sensing possibilities

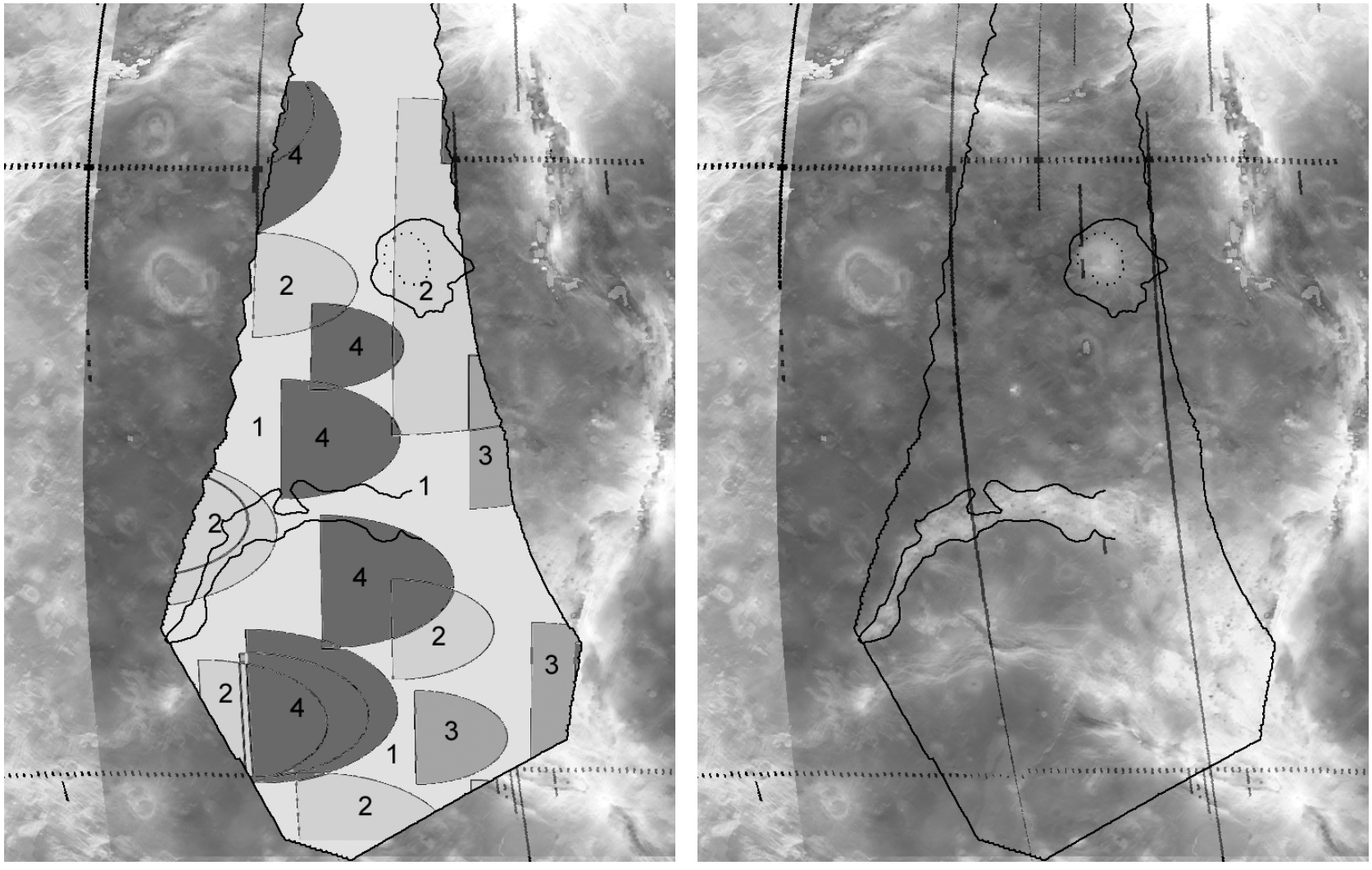
Large antennas at the Earth, observing part of the Venus surface…

…or relatively small antennas in orbit working in synthetic aperture mode

Model of Magellan S/C



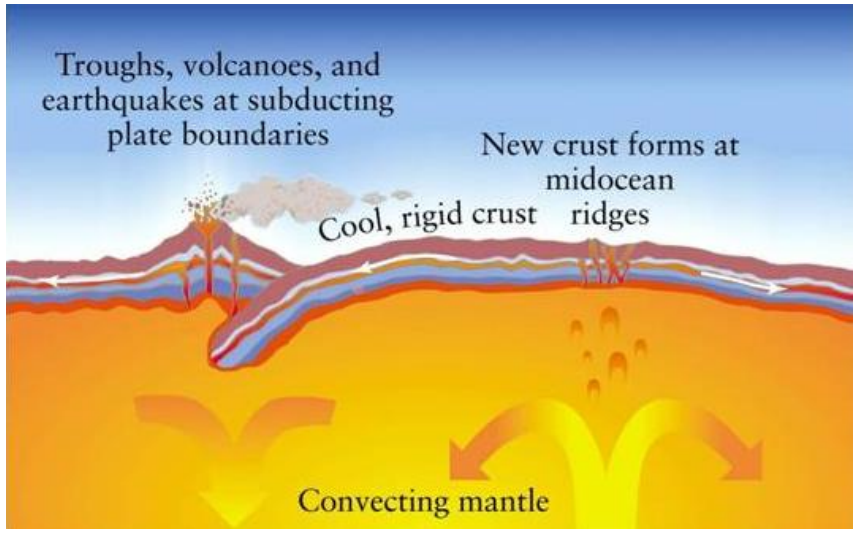




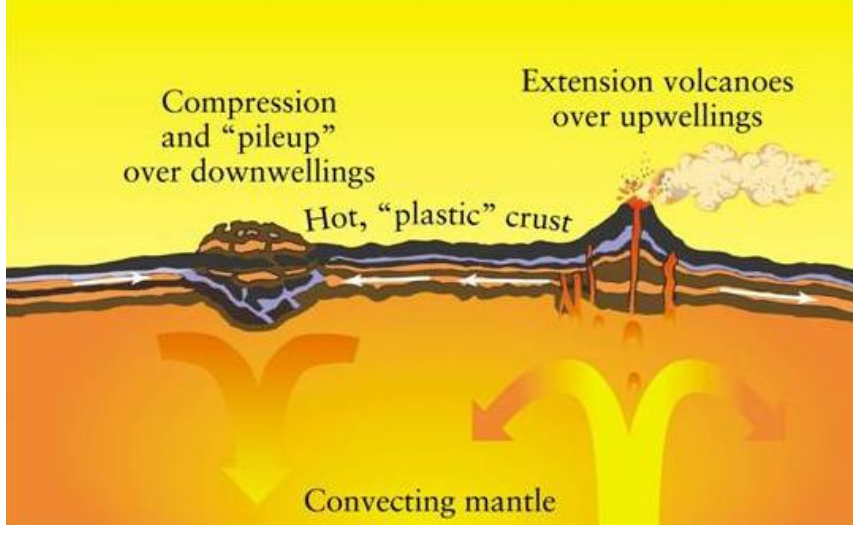
Impact crater halos

SAR image

Map of radar-dark parabolas from impact events in SW of Beta-Region



Earth



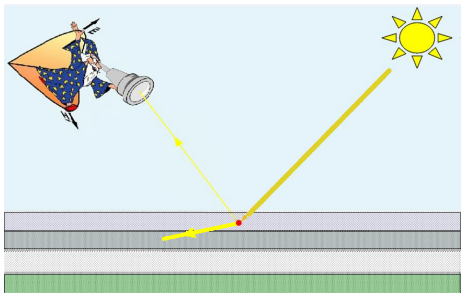
Venus

Earth and Venus crusts. Pictures are from http://venus.aeronomie.be

Model of light scattering in arbitrary atmosphere-like medium

The goal

Model of light scattering in arbitrary medium using Monte-Carlo simulations



Medium properties:

- Rare particles (there is no interference)
- Any particles with any phase function and single scattering albedo
- Particles concentration as a function of coordinates

Implementation

There is the kernel (C++ library) which can perform actual simulations and several front-ends for simplified configurations

Supported features:

- Various kinds of light sources (point, surface, *etc.*)
- Various kinds of particles (analytical and tabulated phase functions)
- Various kinds of light receivers (point, orthographic, spherical, *etc.*)
- Platform independent multi-threaded kernel code