Earth observed as an exoplanet: VIRTIS-M/Venus Express and Rosetta data analysis.

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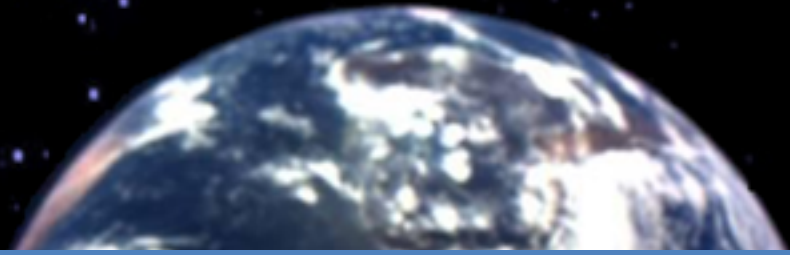


STUDY OUTLINE

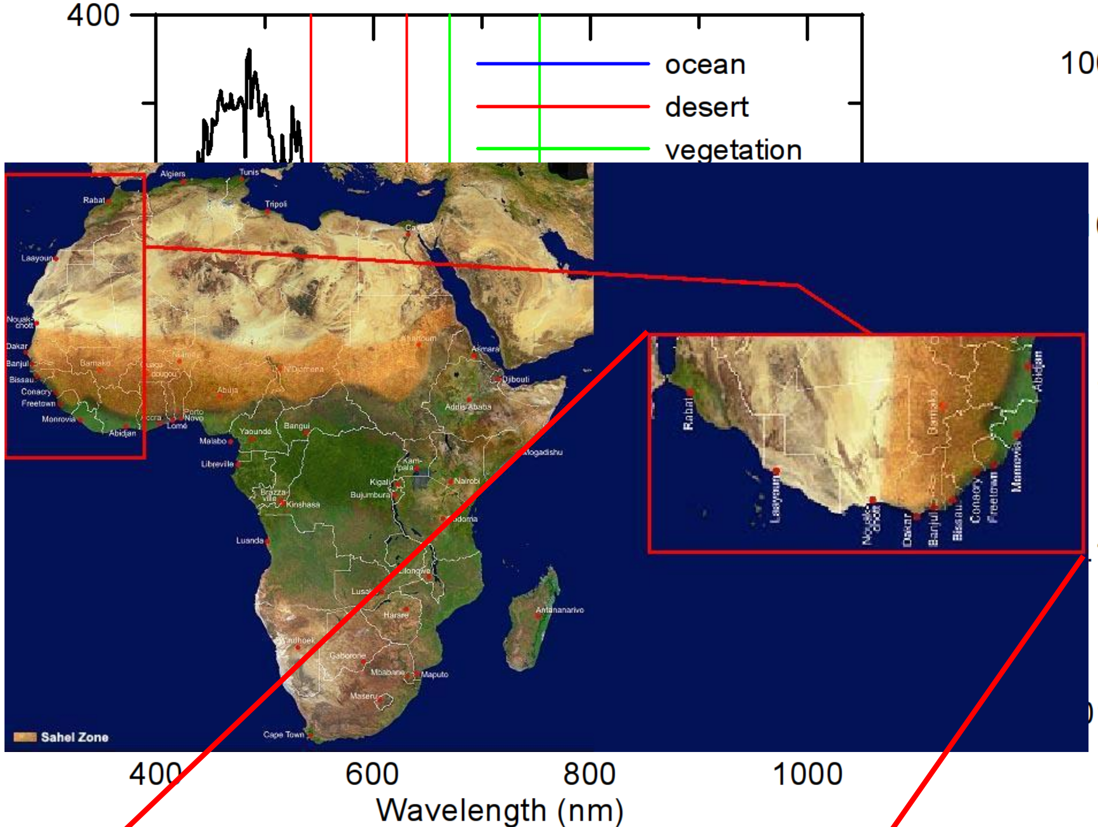
1) Analyze the data registered from the VIRTIS-M imaging spectrometer on board on both the Rosetta and the Venus Express (VEx) spacecrafts;

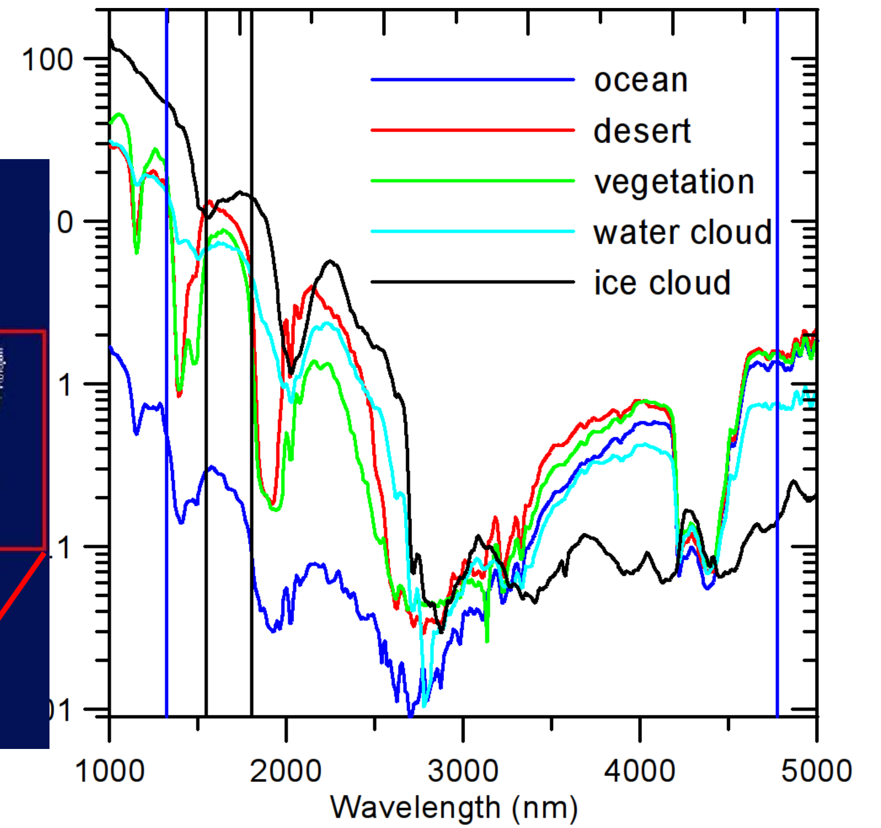
2) Select spectral endmembers from Rosetta Earth resolved data to generate Earth-like planets observations with our own planet simulator tool → test the capability to identify the different endmembers when the planet is observed as a single pixel;

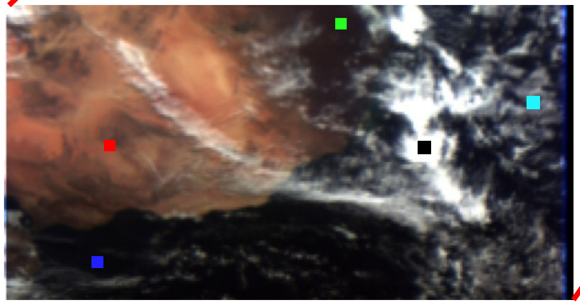
3) Compare the simulator results with a set of 48 observations from the VEx dataset in which the Earth is observed from distances at which it is sub-pixel size;

4) Planned analysis of the data by means of the MITRA RT tool (Oliva et al., 2016; Sindoni et al., 2017; Adriani et al., 2015; Oliva et al., 2018; Sindoni et al., 2013)

CHARACTERIZATION OF DIFFERENT CLASSES OF REFLECTING SURFACES







Rosetta/VIRTIS-M 00216726248
Date: 2009-11-13 T09:44:47
Target distance: 72000 km

R = 698 nm
G = 549 nm
B = 438 nm

MASKS SPECTRAL CONDITIONS

Clear sky ocean: $R_{1321} / R_{4775} < 1$

Desert: $R_{542} / R_{630} < 1$

Vegetation: $R_{670} / R_{753} < 1$

Clouds: total - ocean - desert - vegetation

H_2O **ice clouds**: $R_{1802} / R_{1547} > 1$

CHARACTERIZATION OF DIFFERENT CLASSES OF REFLECTING SURFACES

clear sky ocean

$R_{1321} / R_{4775} < 1$

R = 698 nm

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B = 438 nm

Desert

$R_{542} / R_{630} < 1$

Rosetta/VIRTIS-M 00216726248

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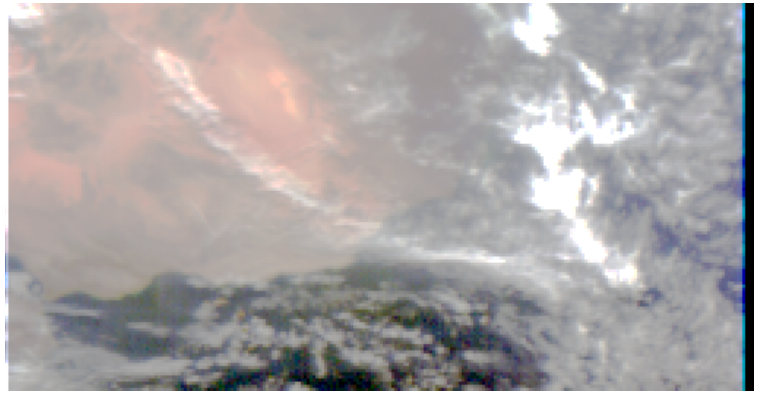


vegetation

$R_{670} / R_{753} < 1$

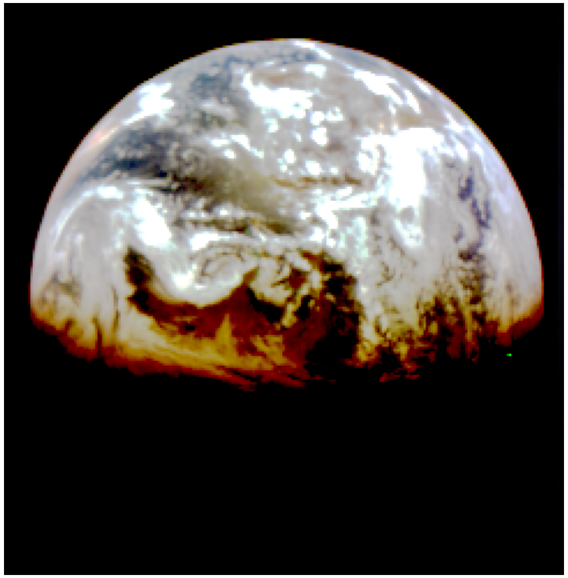
Clouds

water ice clouds

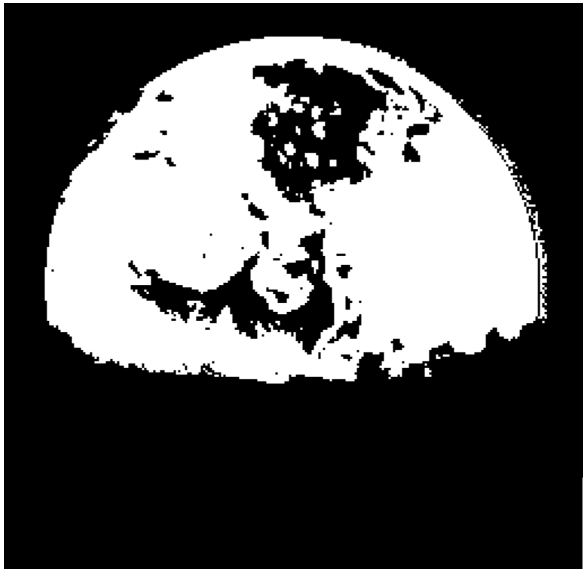
Total– ocean –desert / vegetation

$R_{1802} / R_{1547} > 1$

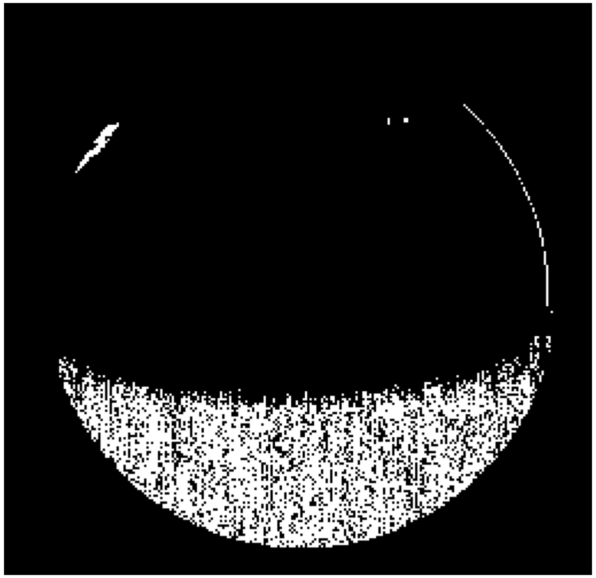
THE EFFECT OF THE CLOUDS FROM THE DISTANCE



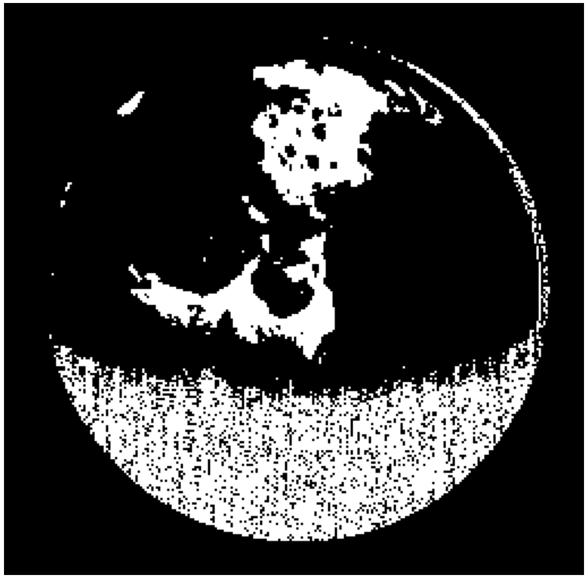
ROSETTA VIRTIS-M-VIS: 00216741598
Date: 2009-11-13 T14:00:37
Target distance: 221600 km



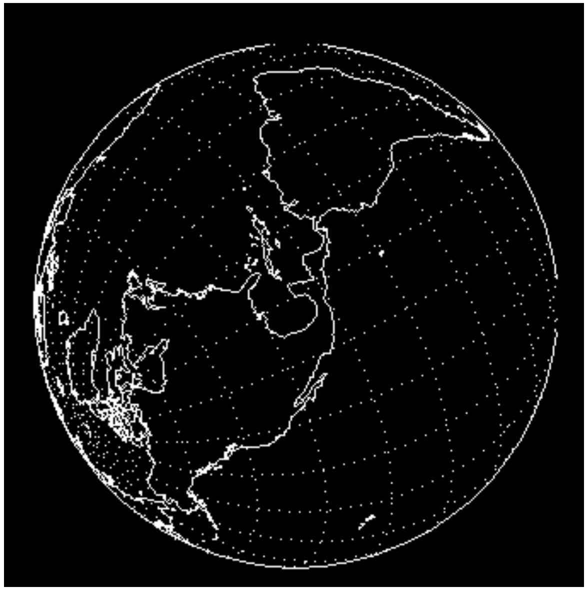
clouds



Desert



vegetation



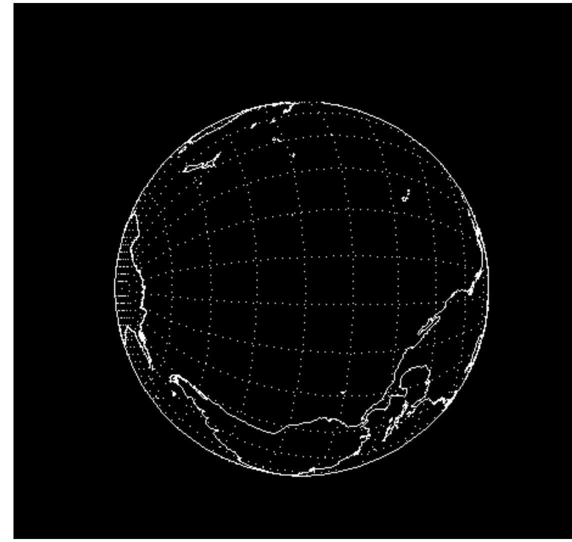
Increasing the distance from the target affects the capability of separating different types of reflecting surfaces. The clouds start to have a greater impact on the observed spectra.

DISTANT OBSERVATIONS

VEX VIRTIS-M-VIS: VV9999_09
Date: 2005-11-23T 00:28:43
Target distance: 3500000 km

At this distance the clouds have a major impact and it is more difficult to disentangle the presence of different types of surface.

However, the observation geometry has a fundamental role.

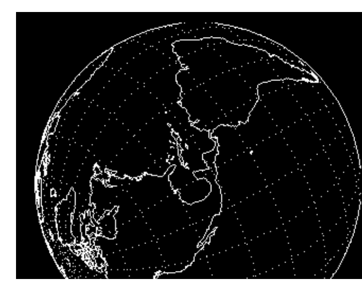


ROSETTA VIRTIS-M-VIS: 00216741598
Date: 2009-11-13 T14:00:37
Target distance: 221600 km

resized to the same dimensions of the VEX cube

Vegetation can still be detected if present!

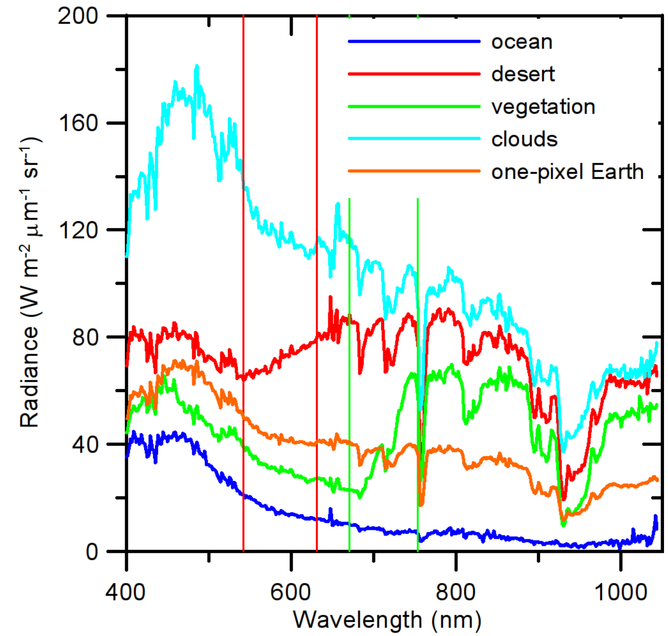
vegetation mask
$R_{670} / R_{753} < 1$



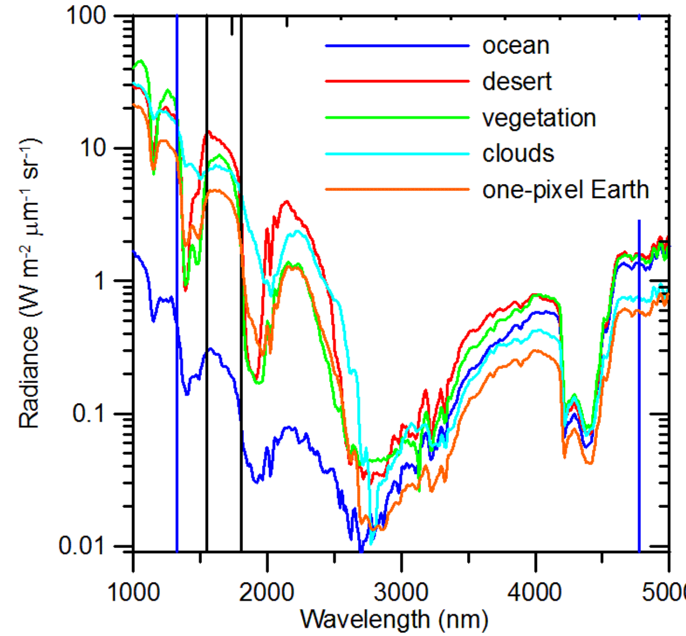
PIXEL SIZE OBSERVATIONS

ROSETTA VIRTIS-M-VIS: 00216741598
Date: 2009-11-13 T14:00:37
Target distance: 221600 km

resized to a single pixel
VIS (**orange spectrum**)



resized to a single pixel
IR (**orange spectrum**)



When the observation is integrated into a single pixel, all the information relative to the different types of surface is diluted. The peculiar spectral signatures are difficult to spot in the single pixel spectrum.

PLANETS SIMULATIONS: SIZE, DISTANCE AND GEOMETRY

ROSETTA VIRTIS-M-VIS: 00216741598
Date: 2009-11-13 T14:00:37
Target distance: 221600 km

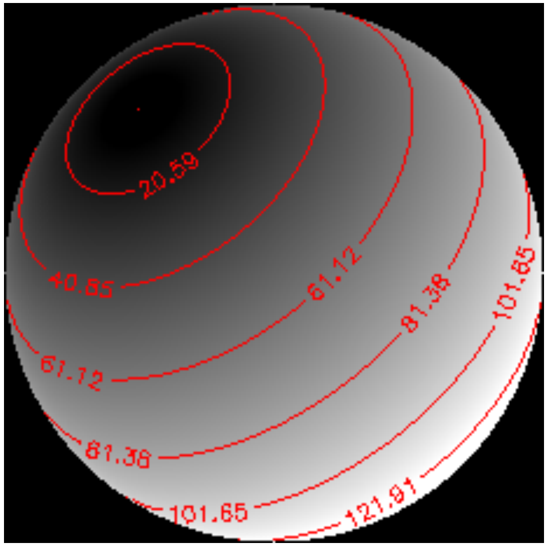
The emission angles are not varied and the boresight is always at the planet's center. Incidence angles can be varied at will specifying the azimut and right ascension of the sun with respect to the boresight. See the examples at right.

Earth and the VIRTIS spectrometer are considered as prototypes of the planet to be created and of the instrument observing it. The starting distance is the same as that of the ROSETTA cube at left. The adopted parameters are:

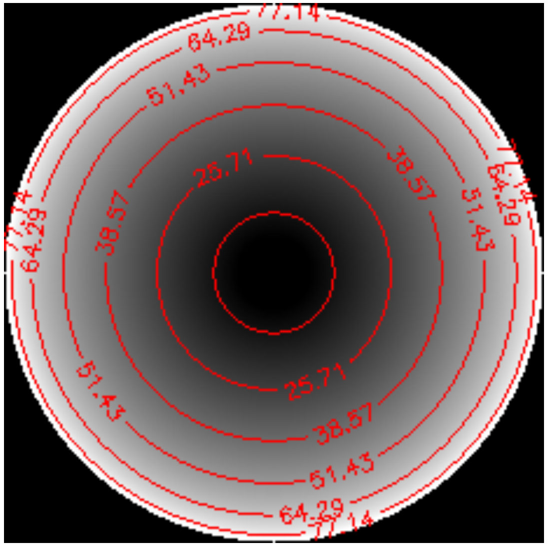
R = 6371 km
D = 221600 km → INTEG. → 2xD → INTEG. → 10xD → INTEG. → 236xD (PIXEL SIZE)
IFOV = 250 µrad
Diameter in pixels = 231

The planet is divided in ocean, desert and vegetation, and clouds which are themeselves split up in non-ice (water clouds) and ice water clouds (ice clouds). All classes sum up to 100%.

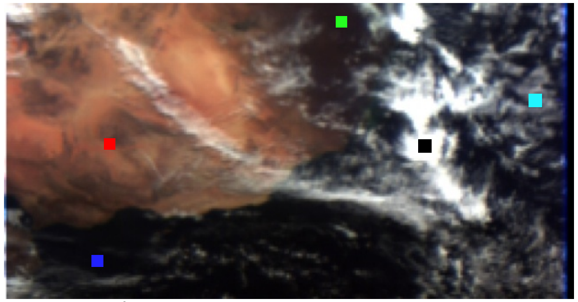
INCIDENCE



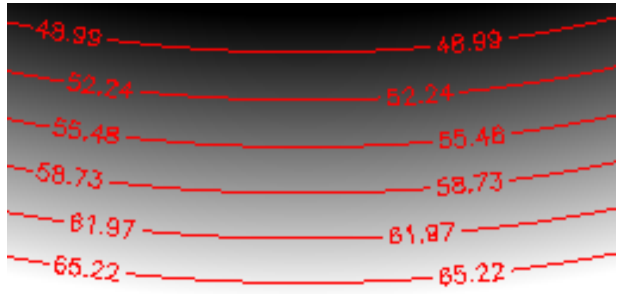
EMISSION



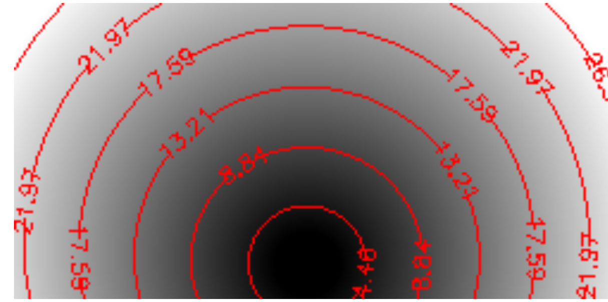
PLANETS SIMULATIONS: PHOTOMETRIC CORRECTION



Rosetta/VIRTIS-M 00216726248
Date: 2009-11-13 T09:44:47
Target distance: 72000 km



Incidence angles (°)



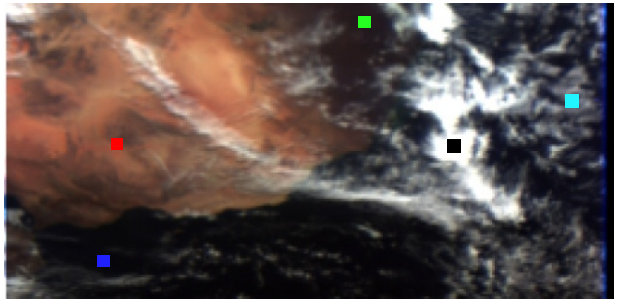
Emission angles (°)

The endmembers have been selected with a particular observing geometry and, hence, they must be processed in order to be used to craft the planet with the desired incidence and emission angles conditions. Even if inadequate for bodies with an atmosphere where multiple scattering is significant, at the first order we adopted the Lommel correction to obtain the endmembers in nadir condition (i = 0°; e = 0°) and to rescale their intensity according to the observing geometry of each planet's pixel:

$$I(i,e) = \frac{\mu_0}{\mu_0 + \mu} I(0,0)$$

where *I* is the radiance, μ_0 is the cosine of the incidence angle *i* and μ is the cosine of the emission angle *e*. In the future we plan to use the MITRA RT tool to correctly reproduce the spectra at different observing geometries in order to avoid using the Lommel correction since it produces enhanced limb brightening.

PLANETS SIMULATIONS: SPECTRAL INDEXES



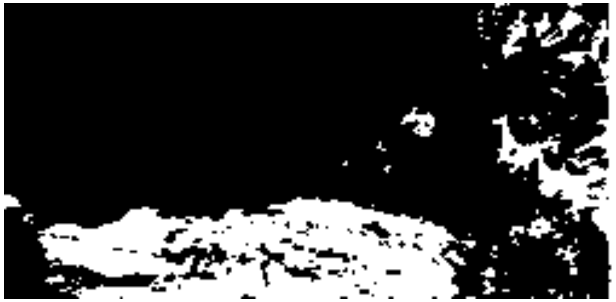
Rosetta/VIRTIS-M 00216726248
Date: 2009-11-13 T09:44:47
Target distance: 72000 km

Normalized Difference Veget. Index (vegetation mask):

$$\text{NDVI} = \frac{R_{860} - R_{650}}{R_{860} + R_{650}} > 0$$

Normalized Difference Soil Index (desert mask):

$$\text{NDSI} = \frac{R_{570} - R_{620}}{R_{570} + R_{620}} < 0$$



Normalized Difference Water Index (ocean mask):

$$\text{NDWI} = \frac{R_{427} - R_{900}}{R_{427} + R_{900}} > 0{,}4$$

Cloud mask:

All pixels – vegetation – desert – ocean

Ice Clouds mask:

$$\frac{R_{1547}}{R_{1802}} < 1$$

PLANETS SIMULATIONS: SPECTRAL INDEXES COMPARISON

vegetation mask

$$NDVI = \frac{R_{860} - R_{650}}{R_{860} + R_{650}} > 0$$

vegetation mask

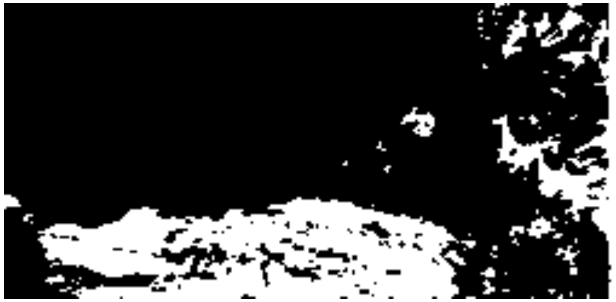
$R_{670} / R_{753} < 1$

desert mask

$$NDSI = \frac{R_{570} - R_{620}}{R_{570} + R_{620}} < 0$$

desert mask

$R_{542} / R_{630} < 1$



ocean mask

$$NDWI = \frac{R_{427} - R_{900}}{R_{427} + R_{900}} > 0{,}4$$

ocean mask

$R_{1321} / R_{4775} < 1$

cloud mask

ice clouds mask

$\frac{R_{1547}}{R_{1802}} < 1$

All pixels – vegetation – desert – ocean

cloud mask

ice clouds mask

$\frac{R_{1542}}{R_{1802}} < 1$

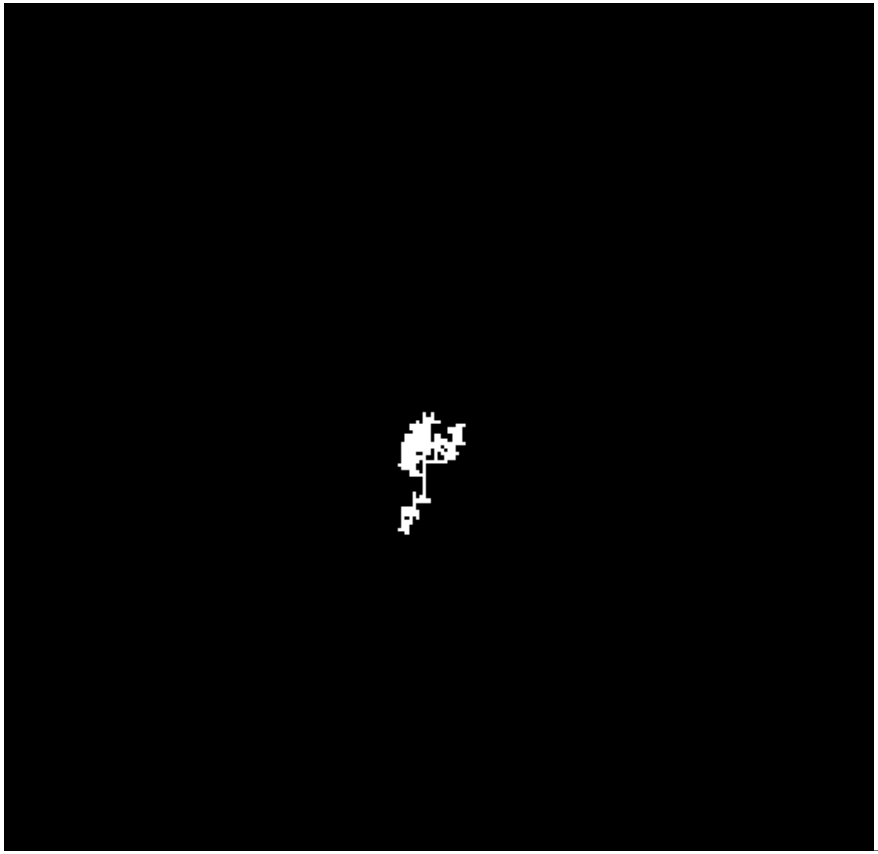
All pixels – vegetation – desert – ocean

PLANETS SIMULATIONS: BUILDING A PLANET

The percentage of each endmember is allowed to vary from 0 % to 100 % with steps of 10 % so that at any time the total sums up to 100 % (see below).

0 % < Ocean (OC) < 100 %
0 % < Vegetation (VG) < 100 % - OC
0 % < **Ice Clouds (IC)** < 100 % - OC - VG
0 % < Water Clouds (WC) < 100 % - OC – VG - **IC**
Desert (DS) = 100 % - OC – VG – **IC** – WC

The number of pixels of each endmember is computed from the total number of pixels of the planet multiplied by the related percentages.



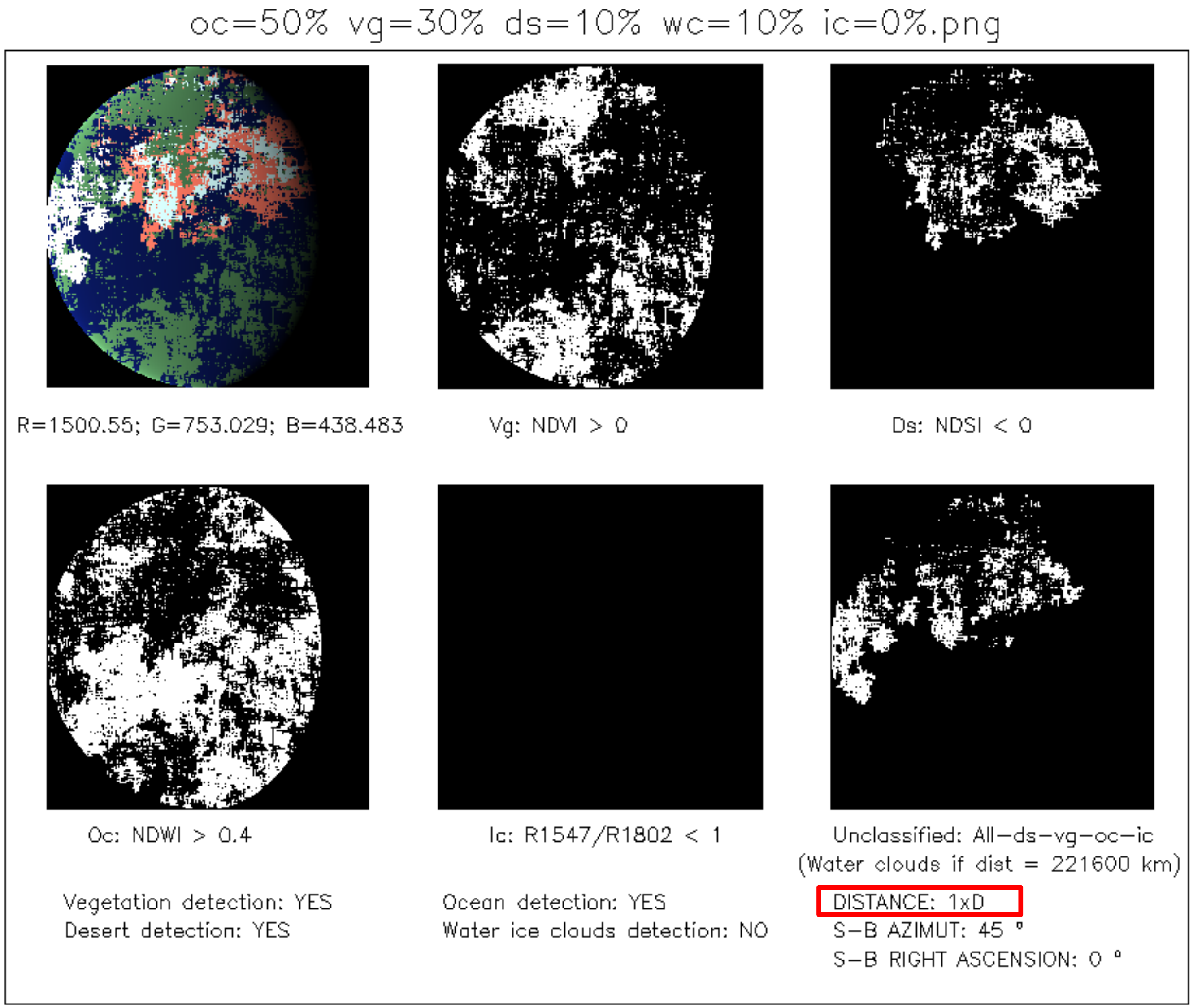
Vegetation is the first class arbitrarily chosen to fill in the planet starting from the center. As vegetation pixels are spawned (they are forced to be adjacent among each other following a random logic) their number is decreased, until a certain condition based on random number generation is hit in the algorithm. When this happens, the class switches to another endmember and the process is repeated until all the pixels of all classes have been depleted. In the example above a planet with OC = VG = DS = WC = IC = 20 % is generated with the implemented algorithm (false colors).

PLANETS SIMULATIONS : DIFFERENT DISTANCES

Oc = ocean
Vg = vegetation
Nc = no clouds (cloud free)
Wc = water clouds (no ice)
Ic = ice water clouds

S-B = Sun-Boresight angle (the azimut is positive in the clockwise direction with respect to the boresight, located at the center of the planet; the right ascension is positive in the northward direction)

Unclassified pixels are obtained from the subtraction of all the classes from the total. At the minimum distance D = 221600 km these pixels are classified as water clouds.



SINGLE PIXEL EARTH: ENDMEMBERS DETECTIONS

- **DESERT** can be detected at the maximum distance only if its percentage is higher or equal than 80 %. Lower concentrations get the desert spectral signature diluted with distance and the other endmembers dominate the signal.

- **OCEAN** has been detected only when the ice clouds are almost absent (IC ≤ 10%) and the total cloud coverage in general is ≤ 50%. Different combinations of the other endmembers were possible but it has never been detected with OC < 40%.

- A minimum of 20% of **VEGETATION** was detected but only in clear sky conditions (no clouds). It has never been detected when the cloud coverage is > 40%.

- **ICE CLOUDS** have been detected at all percentages. However, they were never detected with more than 20 % of desert and more than 40 % of vegetation. Ocean was not a bias instead.

THE RESULTS OBTAINED WITH OUR SIMPLE PLANET SIMULATOR SHOW THAT, WHEN THE PLANET IS OBSERVED AS A SINGLE PIXEL, **THE SURFACE ENDMEMBERS CAN BE DETECTED ONLY WHEN THE TOTAL CLOUD COVERAGE IS LESS THAN 40% IN THE FOV**.

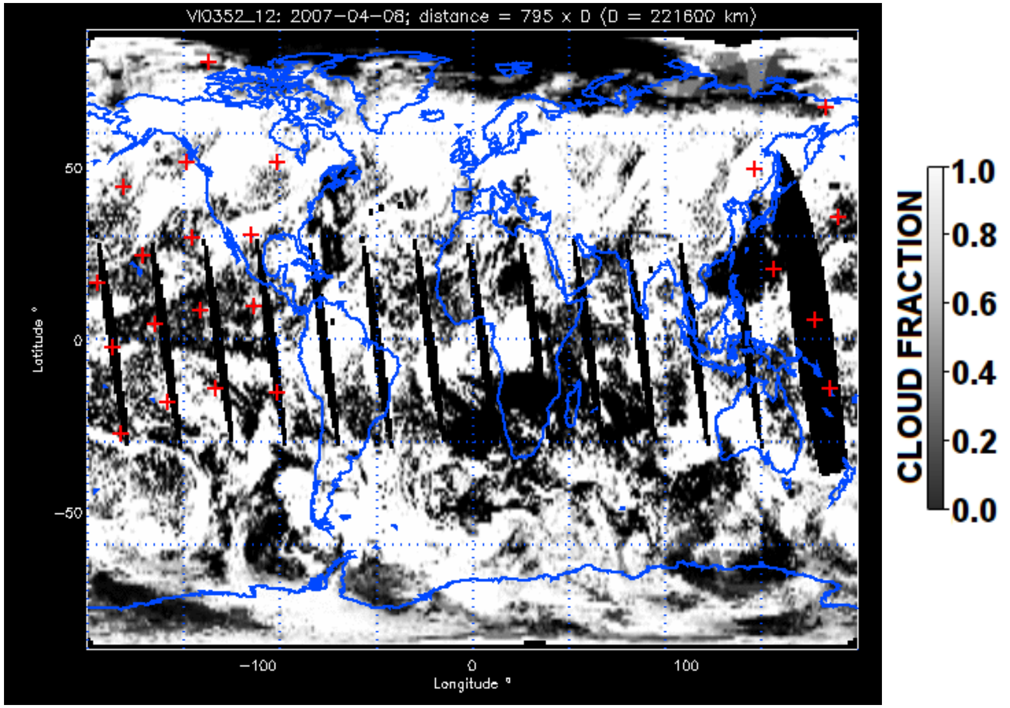
ENDMEMBER DETECTIONS WITH VEX EARTH SINGLE PIXEL DATA

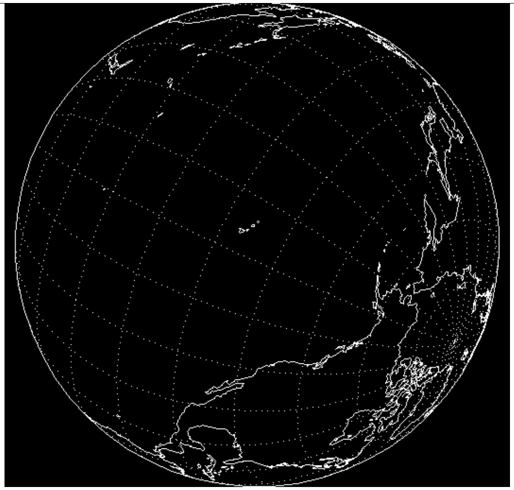
Our results show that the surface endmembers (OC, DS, VG) can be detected only when the total cloud coverage (WC + **IC**) is less than 40% (even if we have been able to detect ocean with WC = 50% in two cases). The comparison of these results with VEX Earth data is not trivial: in order to detect a particular endmember we need an Earth observation in which that endmember is actually falling in the field of view with a sufficient coverage to be detected. Moreover, clouds should not be covering more than 40% of the observed hemisphere.

- Since in most cases Earth is sub-pixel size, we computed the oberving geometry with the JPL NAIF-SPICE libraries and kernels (Acton et al., 1996) by dividing VIRTIS IFOV in order to obtain more than only 1 intercept point with the planet.

- The cloud coverage of each observation has been estimated from the Aqua/MODIS daily cloud fraction data (Nasa Earth Observations website).

- To obtain the total cloud coverage of each single pixel Earth observation we averaged the cloud fraction related to the longitude and latitude of each intercept point (red crosses, upper right).





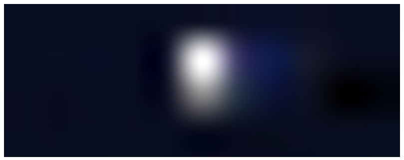
CUBE ID: VI0352_12

CUBE date: 2007-04-08

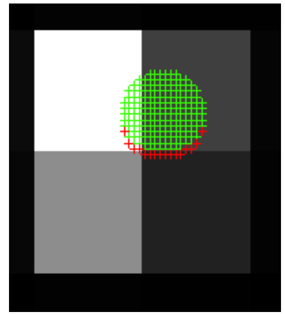
Average cloud coverage: 53%

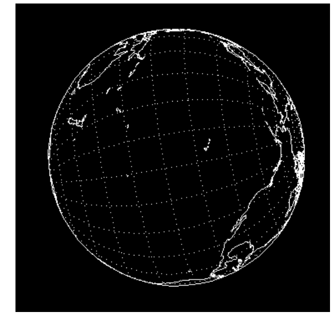
PRE-PROCESSING OF VEX EARTH-DATA NEEDED BEFORE THE ANALYSIS

Some instrumental effects must be taken into account when dealing with VEX Earth dataset. Indeed, these are point source observations and the point spread function, ITF, order sorting filters and calibration issues must be dealt with carefully. Moreover, straylight contamination is being assessed.



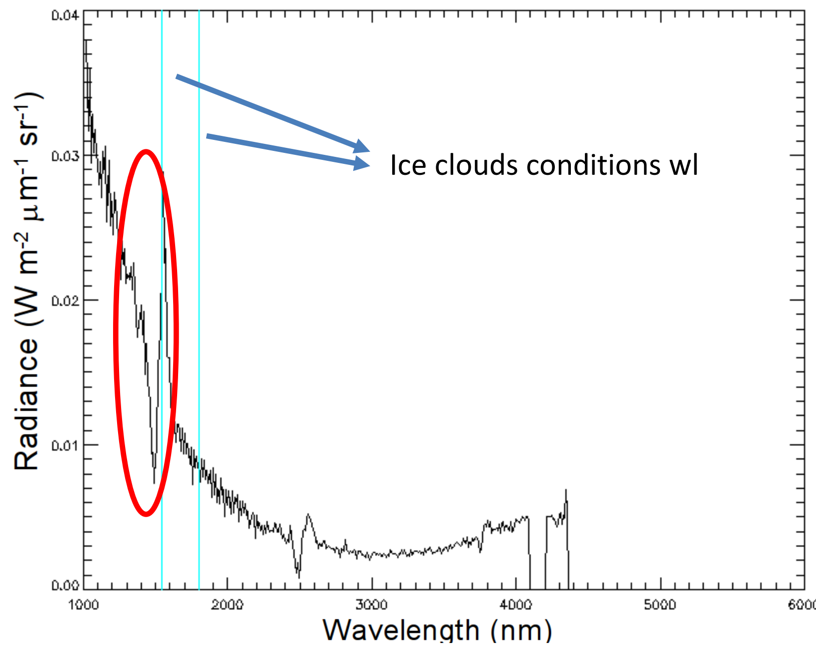
VEX VIRTIS-M-VIS: VV448_07
Date: 2007-07-13; T00:41:11
Target distance: 66000000 km





In the example above a VEX cube is shown at left; the intercept points of the geometry are shown in the middle panel (+ = dayside; + = nightside); the observing geometry of the cube is displayed at right → mostly ocean in the field of view!

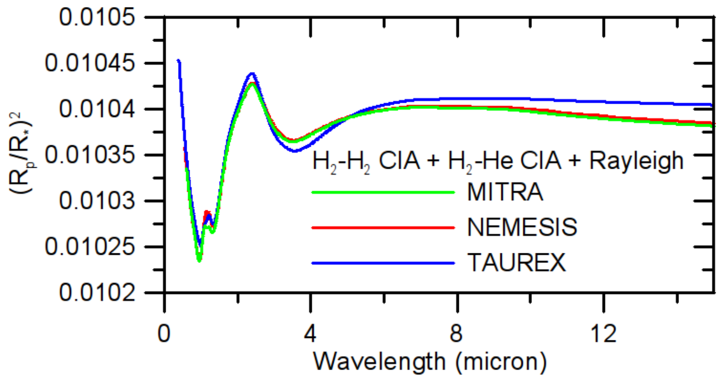
At right, a spectral artifact is shown (red ellipse) to stress how it can affect the spectral conditions application on the data (cyan vertical bars indicate the wavelengths chosen to discriminate the ice clouds).

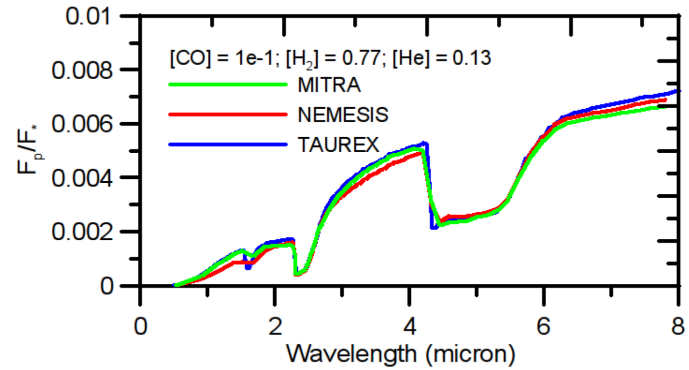


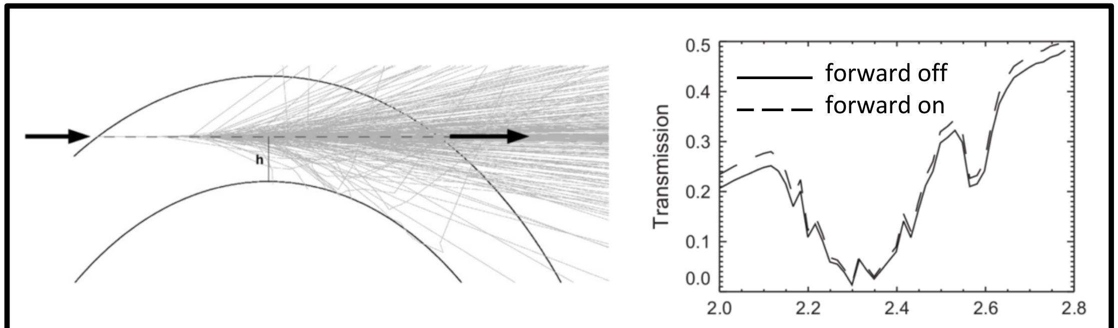
MITRA RT TOOL

The MITRA RT tool (Oliva et al., 2016; Sindoni et al., 2017; Adriani et al., 2015; Oliva et al., 2018; Sindoni et al., 2013) has already been updated to simulate primary transit (left) and secondary eclipse (right) events and has been validated, with the approximation of no scattering by the clouds, with other models within the ARIEL Spectral Retrieval WG.

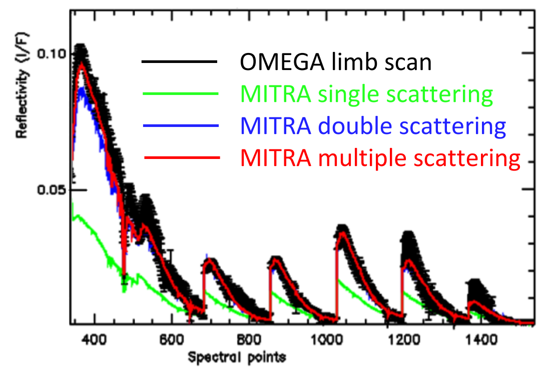
Jupiter-like planet with an isothermal T-P profile (1500 K) transiting a Sun-like star.







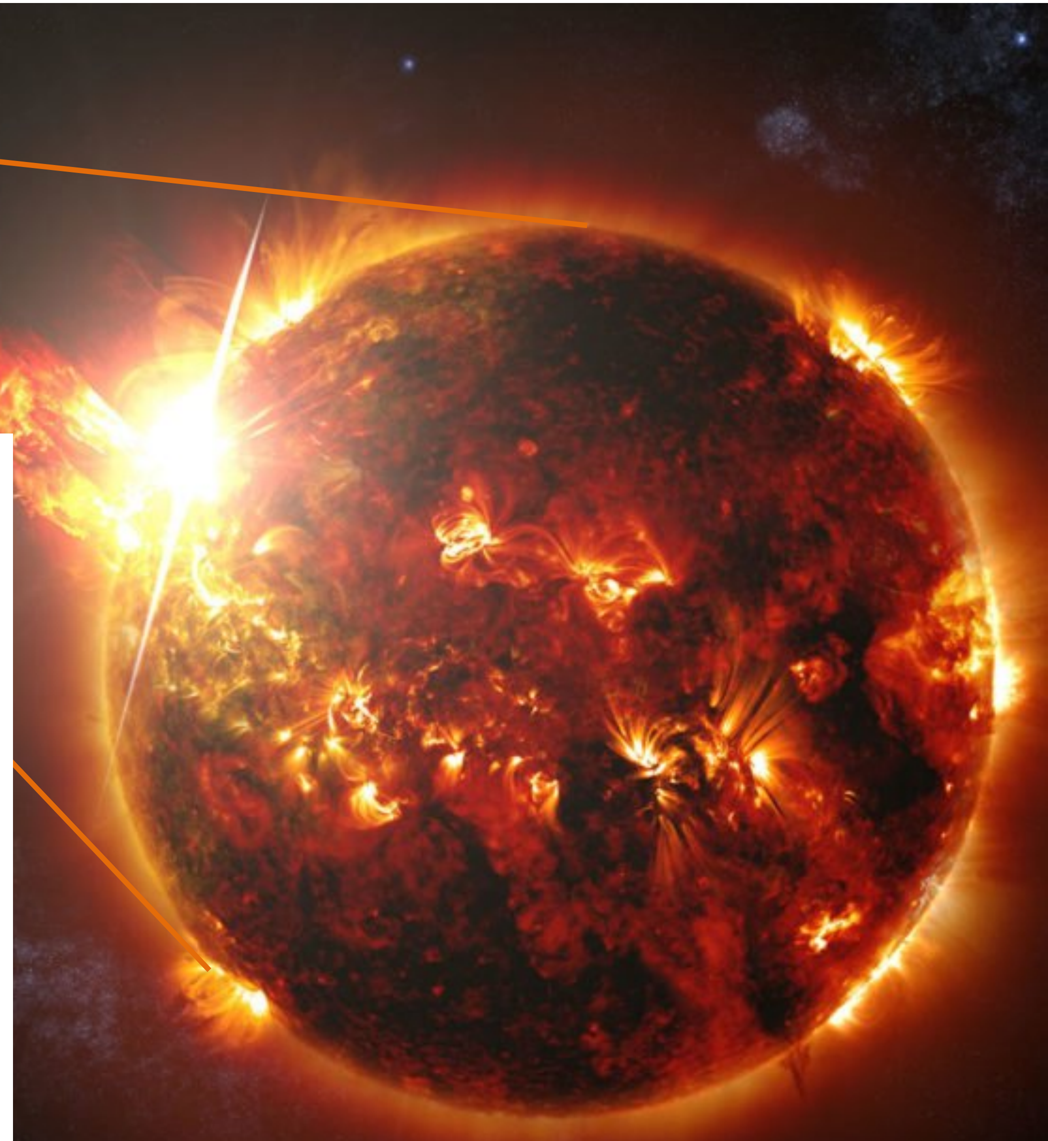
De Kok & Stam (2012)



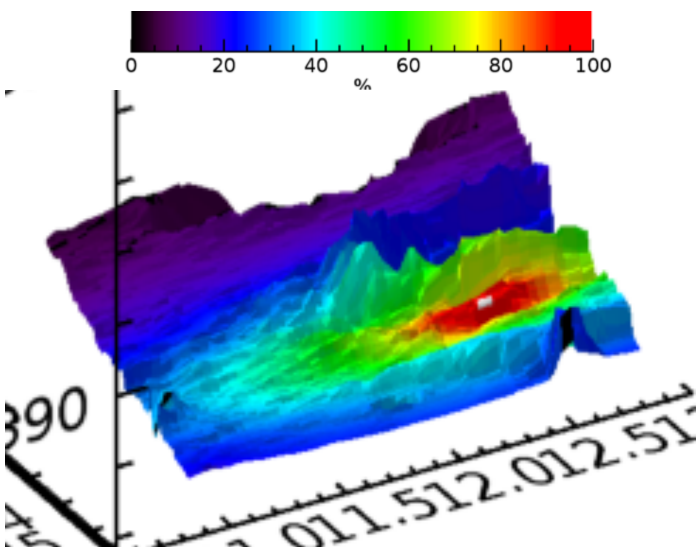
The MITRA tool can perform full multiple scattering simulations in spherical geometry and is currently being applied to study Exomars/TGO-NOMAD nadir, limb and solar occultation data. Hence, it can be used to quantify the effects of multiple scattering in the abovementioned simulations.

MITRA RT TOOL

HANDLING OF THE EXTENDED SOURCE AND INTEGRATION OF THE SIGNAL.



EXTENDED SURFACE SOURCE HANDLING TO DEAL WITH OMEGA LIMB SCAN DATA



SUMMARY AND FUTURE WORK

- Spectral endmembers describing some of Earth’s different classes of relfecting surface have been selected and their reliability tested with commonly used spectral indexes.

- The capability to detect these classes from the observed radiance of the planet is affected by the target distance and by the presence of clouds. The surface endmembers cannot be detected when the cloud coverage is larger than 40% in the field of view.

- The analysis carried on with our planet simulator will be performed on Venus Express/VIRTIS-M Earth sub-pixel data and the results compared with the simulations.

- The MITRA tool will be used to evaluate the effect of multiple scattering in transit and eclipse observations and will be used to refine the planet simulator.