Astrophysical light scattering problems

Experiments and instrumentation

Photometry, polarimetry, and spectroscopy

Misc. topics

Antti Penttilä

Contents

- Sample characterization and preparation
- Simulated asteroid imaging

Experiments – models

- To simulate material that is measured or observed, we need
  - Size and shape of the particle/particles
  - Geometry of the macroscopic scale, i.e., packing geometry of regolith particles
  - Refractive index or indices of material(s)

Sample characterization – microscopy

- When measuring scattering properties of laboratory samples, the characterization of the sample is extremely important
- Especially when the measured properties might be used in/with/in comparison to simulations, there needs to be a good understanding of what is being measured and what is being simulated
- Normal optical microscopes (bright field microscopy) are *diffraction-limited*, meaning that they cannot see details below the Abbe diffraction limit

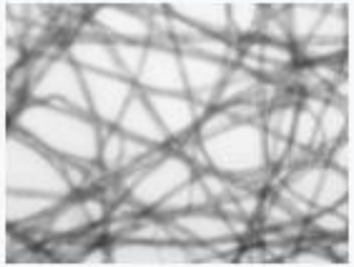
$$d = \frac{\lambda}{2\,n\,\sin\theta}\,,$$

where λ is wavelength, and $n\sin\theta$ is the so-called numerical aperture *NA*.

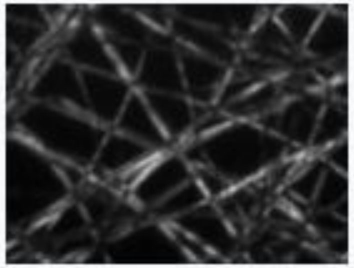
- With numerical apertures as 1.4 at best, diffraction limit for 500 nm light is about 200 nm
- Then again, 200-nm structures will have influence when simulating light scattering behavior in visible wavelengths

Sample characterization – microscopy

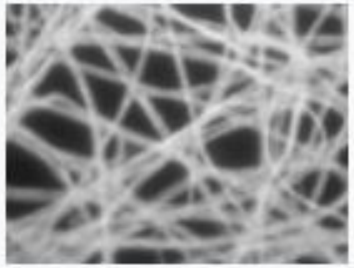
Different optical microscopy techniques, image credit Wikipedia



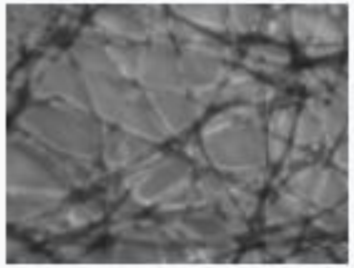
Bright field illumination, sample contrast comes from absorbance of light in the sample.



Cross-polarized light illumination, sample contrast comes from rotation of polarized light through the sample.



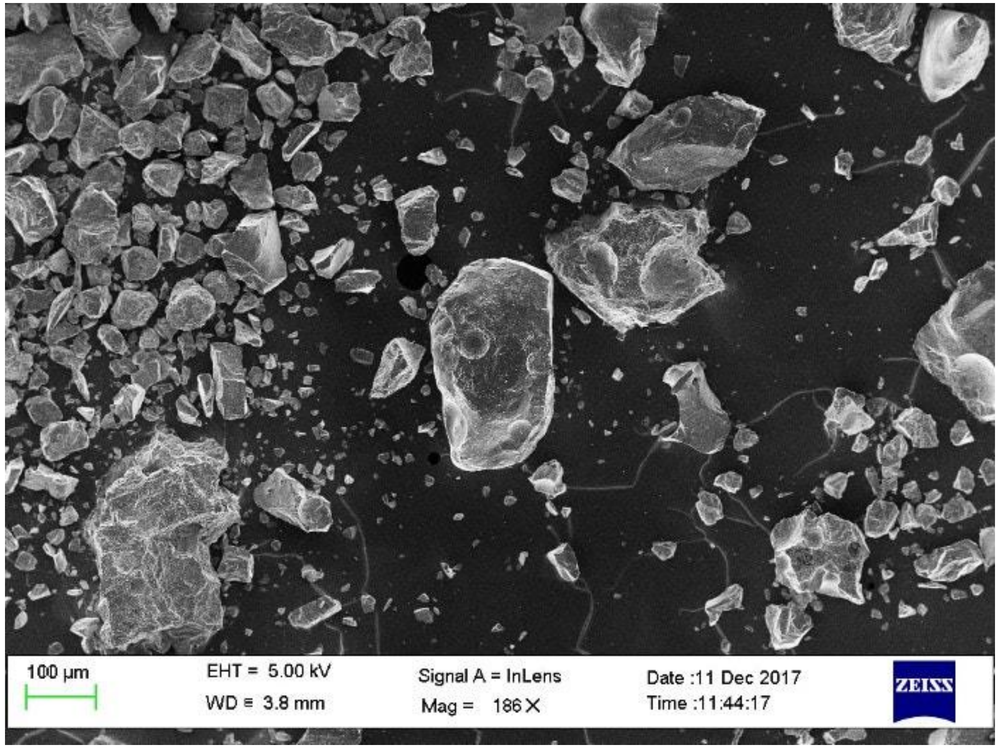
Dark field illumination, sample contrast comes from light scattered by the sample.



Phase contrast illumination, sample contrast comes from interference of different path lengths of light through the sample.

Sample characterization – microscopy

- Electron-beam microscopes (scanning SEM or transmission TEM) can overcome the optical diffraction limit
- Downside: samples need to be coated
- If we can see ~10 nm structures, then one image field shows ~1 μm^2. How many images we need to have representative sample of the target?
  - Interesting structures in ~10 μm and 10 nm scales, how to combine?



SEM image of JSC-1A lunar regolith simulant. Image credits: Granada-Amsterdam light scattering database.

Sample characterization – microscopy

- Relevant reflection/scattering/absorption processes can happen on the surface, but also below the surface. X-ray microtomography can give 3D structure up to voxel resolution of some tens of nanometers, but usually to ~µm voxel size
- Problems:
  - One needs good contrast between materials to separate them
  - Data volumes can become huge
  - How to include the information in models

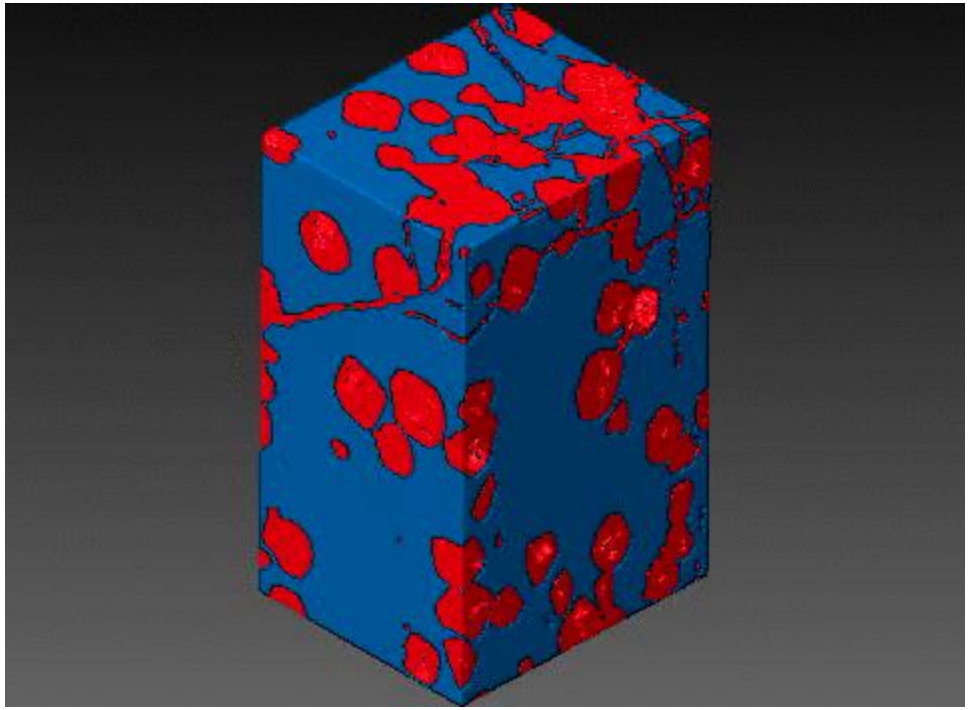


Image credits: Wikipedia, Bread and butter with sage and rosemary lemon

Sample preparation – space environment

- There is a known mismatch problem between laboratory measurements and astronomical observations
- Spectral properties of meteorites (measured in laboratory) are somewhat different to those observed by asteroids or comets (slope, absorption band depth)
- Asteroid surfaces:
  - Wide size distribution of regolith dust, down to very small sizes
  - Packed in microgravity and vacuum
  - Can have very cold temperatures
  - Space-weathered material on top
- Meteorites in laboratory:
  - One piece of rock, or size fractions of grounded samples
  - Particulate samples packed in standard gravity
  - Not in vacuum, at least not always, can include moisture from ambient air
  - Not very cold temperatures for very long time
  - No space weathering, space-weathered loose dust lost during entry to Earth, original surfaces possibly melted during entry

Sample characterization – size distributions

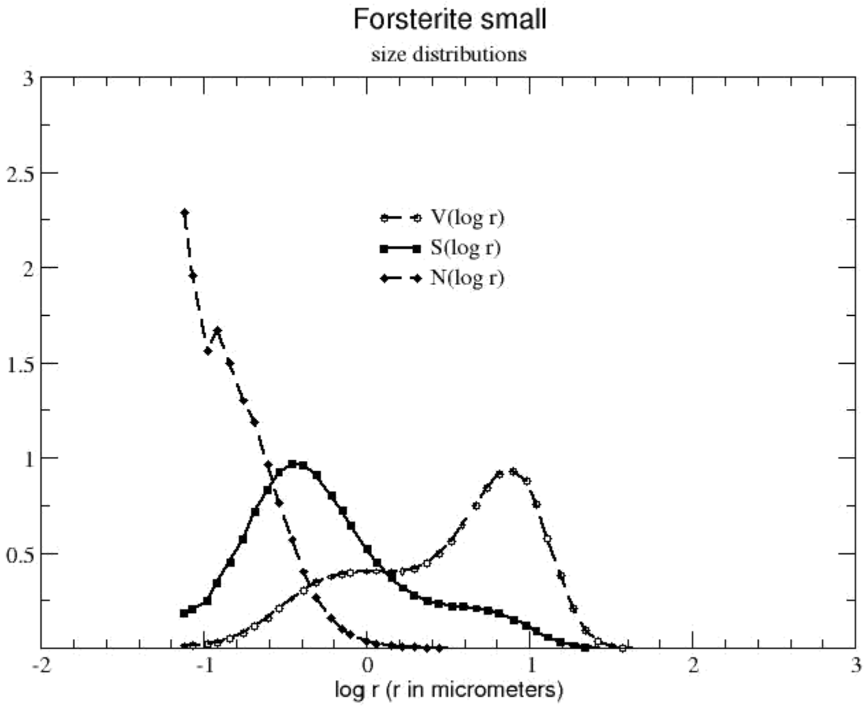


Figure from Granada-Amsterdam Light Scattering database, Forsterite size distribution

- Size distribution describes the distribution of particle sizes in the sample. Sounds simple, but includes some caveats
  - Distribution can be functions of the *number* of particles of certain size, the *surface area* of particles of certain size, or the *volume* of particles of certain size
  - In simulations we usually need the number of particles in different size fractions
  - Particle size measurements usually provide the volume of particles in size fractions
  - Finally, distributions are often presented rather in $\log r$ than r

Sample characterization – size distributions

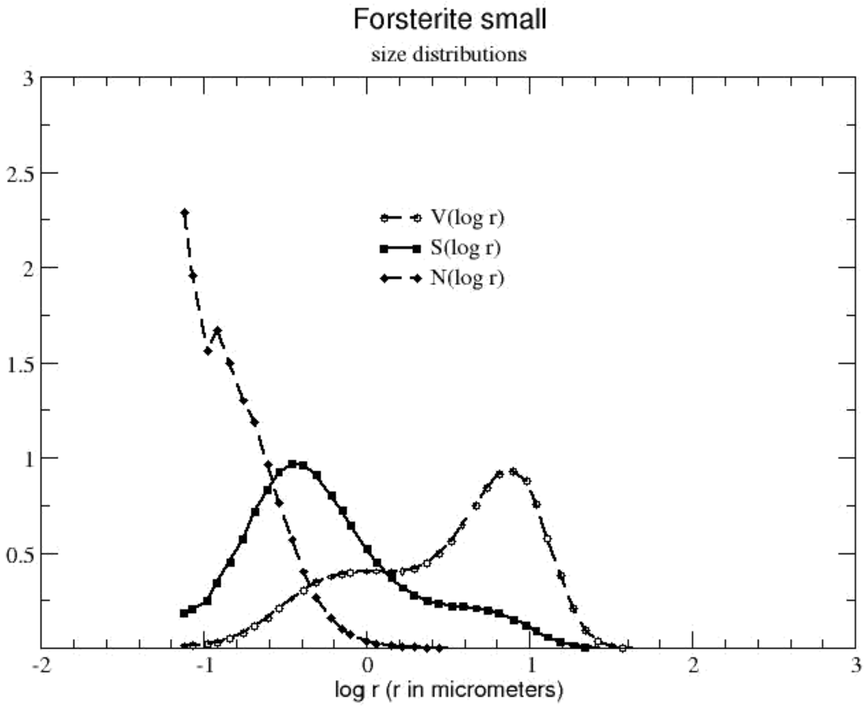


Figure from Granada-Amsterdam Light Scattering database, Forsterite size distribution

- Particle sizes can range over several magnitudes, e.g., from 0.1 μm to 10 or 100 μm
- In simulations – in same volume you can have **one** d=20 μm particle, or **one million** d=0.2 μm particles
  - Hard to do simulations having both ends of the size distribution – would require tens of millions of particles in total to reproduce the particle distribution
- Analytical size distributions:
  - If volume-based distribution is $v(r)$, then number-based distribution $n(r) \propto {}^{v(r)}/_{r^3}$
  - For example, if volume distribution is power law with index κ, then number distribution is also power law but with κ*= κ-3
    - This indicates that the original κ should be > 4

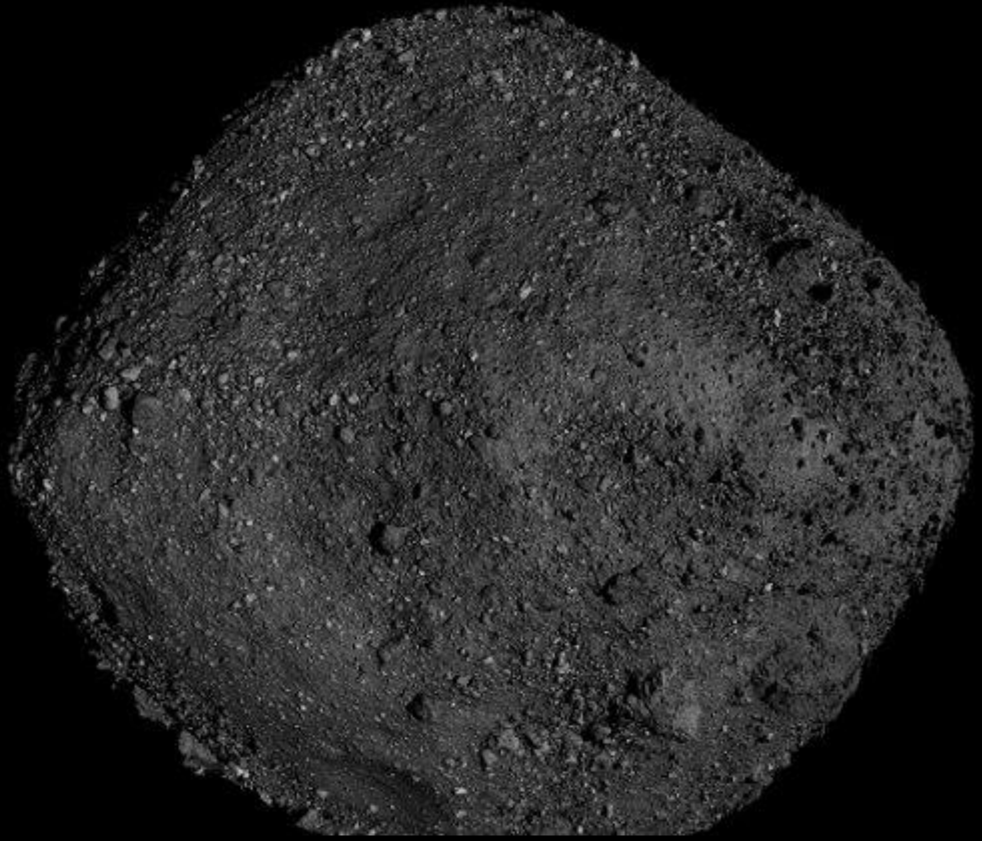
Sample characterization – refractive indices

- Refractive index of material can be measured, but not always easily
- Refractive index $m(\lambda) = n(\lambda) + i\,k(\lambda)$ is a complex quantity, and function of wavelength
- Real part more easily measured, e.g., via ellipsometry
  - Measures differences in reflection (or transmission) from polished, smooth surface between parallel and perpendicular polarizations
  - Needs perfect surface
- Complex part more difficult to measure
  - Kramers-Kronig analysis sometimes applied
  - Often requires modeling – unrealistic models produce unrealistic values
  - Danger of circular argument: Complex refractive index inferred using Hapke model, then used in optical simulations using Hapke model – everything looks consistent, but are the values correct?

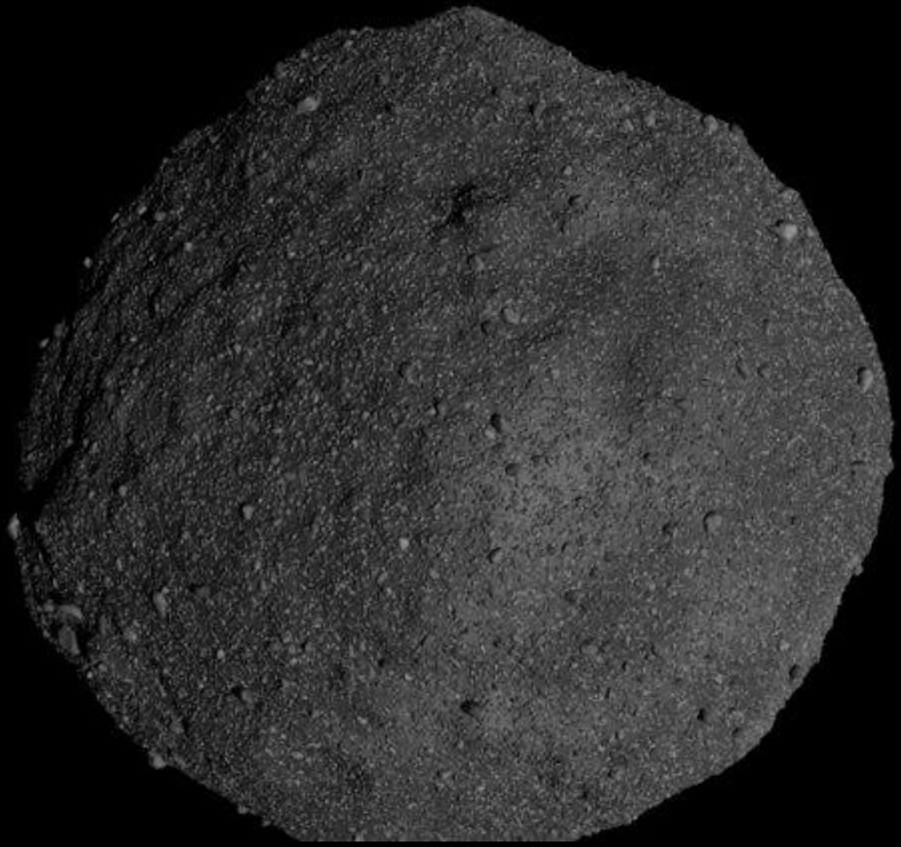
Simulated asteroid imaging

- We and some other groups are working on combining world-class 3D rendering tools (such as Blender) with typical photometric functions in planetary sciences, shape models of solar system targets, and spacecraft trajectories
- Goal: to be able to simulate beforehand what the imaging instruments will see
- Some projects:
  - Shape viewer by Jean-Baptiste Vincent
  - SISPO by Aalto/Tarto groups
  - Blender asteroid hyperspectral imaging by us

Bennu

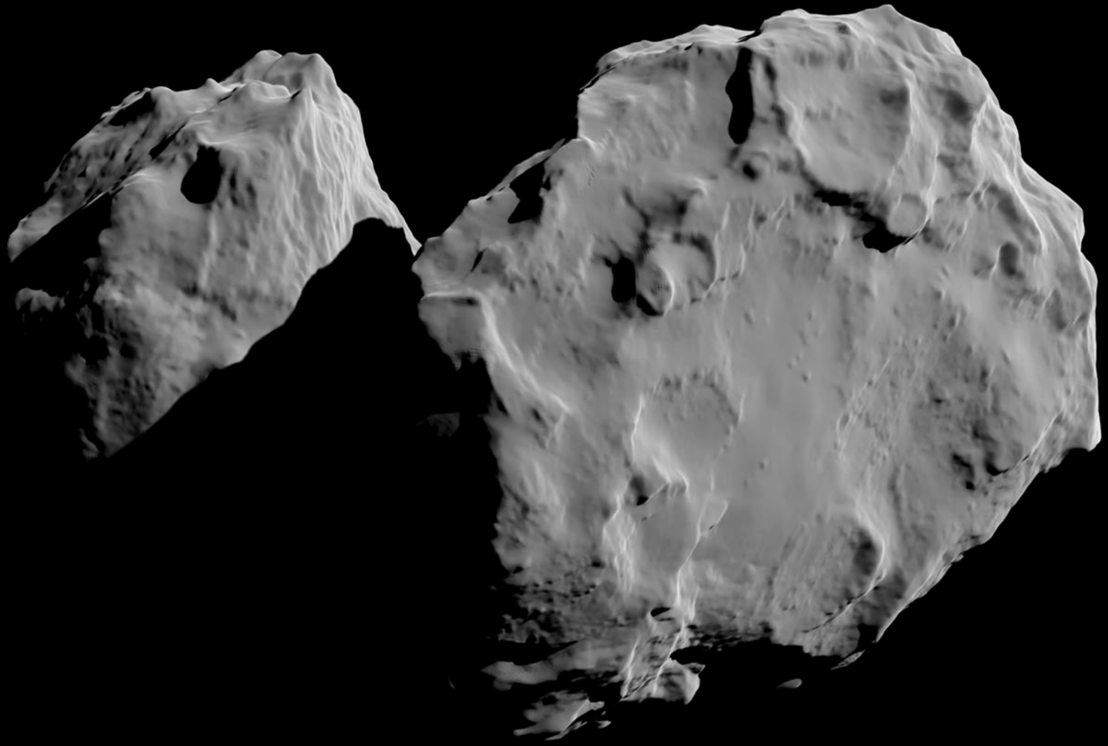


NASA's laser altimetry model with high-res imagery overlay

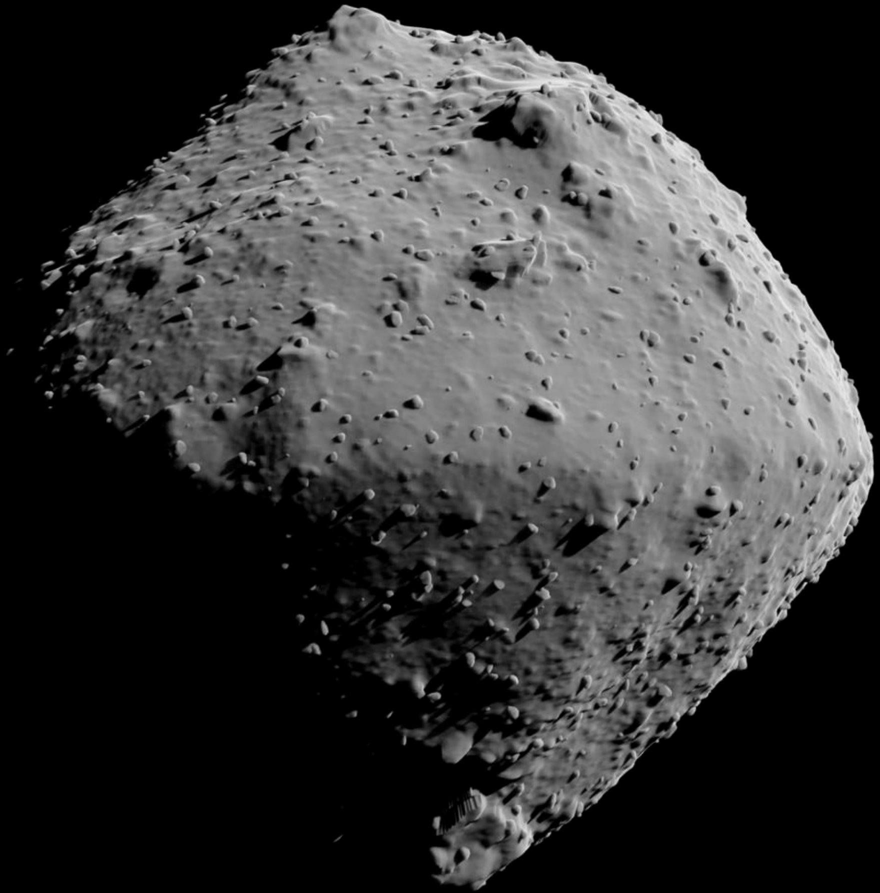


Our Blender model using low-res Bennu shape and procedural roughness and boulders

Other Blender rendering examples



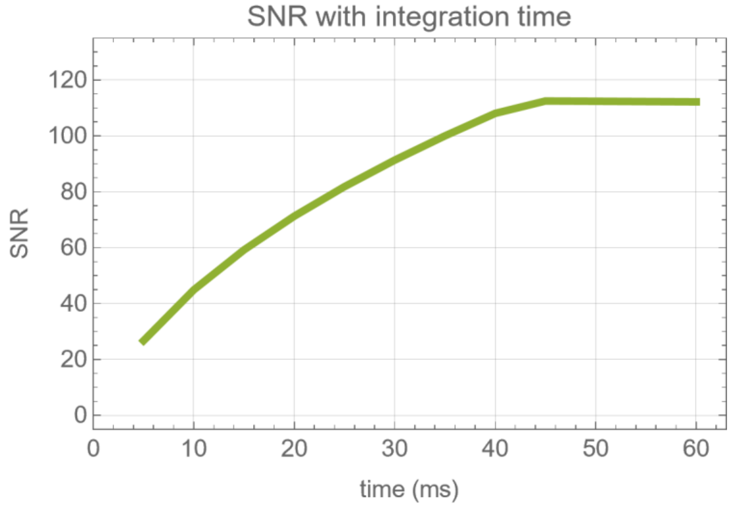
67P/C-G, McEwen photometric function



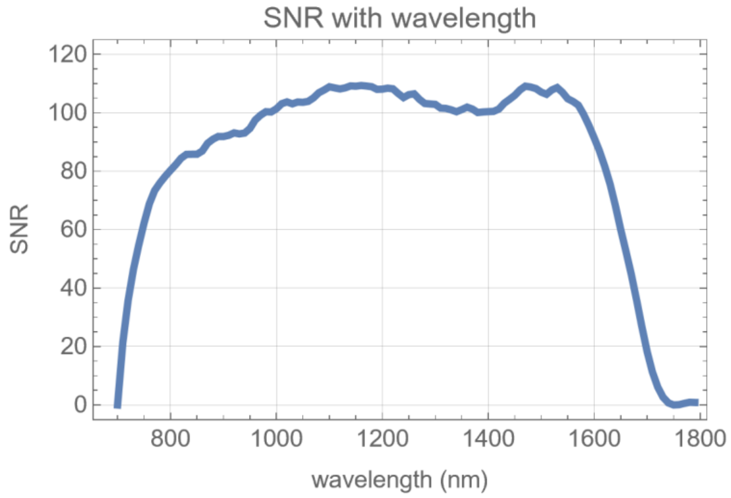
Ryugu with added boulders,
McEwen photometric function

SNR analysis for VTT NIR camera

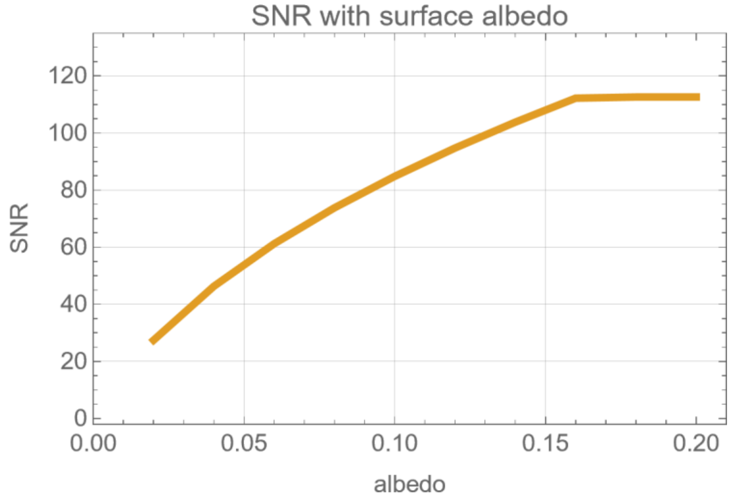
- Input: the noise parameters of the camera
  - Read noise, dark current, integration time, full-well capacity
- Output: the camera SNR as a function of wavelength, surface albedo, or integration time



With fixed wavelength 1200 nm and surface albedo 0.15



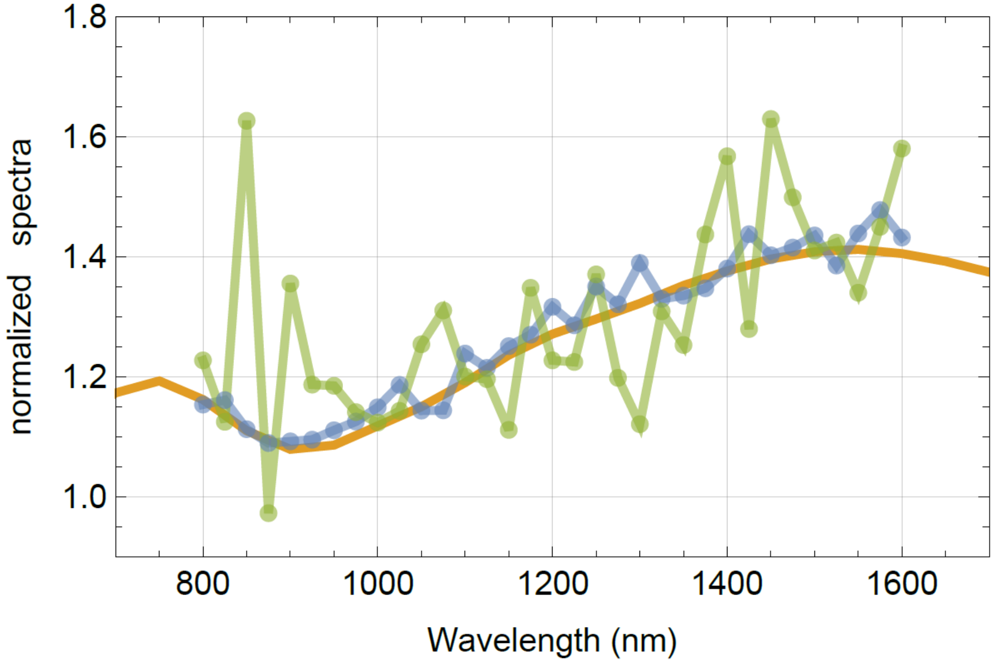
With fixed integration time 40 ms and surface albedo 0.15



With fixed wavelength 1200 nm and integration time 40 ms.

Spectral retrieval analysis for the camera

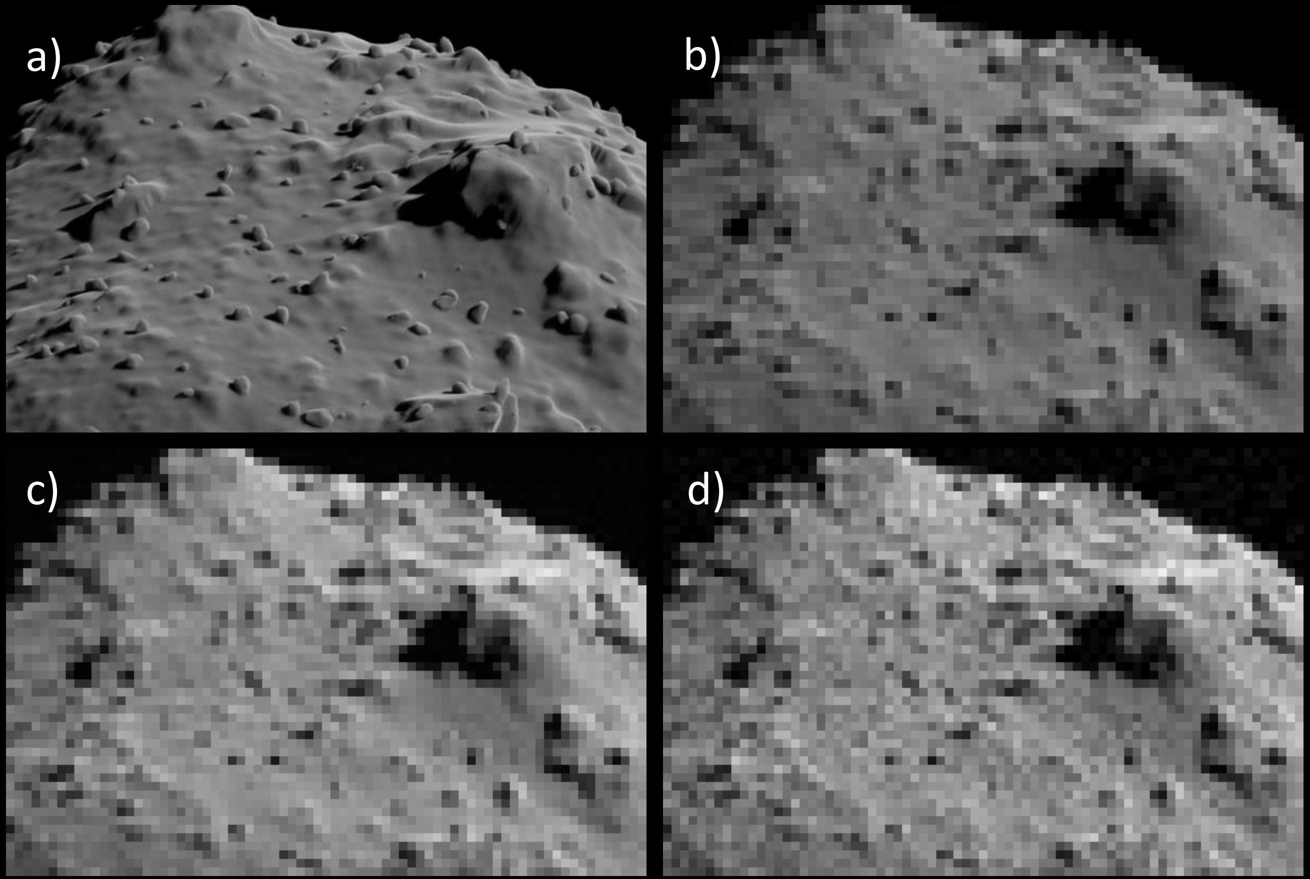
- Input: camera noise parameters and target spectra
- Output: simulated retrieved spectra. Either one or more random spectra or an envelope for 3σ error interval.



’Perfect’ spectrum (S-type asteroid, orange line) and two simulated observed spectra. Simulated observations are done at 25 nm intervals. The blue line is with observing with VTT NIR camera, 10 ms integration, max. SNR at ~1100 nm is 70. The green line is with 1 ms integration, max. SNR 19. Spectral retrieval seems possible with 10 ms integration (SNR 70), but not with 1 ms (SNR 19).

Image SNR analysis

- Input: perfect image from Blender and camera noise parameters
- Output: image with realistic noise as seen in the real observation



High-resolution patch of target’s surface **a)** and different simulated observed images. Image **b)** is with 640×512-pixel ASPECT NIR camera from 20 km distance but without noise. Image **c)** has 10 ms integration, while **d)** has 1 ms integration. Boulders on the target are 2–15 m in size. Noise from 10 ms integration is neglectable, from 1 ms integration not.