Imaging simulation tool for small solar system objects

Antti Penttilä
University of Helsinki

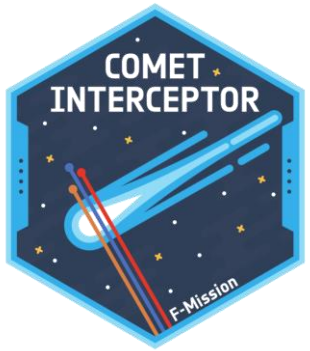
With contributions by Meri Kolehmainen, Anne Keski-Vakkuri, Leonardo Negri, Noora Halla-aho, Joel Jääskeläinen, Mario F. Palos, Tomas Kohout (UTU), Antti Näsilä (VTT), Richard Cole (VTT)

Nordic-Baltic Astronomy Days 2026, Turku

Motivation

- Space mission operations need to be planned beforehand
- This invokes questions like:
  - What do we see with camera *XXX* in mission phase *YYY* when observing geometry is *ZZZ*?
  - What is the quality of the images with detector *XXX* in geometry *YYY* and with integration time *ZZZ*
  - What is the quality of scientific products from the image with certain detector/geometry/integration etc.

- We are especially interested in these questions in relation with VTT Fabry-Perót interferometric hyperspectral camera on ESA space missions
  - **Hera**/MILANI smallsat, ASPECT instrument targeting Didymos binary asteroid system
  - **Comet Interceptor** MIRMIS instrument with yet undecided target, hopefully new long-period comet

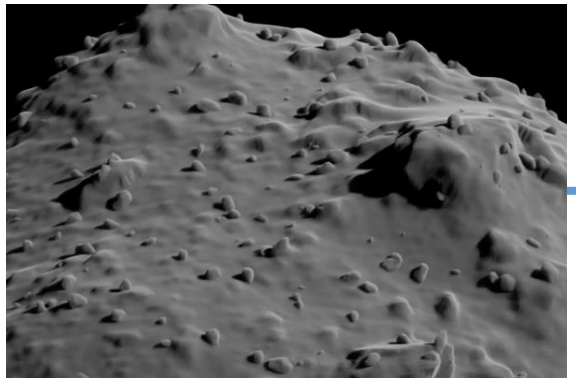


Goals for the tool on what the instrument is seeing

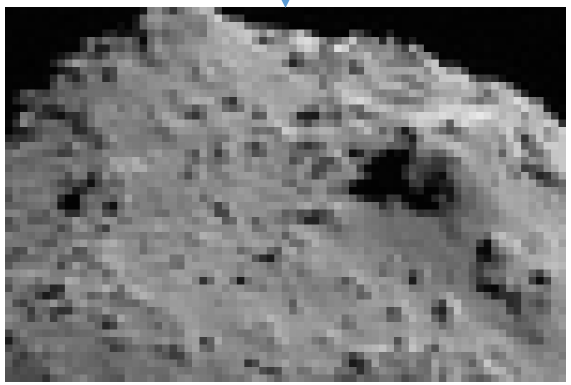
- Physically “correct” and traceable imaging simulations of surfaces (asteroid, comet nucleus) and particle and gas volumes (cometary coma)
- Correct physical units such as radiance
- Description of surface scattering with photometric functions and their parameters typical for planetary science
  - Disk functions: Lommel-Seeliger, Lambert
  - Phase functions: polynomial (ROLO), exponential, linear-magnitude
- Description of particle/gas volumes by particle or molecule density, particle size, particle refractive index or molecule absorption spectra
- 3D shape models for the targets
- (Simple) coma density models
- Accurate observing geometries from SPICE kernels

Goals for the tool on what the instrument is outputting

- Physically correct models for instrument optics transmissions and detector noise components
- Correct units in noise modeling
  - Irradiance goes in
  - Photons transform into electric charges in the detector
  - Detector noise components in unit charges
  - Detector transforms charge counts into digital numbers with some bit depth
- Instrument output is binary stream of digital numbers



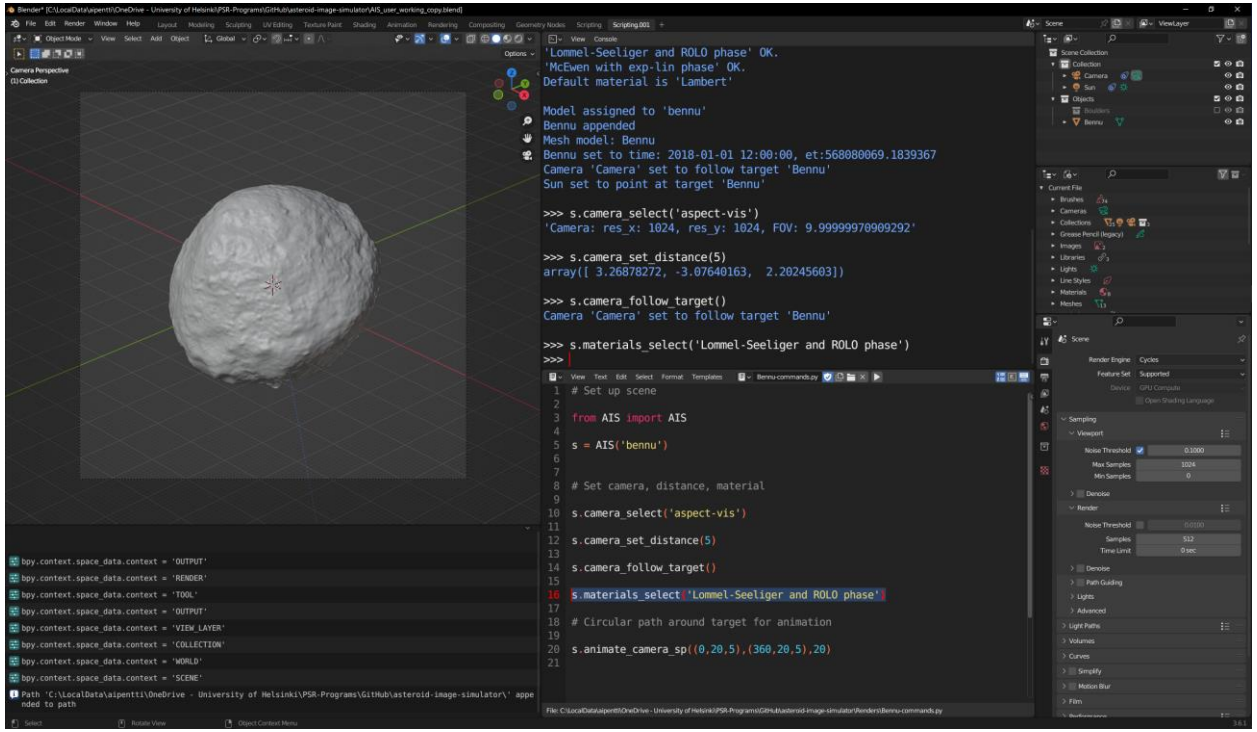
‘perfect’ image and ‘real’ image with correct detector resolution and noises



Design choices for the tool

- The 3D imaging simulation at one wavelength is done in Blender open-source 3D modeling software
- Image simulation part implemented as a Python module working inside Blender's Python console
- Disk and phase functions implemented as Blender shader nodes
- The GUI tools from Blender available, as well as Python command line using the Python module functionality

- Shape models as Blender targets
- SPICE kernel functionality embedded in the Blender Python console for observation geometry

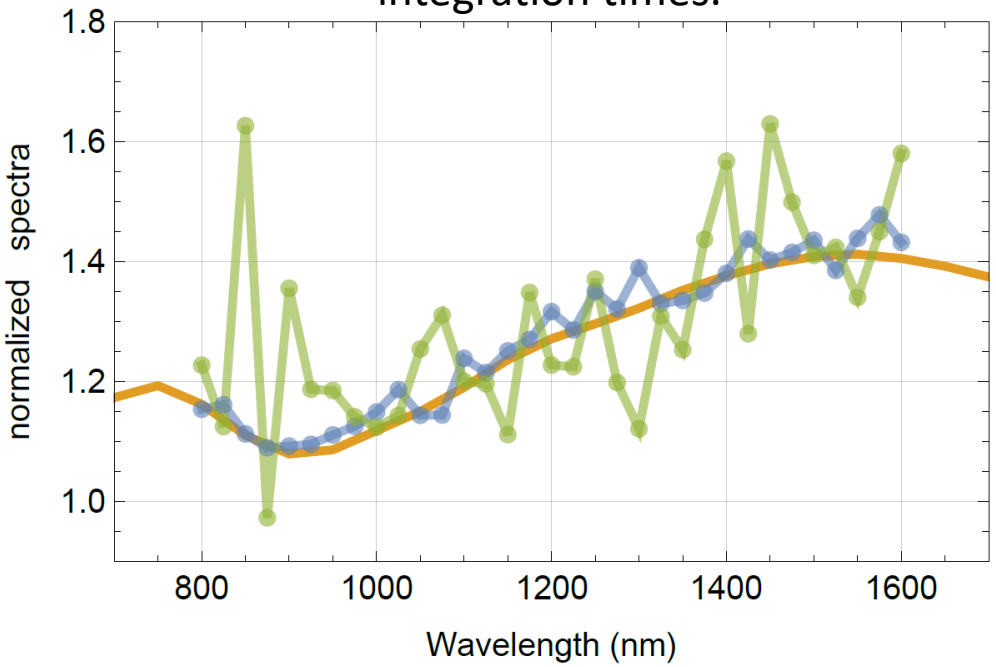


...design choices for the tool

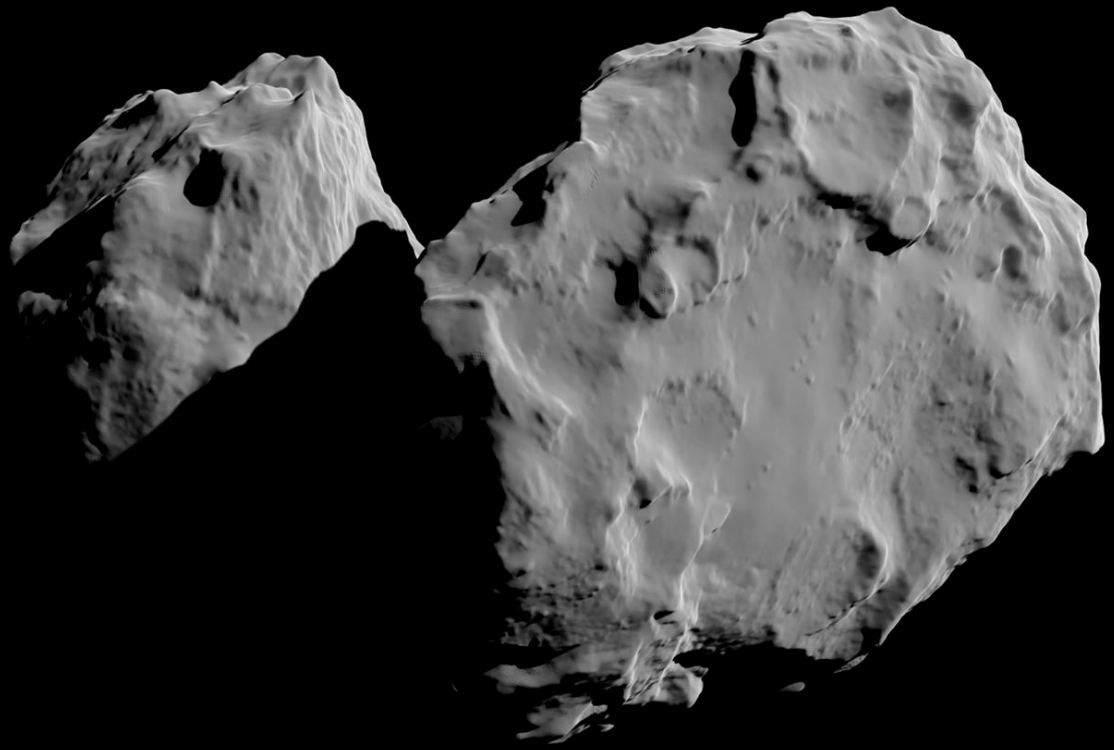
- Instrument simulation as stand-alone Python module outside Blender
- Uses generated images from Blender with additional information to convert image digital numbers into → radiance factor → irradiance (at lens) → flux (detector pixel) → unit charges → digital numbers → binary data stream
- With spectral instruments, if surface phase function assumed wavelength-independent, single image can be expanded into spectral datacube by multiplying by target reflectance spectrum

- For wavelength-dependent cases (comet with gas and dust coma), different wavelengths need to be individually rendered in Blender

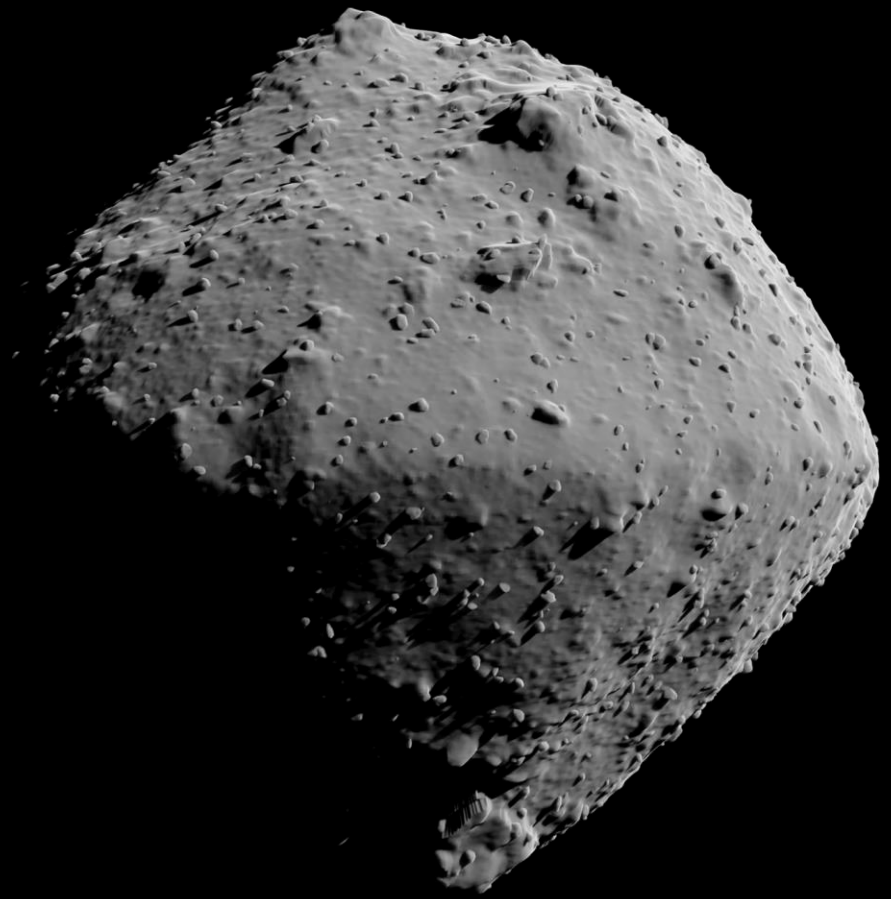
'Perfect' spectrum (orange line) and two simulated observed spectra with noises corresponding different integration times.



Showcase of results with current version of the tool



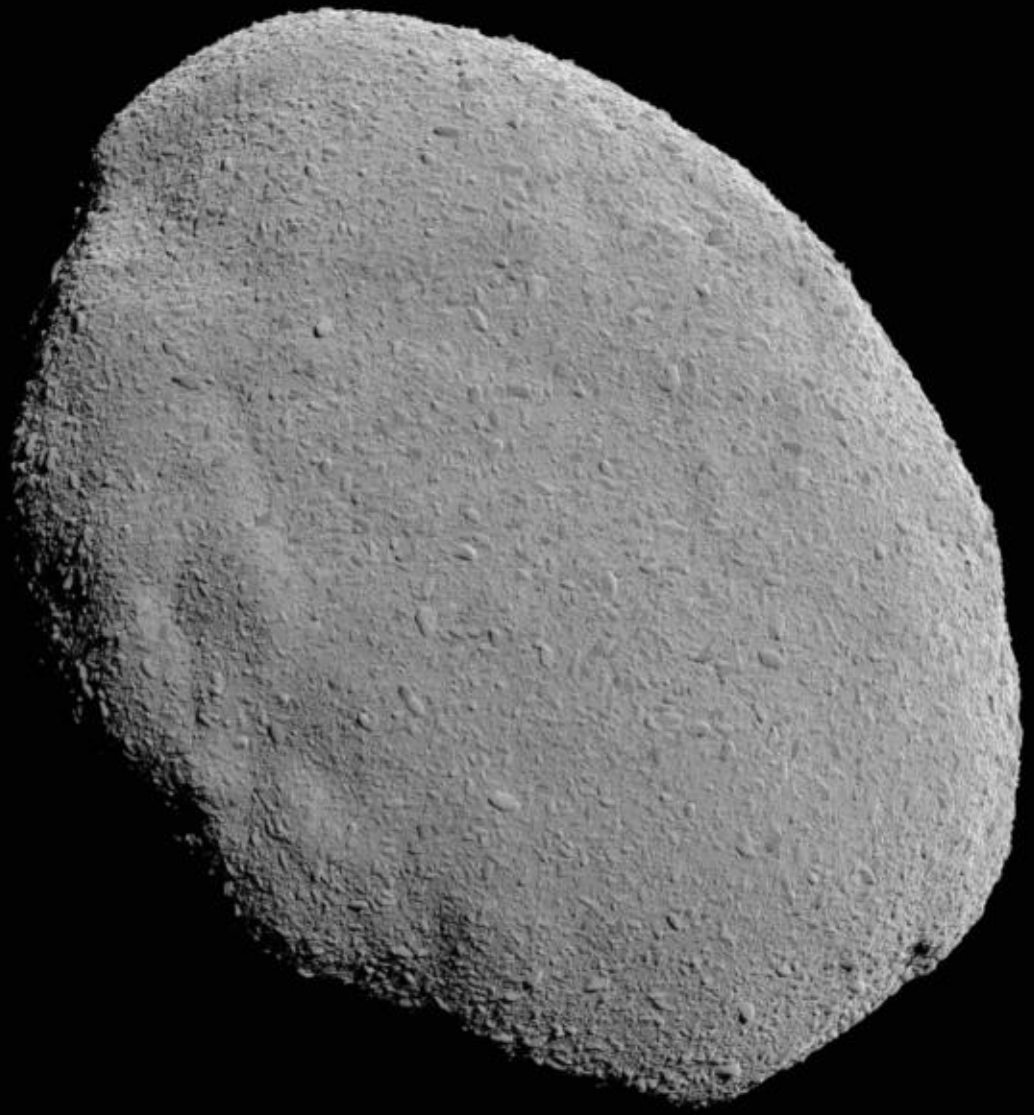
67P/C-G, McEwen photometric function

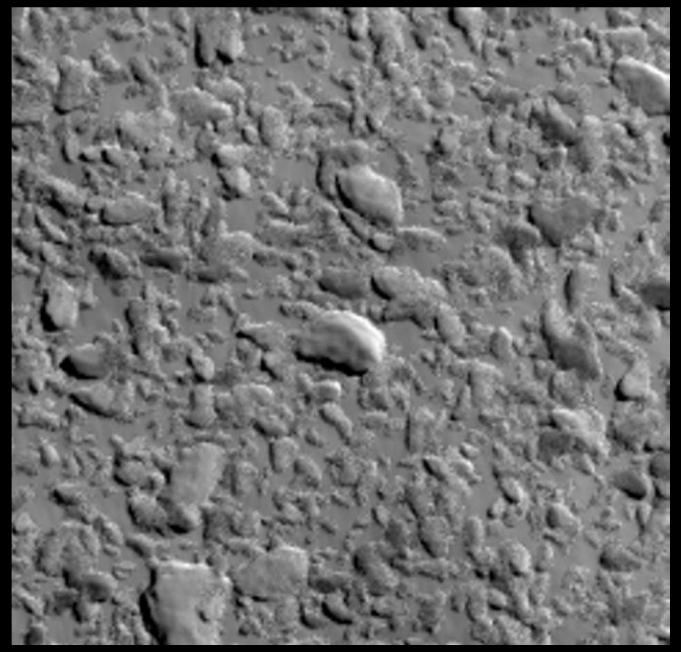


Ryugu with added boulders,
McEwen photometric function

Instrument orbiting an asteroid

...result showcase

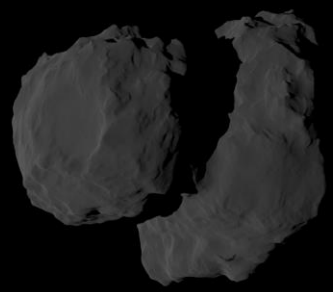


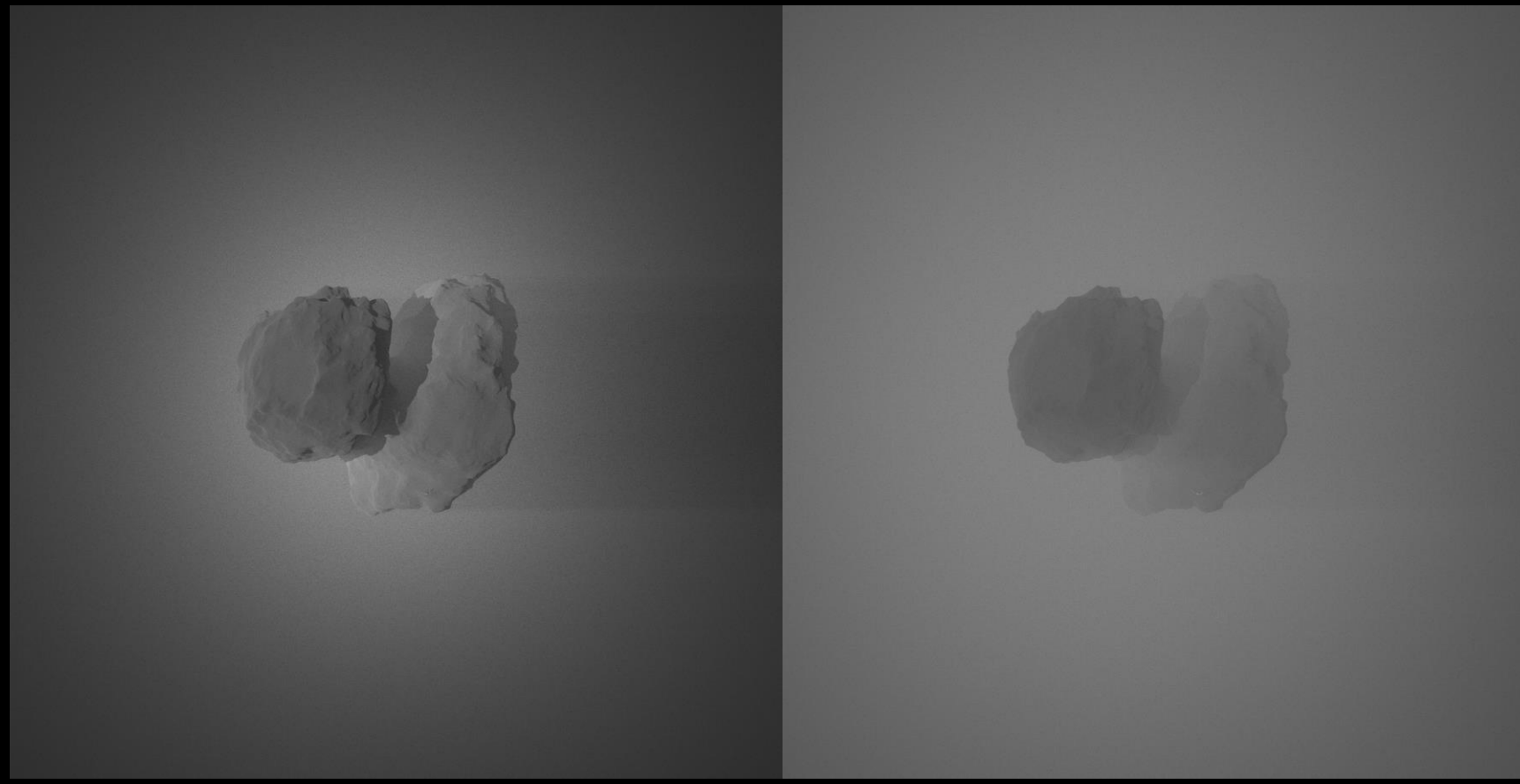


Didymos imaged with ASPECT camera from 5 km distance (left), and zooms on one surface patch (right) either without noise (up), or with added instrument noise (down)

...result showcase

Different levels of dust around a comet nucleus





Current state

- There are working versions (https://bitbucket.org/planetarysystemresearch/asteroid-image-simulator), but current plan is to rewrite all from scratch again ☺
- The programming logic can use revising so that it is easier to maintain and add features afterwards