Astrophysical light scattering problems

Experiments and instrumentation

***Photometry**, polarimetry, and spectroscopy*

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- Why photometry
- Stokes parameters and Mueller calculus
- Detectors
- UH light scattering laboratory
- Granada-Amsterdam light scattering laboratory and database

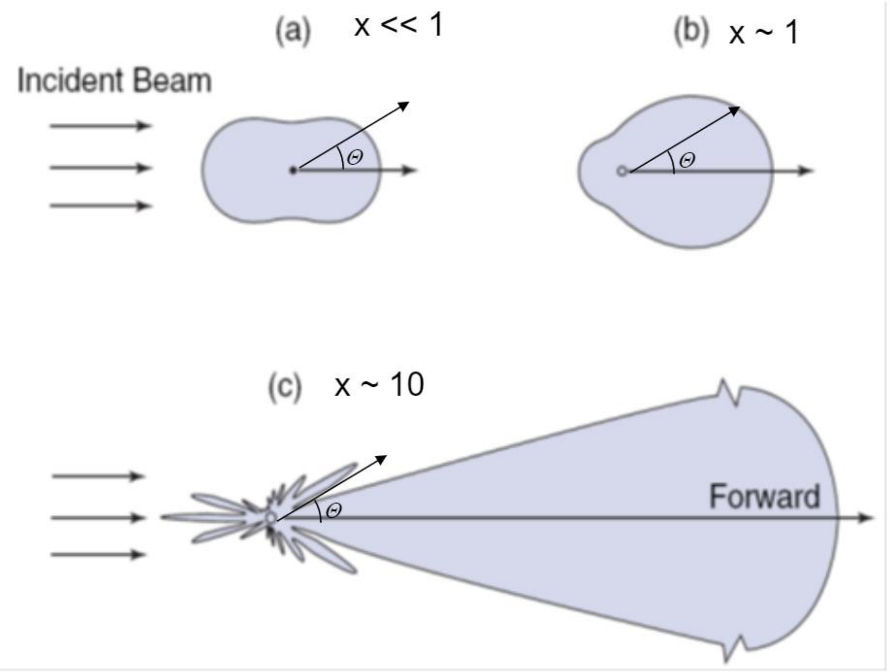
Why photometry

- Studies intensity, power, brightness
- With asteroids, for example, can be related to size
  - Asteroids are point-sources in telescope image, so not resolved targets
  - If the albedo is known, brightness (absolute magnitude) gives size
- Brightness (magnitude) changes with phase angle between the Sun and Earth (observer), this so-called *phase curve* can tell about the composition
- Surfaces scatter light differently to different directions (BRDF)
  - Can be used to identify surfaces
- Photometric corrections need to be done to compose single image/map from individual smaller images (c.f. remote sensing of Earth, imaging of asteroids/moons/planets in space missions)
  - Correct the brightness levels to match single imaging geometry

Why photometry

- We need also photometric information about small particles (scattering phase function) if we want to simulate the scattering processes in material/surface consisting of these small particles (c.f. regolith on asteroid surface)

Phase Function



Θ = Scattering angle

$p(\Theta)$ = Scattering phase function

Azimuthally symmetric for spheres and randomly oriented particle ensembles

Essential for determining the source function for scattering

Very strong, narrow forward peak develops for largest particles (diffraction peak).

The *time-averaged* properties of light can be described with 4 Stokes parameters, collected in a vector $\vec{\boldsymbol{S}}$

$$\vec{\boldsymbol{S}} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

From these 4 parameters, I describes the intensity, and the rest three the polarization state of the radiation. Q and U describe the linear polarization, and V the circular polarization.

For fully polarized coherent radiation, $I^2 = Q^2 + U^2 + V^2$, but for non-coherent, partially polarized light, $I^2 > Q^2 + U^2 + V^2$.

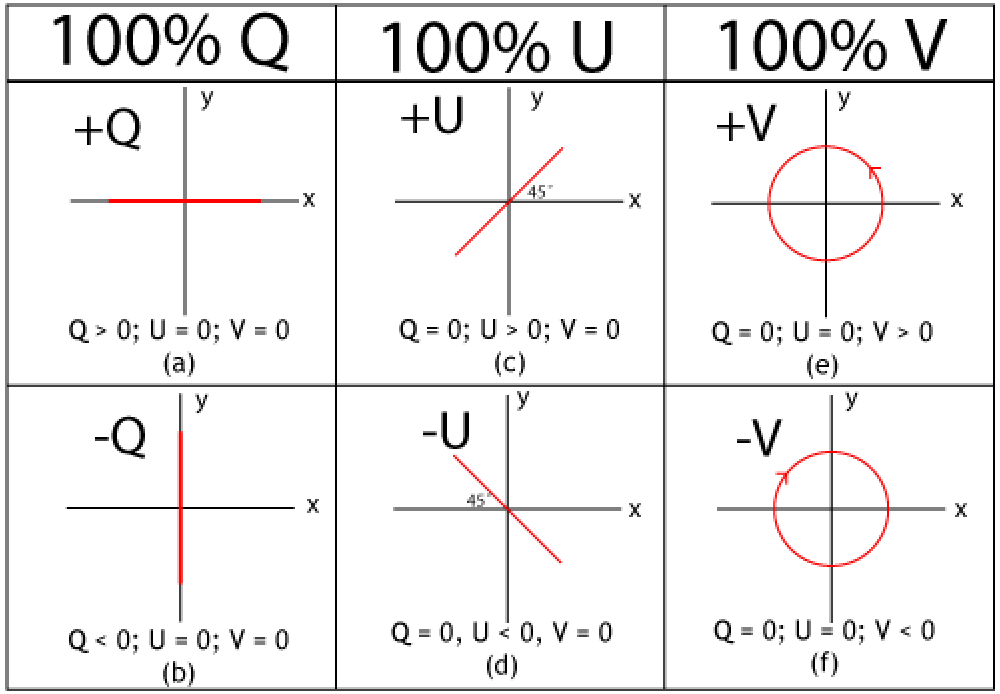


Figure source: Wikipedia, Dan Moulton

Examples of four fully polarized states.

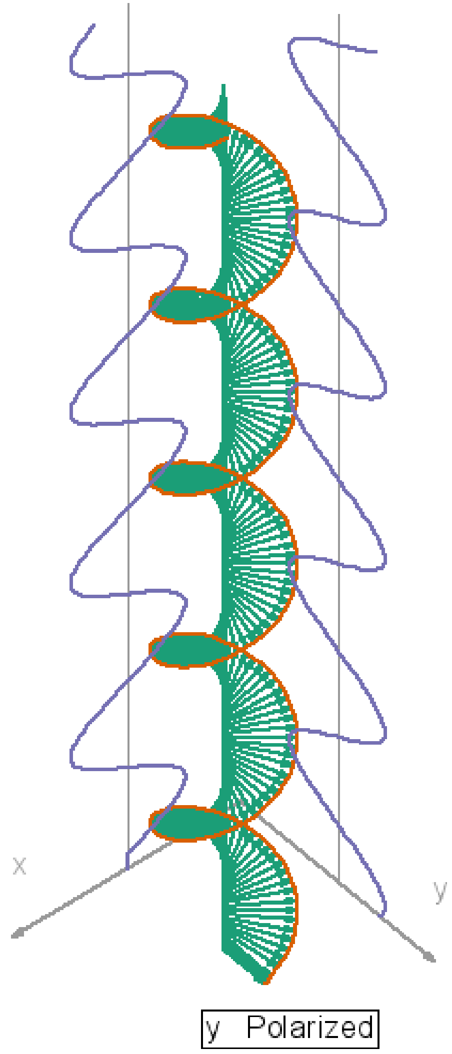
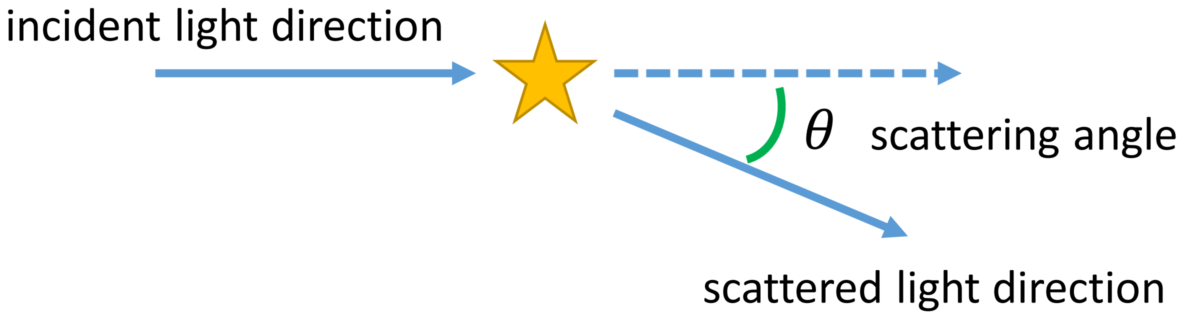


Figure source: Wikipedia, Davidjessop

When incident light scatters from a particle, the scattering event can be described with a Mueller matrix $\mathbf{F}$. The Mueller matrix maps the Stokes parameters of the incident light (inc) into Stokes parameters of the scattered light (sca).

$$\begin{pmatrix} I_{sca} \\ Q_{sca} \\ U_{sca} \\ V_{sca} \end{pmatrix} = \frac{\lambda^2}{4\pi^2 D^2} \begin{pmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ F_{21} & F_{22} & F_{23} & F_{24} \\ F_{31} & F_{32} & F_{33} & F_{34} \\ F_{41} & F_{42} & F_{43} & F_{44} \end{pmatrix} \begin{pmatrix} I_{inc} \\ Q_{inc} \\ U_{inc} \\ V_{inc} \end{pmatrix}$$

The Mueller matrix describes scattering into certain direction, so it is a function of scattering angle (or angles, see next slide) $\mathbf{F}(\theta)$.



If Muller matrix is describing scattering from one particle in random orientation (one particle rotating randomly over time), or collection of particles in random orientation (similar particles in random orientations at every time step), the Mueller matrix has a simpler form with certain symmetries:

$$\begin{pmatrix} I_{sca} \\ Q_{sca} \\ U_{sca} \\ V_{sca} \end{pmatrix} = \frac{\lambda^2}{4\pi^2 D^2} \begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{44} \end{pmatrix} \begin{pmatrix} I_{inc} \\ Q_{inc} \\ U_{inc} \\ V_{inc} \end{pmatrix}$$

Detectors

- Detectors (for UV-Vis-NIR range, at least) are not measuring the phase of the light (EM wave), nor the amplitude variation
- Detectors are only measuring time-averaged power (intensity) of light
  - In Stokes parameters presentation, this means the component I
  - Components Q, U, and V cannot be directly measured
  - Polarization states are measured indirectly, shown later

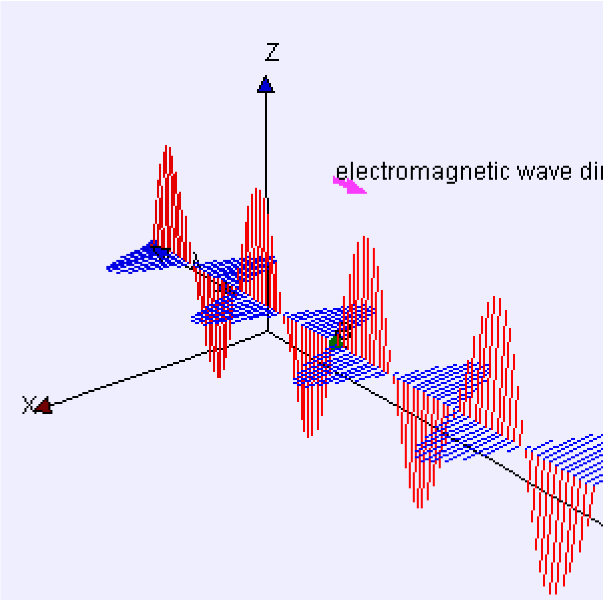


Figure source: Wikipedia, Lookang, thanks to Fu-Kwun Hwang and author of Easy Java Simulation = Francisco Esquembre

- Optical power or intensity can be measured with a (optical) power meter
  - Other terms: radiometer (usually IR or UV), photometer, light meter (for photography)
  - Photometer can have photoresistor, photodiode, or photomultiplier
  - Semiconductor photodiodes are most common (silicon, most typically), working in visible wavelengths
  - Photomultiplier tubes are very sensitive detectors for UV-Vis-NIR

- In imaging instruments, CCD and CMOS chips are used

Radiometer. Image source: Wikipedia, Timeline

Photodiode for optical power meter

- Integrating sphere is a spherical cavity, coated with high-reflectivity surface. For visual wavelengths, it is usually PFTE (Polytetrafluoroethylene, i.e., Teflon)
- Integrating sphere is used to gather scattered light into optical power meter

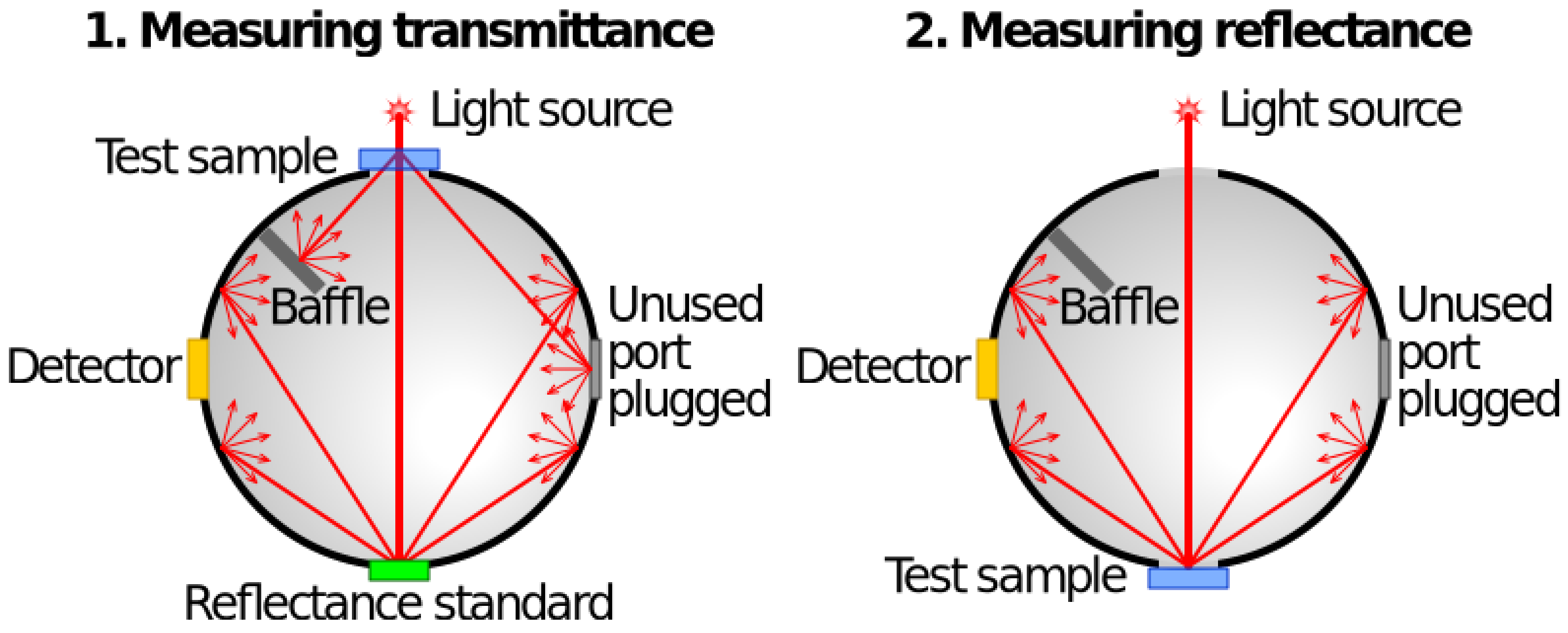
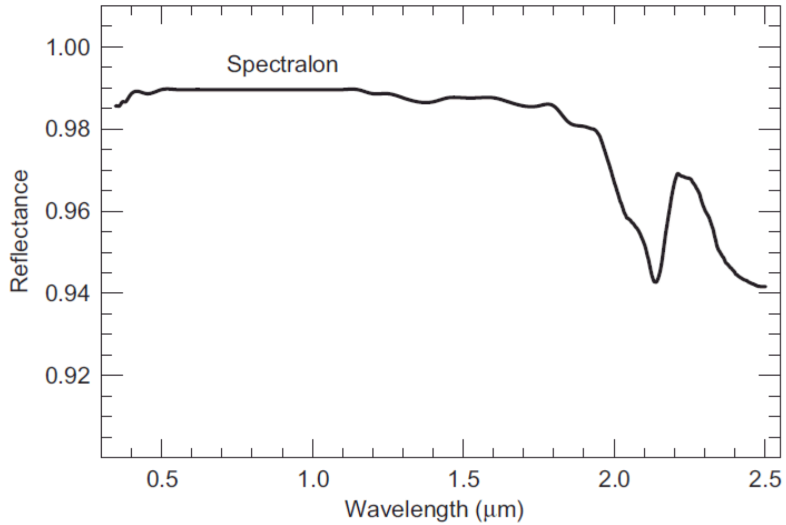


Image source: Wikipedia, Cmglee

- In photometric experiments, absolute optical power measurement is often not needed
- Rather, we need to evaluate the brightness/intensity/reflectivity/albedo of the sample with respect to something known
- In theory, this known sample is called a Lambertian surface
- Lambertian surface is a perfect diffuse surface, that has a constant surface brightness to all viewing directions
  - Optical power per surface area to direction θ from surface normal is proportional to $\cos(\theta)$
  - Reflects all the incident light, geometrical albedo 1
- The real-world version of a perfect Lambertian surface is Spectralon or a PTFE panel



Reflectance spectrum of Spectralon. Figure source: Wikipedia, Kokaly R et al. (2015), International Journal of Applied Earth Observation and Geoinformation. 61.

Photometric devices at UH light scattering laboratory

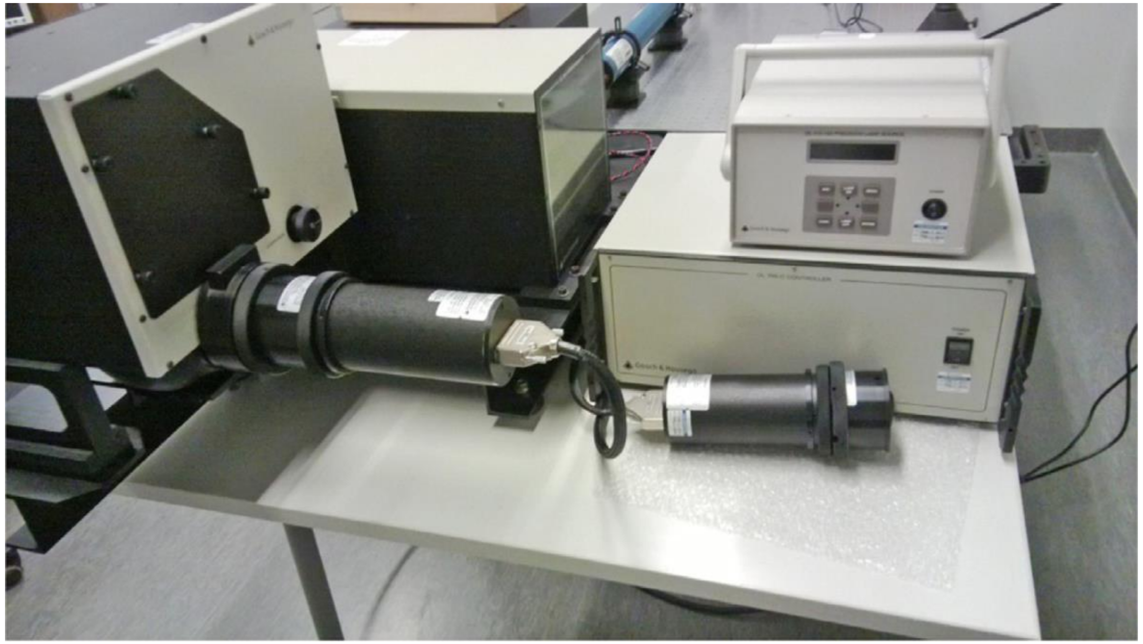
- Newport optical power meter
- Gooch & Housego modular spectrometer
- LightTec goniometer
- Single-particle levitating scatterometer
- imec hyperspectral camera
- LDLS light source

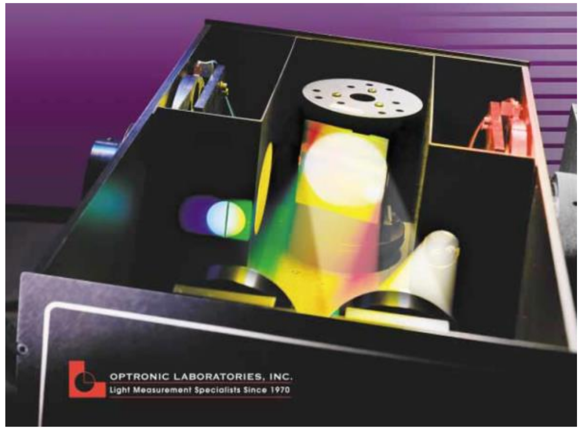
Newport optical power meter

- UV-Silicon detector, wavelength range 200-1100 nm
- USB-connected to computer, measurement software running on computer
- Can measure from pW to mW powers
- Notice that photodiode power meters have non-even response curve to different wavelengths
  - Accurate measurements done with monochromatic (single-wavelength) light, and using the wavelength as input for the absolute power calibration
  - White-light measurements can be done, but results can only be relative
    - Need to be compared with Lambertian disk measurements using the same light source

Gooch & Housego modular spectrometer

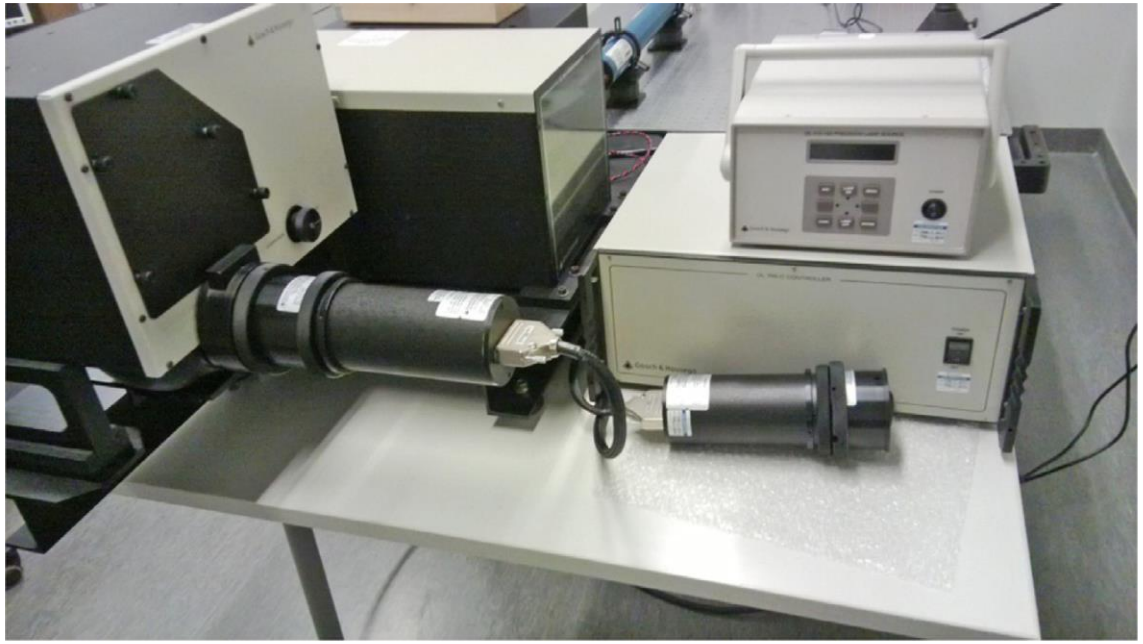
- Modular instrument, consists of
  - Light source unit
    - Two lamps, one for UV and other for Vis-NIR
    - High-quality power source for the Vis-NIR Quartz Tungsten halogen lamp
  - Monochromator unit, selects the required wavelength with a turnable prism
  - Integrating sphere unit
    - Two possibilities, PFTE coated for UV and Vis, gold coated for NIR
  - Detector heads
    - Photomultiplier for UV
    - Silicon photodiode for Vis
    - PbS photodiode for NIR
    - Lock-in signal amplifier

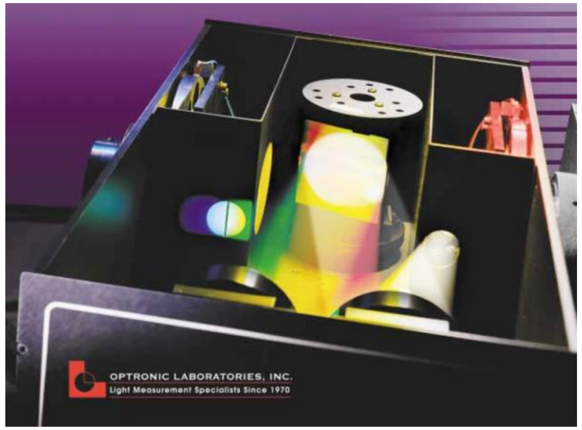




Gooch & Housego modular spectrometer

- Mainly used for spectroscopy, but can be used, in general, to analyze power of reflected or transmitted light
- Slow to operate, rather good signal quality
- Wavelength range 200-3200 nm





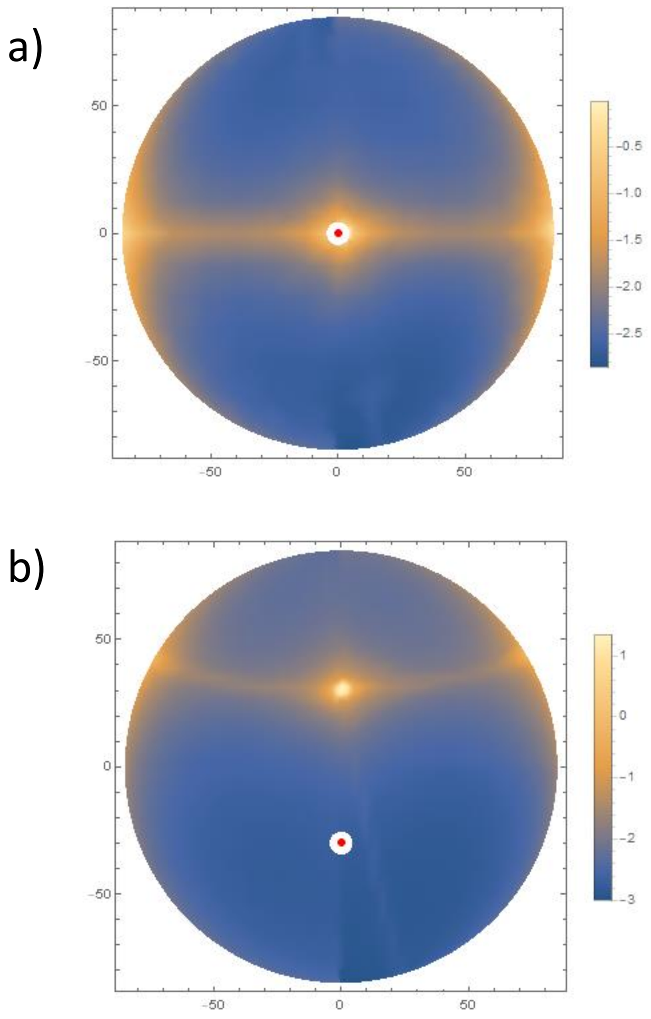
LightTec goniometer

- Goniometer can measure the power of scattered light to all directions
- Incident light is brought via light fiber from light source unit to the end of the source arm
- Scattered light is also transported with an optical fiber from the end of the measuring arm
- Reflection as a function of three angles (incidence zenith angle, measurement zenith angle, azimuthal angle between incidence and measurement in the plane) can be recorded
  - This is used to define BRDF (Bi-directional Reflectance Distribution Function) of the sample

LightTec goniometer

- Our goniometer can measure also on the bottom side of the sample, so transmitted light
- The optical fiber from the measurement head can be connected to a photodiode (integrated power over all incident wavelengths) or to a spectrometer
  - Photodiode has better sensitivity, visual or NIR wavelengths can be blocked with filters in the light source
  - The internal spectrometer has worse sensitivity than our external Maya spectrometer, but the internal one can be controlled with the Lighttec software, therefore automatizing the measurement
- A calibration sample (PTFE) must be measured to calibrate the reflectance levels

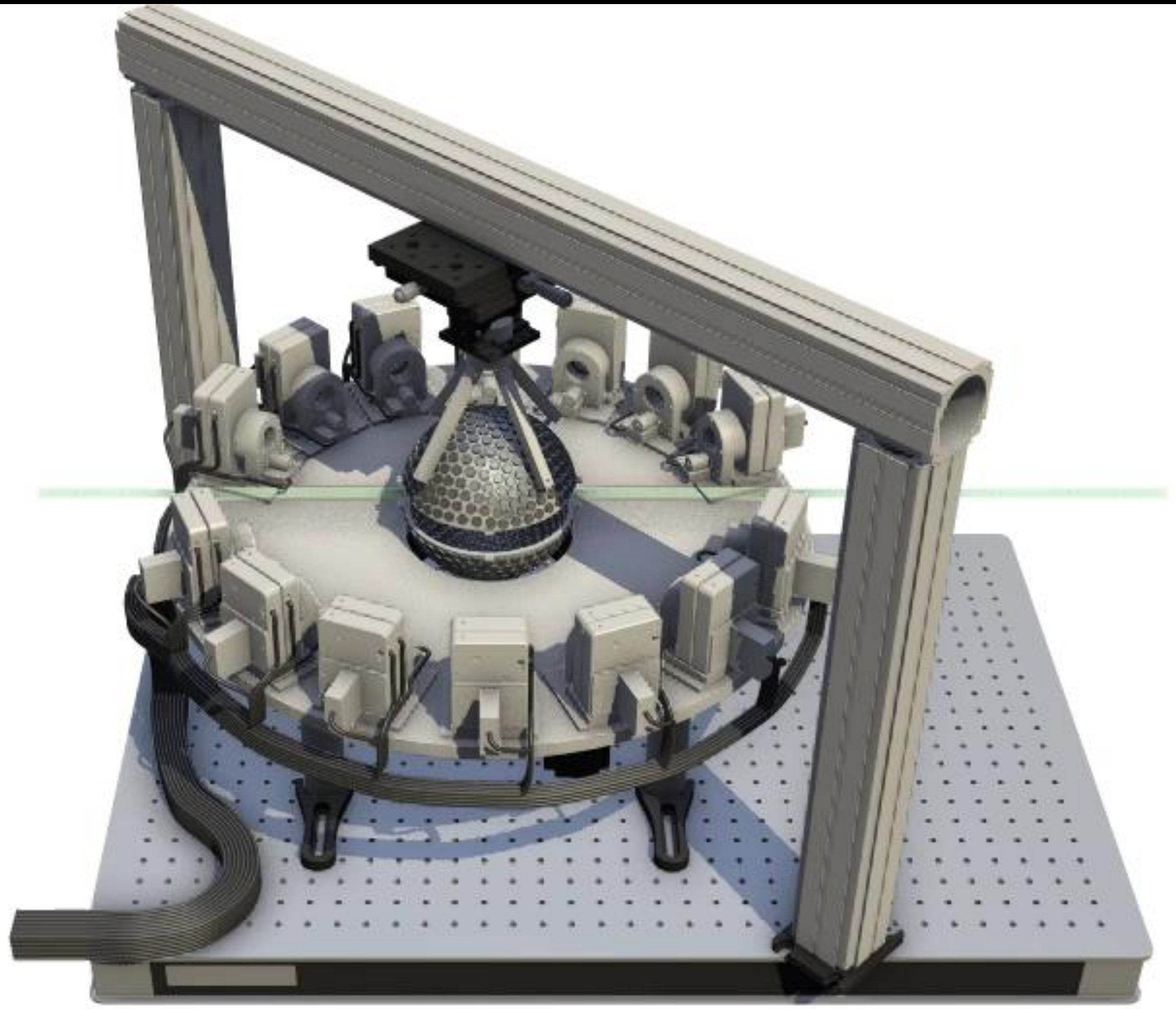
- Example of measurements: BRDF from a CubeSat solar panel
  - In a), incident light coming from zenith
  - In b), incidence at 30 degree from zenith
  - BRDF is visualized in spherical coordinates, distance from the center is the zenith angle, and direction from the center the azimuth angle
  - BRDF show very specular behavior, and some leakage of reflection into sides



Single-particle levitating scatterometer

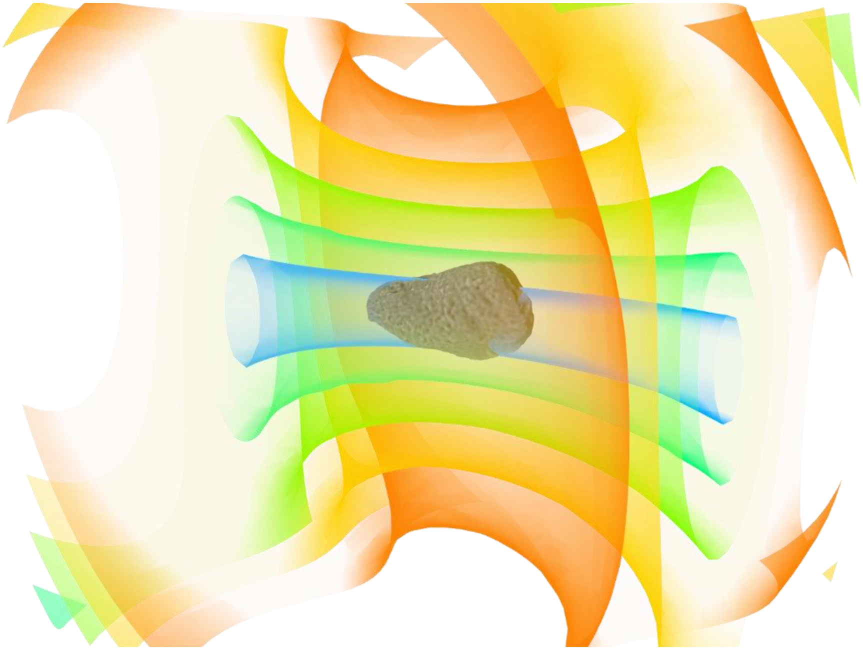
- Our own design, build by UH electronics laboratory
- Measures scattered intensity of single particle that is levitating on an acoustic trap
- Incident light comes from laser-driven light source (xenon plasma heated by laser), giving high-power white light
- White light is filtered into monochromatic
- Incident beam hits the target particle that is levitating
- Scattered light is measured with micro-PMT sensor that is rotating around the target

Single-particle levitating scatterometer

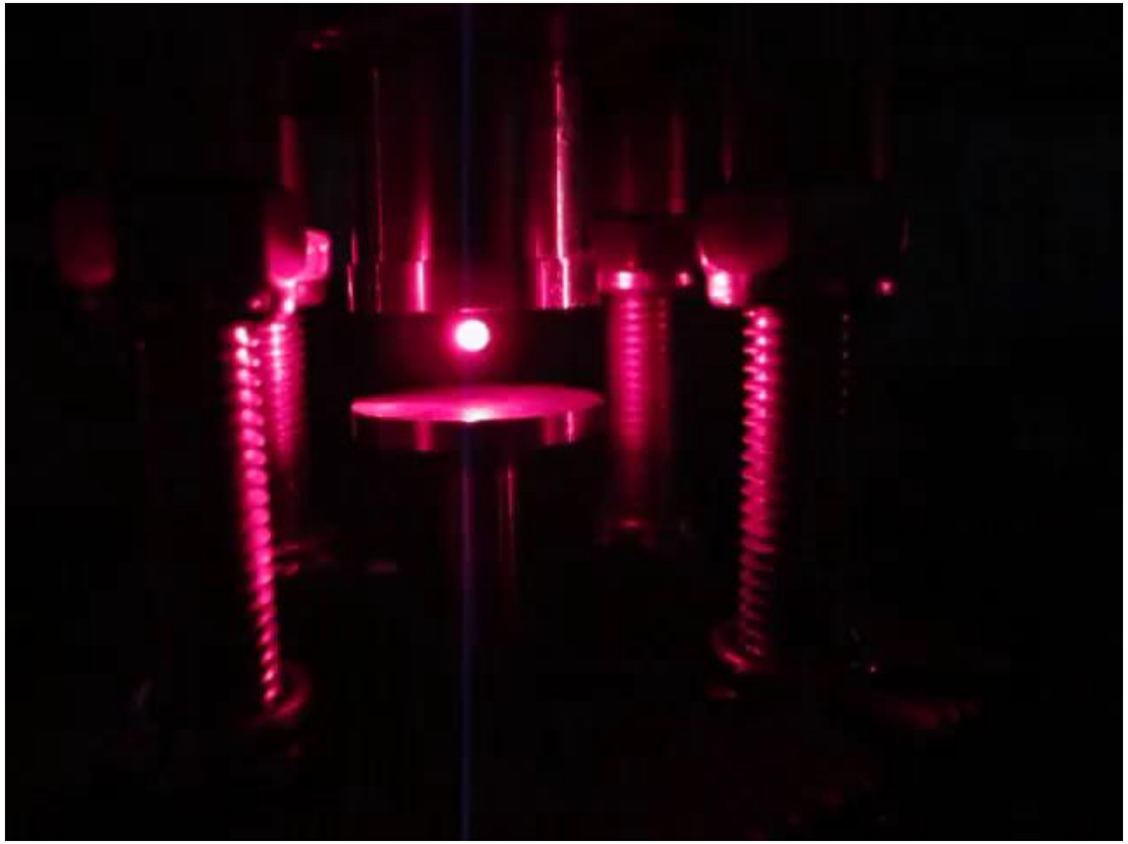


Single-particle levitating scatterometer, levitation

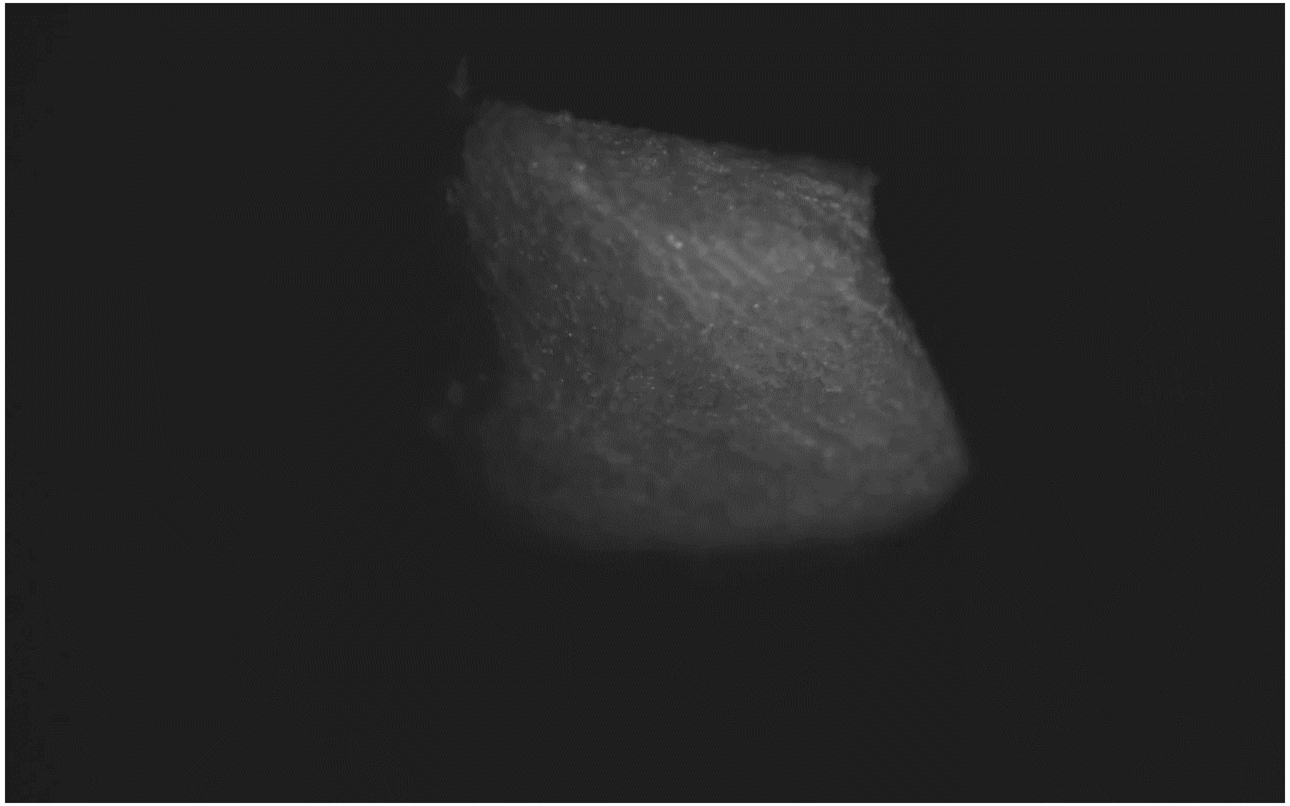
- Standing waves produce a stable Gor'kov potential
- Most current acoustic levitators have symmetric potential wells
  - Small vibrations add up, causing the sample to spin uncontrollably
  - Measurements of spinning samples give a ”weighted” average.
- Adjusting the acoustic field allows creating an asymmetric trap (Helander et al. 2019, forthcoming)
  - Energy minimum achieved when shortest sample dimension lines up with the steepest gradient



Single-particle levitating scatterometer, levitation



Single-particle levitating scatterometer, levitation



imec hyperspectral camera

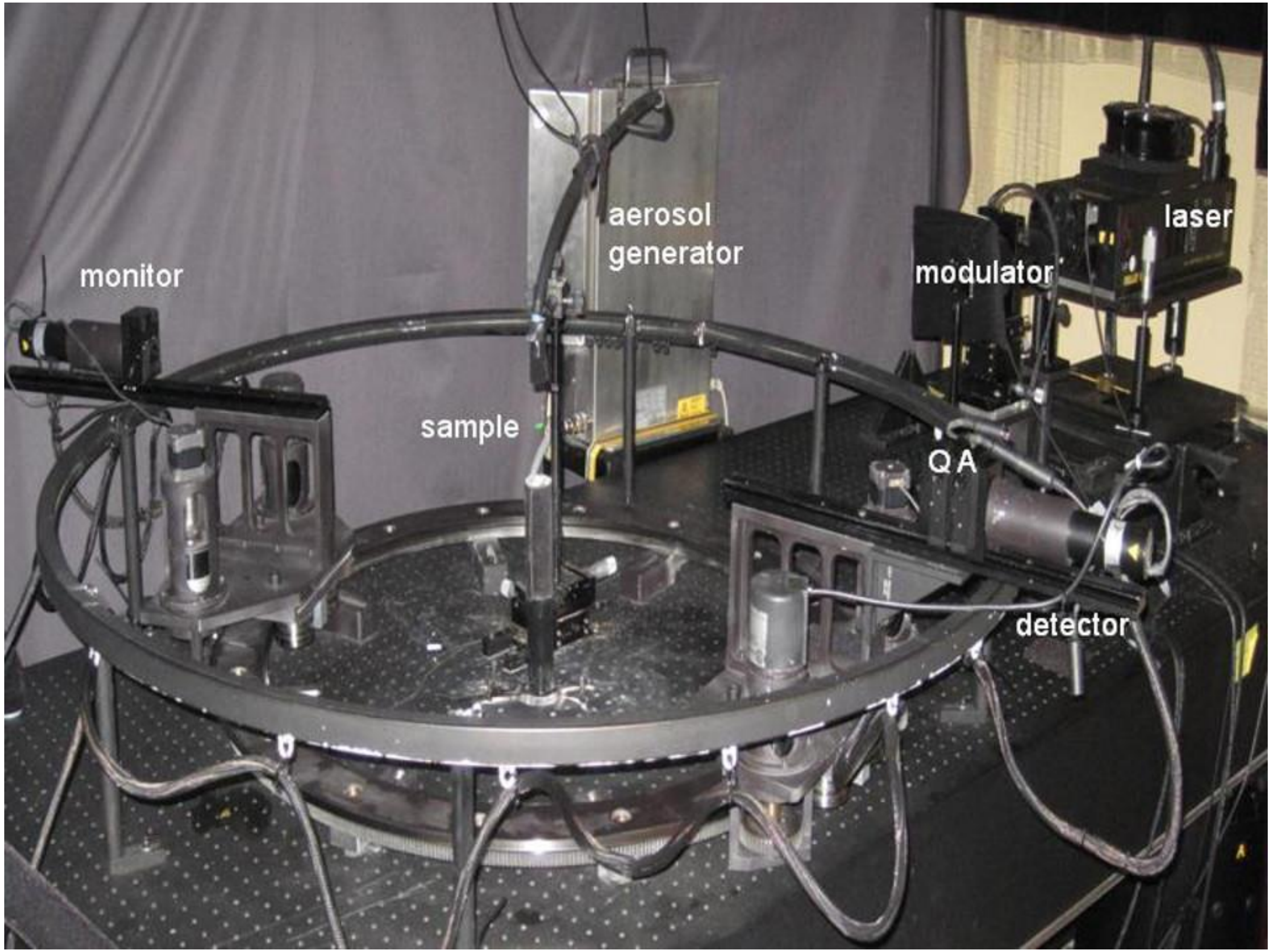
- Snapscan hyperspectral camera
- Can be used to study brightness in many wavelengths or different angles

LDLS light source

- Very powerful white-light source
- Laser beam drives a Xenon plasma lamp
- Can be used with optical power meter or hyperspectral camera for photometric studies
- We are designing a backscattering measurement set-up using this light source and the hyperspectral camera

Granada-Amsterdam light scattering laboratory and database

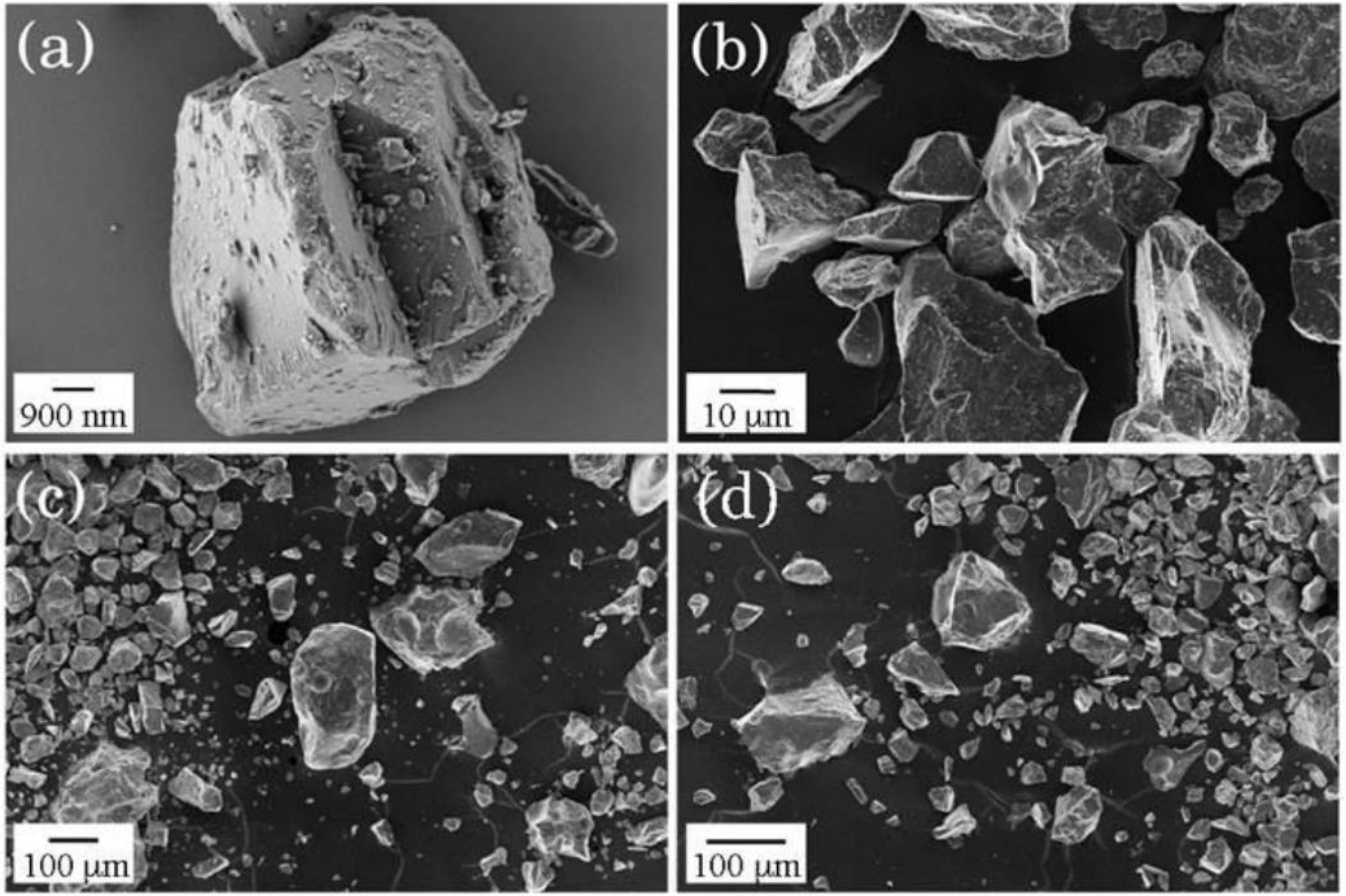
- The Granada-Amsterdam laboratory has the largest database of measured phase functions of small particles
- Samples are silicates, clays, glasses, sand, etc. They also include lunar and Mars analog particles
- Particles are measured in laminar air flow, so result is an average over sizes and orientations



See https://www.youtube.com/watch?v=UaPlRhgV1vo&t=168s

Granada-Amsterdam light scattering laboratory and database

- Lunar simulant shapes in SEM microscope image



- Lunar simulant phase function and other Mueller matrix elements