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# WG4 Meeting in Helsinki

# “Spectro-polarimetric experiments for remote sensing”

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# Spectropolarimetry of Lunar Regolith in the Laboratory

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We have recently obtained six samples of Lunar regolith material from NASA gathered from Apollo missions 11,12,15,16, and 17 and will present the results of laboratory measurements of broad spectrum and narrow-band scattering measurements on these samples. A technique for zero incidence angle scattering will be discussed and results of multiple wavelength measurements of the full Stokes scattering matrix will be presented along with comparisons of similar terrestrial material.

# Meteorite spectrometry in Vis-NIR with classification and radiative-transfer modeling

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The composition of Near-Earth Objects (NEOs) is still largely undetermined due to scarce flyby missions and low-resolution ground-based spectroscopy at the visible and near-infrared wavelengths, which is currently the main source of information on NEO composition. The variation in NEO compositions can also be significant as the result of different dynamical pathways experienced by the NEOs. Yet, knowledge of composition is vital when planning possible mitigation techniques.

The interpretation of NEO spectra is closely tied with surface structure. NEO surfaces are usually covered with regolith, which is a mixture of mineral grains ranging from micrometers to centimeters in size. The inverse problem of deducing the characteristics of the grains from the scattering of light (e.g., using photometric and polarimetric observations) is extremely difficult. Spectrometry of meteorites can be a complementary source of information considering that unweathered meteoritic “falls” are almost pristine samples of their parent bodies. Additional radiative-transfer modeling of meteorite spectra may present a way to interconnect meteorite measurements with actual NEO spectroscopy and thus advance the determination of NEO surface structures and compositions.

We have measured reflectance spectra (350-2500 nm with a zenith angle of reflection range of ±60 degrees) of centimeter-size pieces of 18 different meteorites. The measurements were carried out with the Finnish Geodetic Institute Field Goniospectrometer (FIGIFIGO) (Suomalainen et al., Sensors 9, 2009). Principal Component Analysis (PCA) was performed on the spectra. The analysis suggests principal components of the data can separate undifferentiated ordinary chondrites from differentiated achondrites.

Our measurements expand the database of reflectance spectra of 26 meteorites obtained by Paton et al. (JQSRT 112, 2011). The spectra of meteorites found in both data sets are consistent. Furthermore, we offer a phenomenological single-scatterer (Muinonen and Videen, JQSRT 113, 2012) radiative-transfer model for the measurements. Our intention is to further expand the database of meteorite spectra and develop the joint radiative-transfer model in the future.

# FIGIFIGO: An Advanced Portable System for Spectropolarimetry

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We provide an overview of Finnish Geodetic Institute Field Goniospectrometer FIGIFIGO, an portable automated system for polarised multiangular reflectance measurements, which has been developed and improved in FGI. FIGIFIGO can be operated both on field under sunlight conditions (hemispherical directional reflectance factor, HDRF), and in laboratory using artificial illumination (bidirectional reflectance factor, BRF). The instrument design is primarily for field operation, as the total weight of the system has been kept as low as possible, at around 40 kg, and all critical components are designed to withstand field conditions. The instrument is highly automated and can be operated by two persons. Instrument setup is fast and only takes about 10 minutes. A typical measurement of full hemisphere (200-400 spectra) takes about 15 minutes after setup.

The primary instrument of FIGIFIGO is an ASD FieldSpec Pro FR optical fiber spectroradiometer (350-2500 nm), which is housed inside a rugged casing along with lead acid batteries, electronics and an electric motor. The motor is used to drive a telescopic measurement arm (1.55-2.65 m) from vertical to ±90° for the zenith angle adjustment. The azimuth angle is adjusted by turning the whole device around the sample. The sample is viewed by downward looking optics mounted to the top of the measurement arm and the optics are connected to the spectroradiometer by a 3 meter optical fiber. In addition to regular optics, a set of polarizing optics have been constructed using a Glan Thompson polarizer inside a rotator. The polarizing optics can be used to measure the sample with two or more polarization directions. The whole system is controlled by LabVIEW control software running in a rugged laptop.

During measurements FIGIFIGO is positioned next to the sample and calibrated for current illumination conditions using a Labsphere Spectralon reference panel. The system measures the current GPS position and time, and calculates the Sun zenith and azimuth angles. A hemispherical (fish eye) camera is used to measure the direction of the measurement plane relative to the Sun direction (sensor azimuth direction). Inclinometer is used to measure the zenith angle of the measurement arm (sensor zenith direction). The sample surface is measured from several azimuth directions by moving FIGIFIGO around the sample, and simultaneously a silicon pyranometer is used to record the illumination conditions, clouds, haze, and other atmospheric disturbances.

After the measurements the data are processed using FGI Reflectance toolbox for Matlab that takes in all the sensor data, does interpolations to match the spectra and the direction data, calculates BRF from the measured HDRF data using the diffuse measurements, corrects the spectra with the pyranometer data, and then outputs the data to a library format for easy processing. The library files are stored in the FGI Reflectance Library.

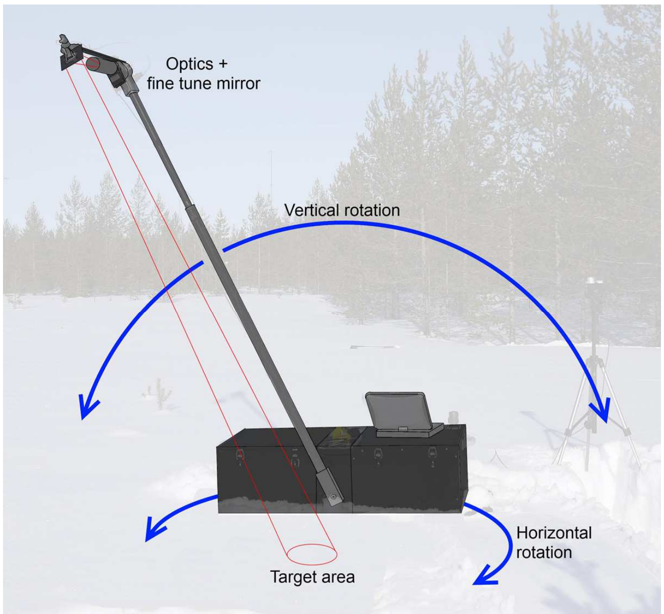


*Figure 1: FIGIFIGO concept: casing, measurement arm, rugged computer, and a sunphotometer on a tripod*

# Remote sensing of the Sun K-corona with the VIS polarimetric channel of the METIS coronagraph on-board Solar Orbiter

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METIS is the *Multi Element Telescope for Imaging and Spectroscopy*, the coronagraph of the Solar Orbiter payload suite designed to study the Sun corona at a distance up-to 0.28 AU with a consequent significant improvement in spatial resolution and at heliocentric latitudes higher than 30° providing unprecedented close-up views of the Sun's polar regions.

The coronagraph will perform visible-light broad-band imaging by means of a novel polarimeter capable to observe the linearly polarised component of the K-corona thanks to an innovative system relying on liquid crystals (LC). Polarimeters based on electro-optically tuneable liquid crystals represent a new technology in the field of observational astrophysics as they are good candidates for replacing mechanically rotating optical groups in most ground-based and space-based applications.

METIS includes two optical paths for i) broad-band imaging of the full corona in linearly polarised visible-light (580-640 nm); ii) narrow-band (10 nm) coronal imaging in the UV HI Ly-α spectral line (121.6 nm). An interference filter (IF) acts both as folding mirrors and filter transmitting the UV radiation and reflecting back the visible light in a suitable direction to provide lodging for the linear polarimeter (Fig. 1).

The science objective of the METIS VL path is the measurement of the K-corona electron density as a diagnostic mean to characterise the physical properties of the hot coronal plasma. This goal is achieved by imaging the linearly polarised K-corona on the VL channel detector. The METIS science driver of deriving the coronal electron density from polarised-brightness (pB) images requires an accuracy of better than 1% in the measurement of linear polarisation. This requirement poses some implications and limitations on the METIS optical design in order to minimise the instrumental residual polarisation associated to the broad-band visible-light polarimeter assembly and to the other optics constituting the visible-light path, like the IF.

The overall polarimeter assembly includes a polarisation modulation package (PMP) with a liquid crystal variable retarder (LCVR) together with a quarter wave (QW) retarder and a linear polariser (LP) plate working as analyser. The assembly is made of two group of lenses: the first group acts as a collimator while the second group as an imaging lens refocusing the light coming from the corona to the VL focal plane hosting a CMOS Active Pixel Sensor.

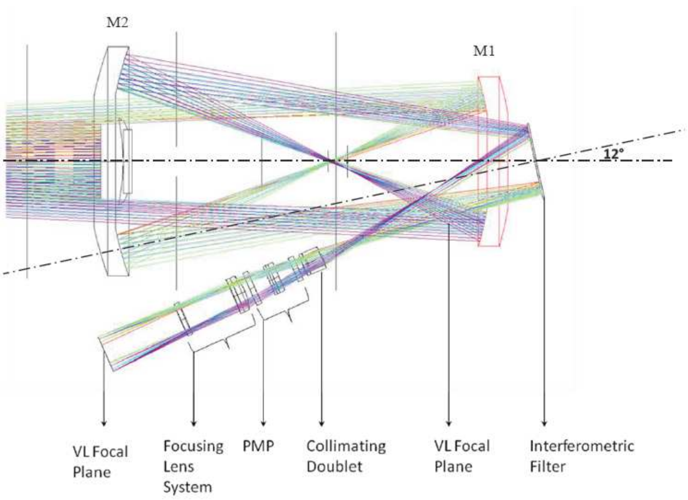


*Figure 1: The VIS light path of the METIS payload*

# A proposal for the development of an integrated visible and UV CMOS detector polarimeter based on a nano-WGP

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Measuring the polarization of radiation provides information about the physical state of matter which is largely uncorrelated with spectral and intensity properties [1, 2] and thus has the potential to enhance the information obtained from the investigated target. In solar physics, for instance, the spectropolarimetry is the only tool that enables the study of the magnetic field from the photosphere to the hot corona through the Hanle and the Zeeman effect [3]. Polarimetry is also a powerful differential technique for future investigations of scattered light from extrasolar planets [4].

Imaging polarimetry is performed by means of a polarization analyser in the optical train. The polarization state of radiation is represented in terms of the Stokes vector (I, Q, U, V), and it is derived by means of sequential images. The sequential acquisition is often a limit to an accurate polarimetric measurement due to the intrinsic variability of the target. An ideal polarization analyser shall be able to acquire simultaneously the required information in order to freeze, in a single snapshot, the polarization state of the target.

Since 1998 the XUVLab laboratory [5], within the Department of Physics and Astronomy of the University of Florence, works on the design, development and characterization of new technologies for space and earth-based instrumentation. The laboratory's activity mainly focuses on the development of optical and electronic systems working in the vacuum UV and visible band of the electromagnetic spectrum. Through the years the XUVLab has contributed to several international experiments, in particular oriented to the observation of the solar corona and to the measurement of its polarized brightness (for instance, SOHO/UVCS [6], ASCE [7], HERSCHEL rocket mission [8]). In the continuous effort of improving the current technologies and studying innovative solutions for future experiments, we are carrying on a project for the design and development of first prototype of an integrated focal-plane broadband detector polarimeter based on a CMOS detector and nano-Wire Grid Polarizers (WGPs) in the visible (VIS) and ultimately in the UV. Borrowing the color-filter Bayer matrix concept, a 2x2 px sub-array hosting 4 differently aligned WGPs realized by parallel-ordered metal nanowires will be developed and tested. The 4 neighbouring pixels, having different polarizing masks, enable the redundant collection of the 3 basic information (I, U, Q), necessary to obtain the linear polarization. The spectral efficiency of a WGP depends on the periodic pitch of the wire grid structures. Wang [9] estimates that the WGP lower cutoff wavelength is about three times bigger than the wire pitch. Using nanowire structures, although challenging to realize, will allow to push this limit down to short wavelength and to provide, as a final goal, an UV transmission polarimeter analyser.

Such a device would be particularly suitable to be hosted in space instrumentation where mass, volume and power budget are restrictive constraint to deal with. A CMOS integrated polarimeter could be profitably used to study fast evolving astrophysical processes such as plasma diagnostic or Sun-Earth weather relationships based on coronal plasma observations and it would have the potential capability of performing polarized brightness measurements in several fields of applications.

**References:**

[1] Tyo et al., Appl. Opt. 40(9), 1450-1458, 2001

[2] Cheng et al., Proc. SPIE 2237, 251-259, 1994

[3] Landi Degl'Innocenti, “Polarization in Spectral Lines” (Kluwer), 2004

[4] Stam et al., A&A 672, 663-672, 2004

[5] Chiuderi et al.,“XUVLAB: Project for an UV Laboratory at the University of Firenze”, ESASP 417, (1998);

[6] Kohl, J. L., et al., “The Ultraviolet Coronagraph Spectrometer for the SOHO”, Sol. Ph. 162, 313-356 (1995).

[7] Gardner, et al., “Advanced Solar Coronal Explorer mission (ASCE)”, Proc. SPIE 3764, 134-146 (1999).

[8] Romoli M., et al, “The Ultraviolet and Visible-light Coronagraph of the HERSCHEL experiment”, Proc. Solar Wind Ten 679, 846-849 (2003).

[9] Wang et al., Appl. Phys. Lett. 90(6), 061104.1-3, 2007

# Polarisation measurements of clay, volcanic sand and snow: implications for the climate changes

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Thickness of ash and other fragments that are thrown out by an exploding volcano determine effects that it has on the underlying snow. To analyze these effects and to support the Soot on Snow (SoS) 2013 campaign organized by the Finnish Meteorological Institute a series of spectropolarimetric measurements was organized in April 2013 in remote area in Sodankylä, Finland. To simulate dust storm event and follow its consequences, a soot of clay and volcanic sand were deposited on a natural snow pack in a controlled way (known amount of dust in different concentration over certain area). The albedo, hemispherical directional reflectance factor (HDRF), polarisation, and other snow properties were monitored on the snow and dusty areas through the following melting period. The measurements have been done using the Finnish Geodetic Institute Field Goniospectrometer FIGIFIGO, an automated portable instrument for multiangular reflectance measurements. The instrument has been calibrated by taking a nadir measurement from a carefully leveled Labsphere Spectralon white reference plate before and after each sequence. The zenith angles were restricted to ±80°. The acquired data were processed using FGI Reflectance toolbox for Matlab that loads all the sensor data, does interpolations to match the spectra and the direction data, calculates BRF from the measured HDRF data using the diffuse measurements, and corrects the spectra with the data taken by pyrometer. In this presentation we report on the primarily objectives, obtained results, climate changes applications and future prospects of the described measurement campaign.

The research leading to these results has been supported through the Academy of Finland projects.

# FGI's Reflectance Library and Future Perspectives

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FIGIFIGO has been developed in the Finnish Geodetic Institute over past decade and there have been several earlier models of the device. Current version is confirmed to be a fast, reliable, man-portable, and accurate device for multiangular spectropolarimetric measurements. Measurements are done on field under sunlight conditions or in laboratory using artificial illumination. After measurements the acquired data are processed using FGI Reflectance toolbox for Matlab that outputs the data to a library format for easy further processing. The library files and relevant figures are stored in the FGI Reflectance Library. The Library has been made semi-public, behind a common password, available on request, and it is accessible through the following web link: https://webdisk.kotisivut.com/fgi/Reflectance_Library. The sub-directories in the 'Reflectance_Library' folder are named accordingly, e.g. "Figs" is the sub-sub-directory containing many plots of the data; "Pictures" - sub-sub-directory containing some photographs of the targets. .pdf and .xml files contain relevant documentation. To read or process the data, look at TOOLS sub-directory (and IDL or Matlab inside). The program "makeallfigures.pro" contains a script to process all or manually selected data and make the figures in relevant sub-directories. You may need to modify the output location. "mittausdataohjelma.pro" is an interactive program. It is possible to mount the directory as a disk using the webdav interface.

Our group can provide with many other specific figures and/or analysis (such as, e.g., specific channels, fixed range) as well as organize measurements of other wanted targets. FIGIFIGO is very portable to go any part of the world. Currently the library contains BRF/HDRF measurements of over 200 samples. Europe, Greenland, and Australia have already been seen. Part of the data is also available at www.specchio.ch. Loading into other public database systems is possible upon request.

# Polarimetry of planetary atmospheres

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Spectropolarimetry at multiple scattering angle offers a unique and unambiguous way to remotely probe the (micro)physical characteristics of a planetary atmosphere. In our group we carry out polarimetric observations of the Earth's atmosphere, solar system planets, and exoplanets. We develop a wide range of instrumentation for these observations: from a dedicated instrument (EPICS) for the 39-m E-ELT, to a satellite instrument (SPEX), to mass-produced spectropolarimeters for smartphones (iSPEX). I present a quick overview of these projects.

# Remote sensing from POLDER/PARASOL Earth polar-orbiting satellite: surface reflection modeling and Surface/Aerosol properties retrieval

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Earth surfaces are important component of the climate system. Their interaction with incoming solar radiation as well as radiative interaction with atmosphere greatly impact on Earth energy budget. Intrinsic reflectance properties of surfaces are described by the Bidirectional Reflection Matrix (BRM) R, which provides a relation between the Stokes parameters of scattered and incident radiation. On the basis of knowledge of the BRM the surface properties can be retrieved from the remote sensing measurements. Moreover, accurate models of BRM at visible and infrared wavelengths are required for retrieval of aerosols properties over Earth surfaces [1].

POLDER/PARASOL Earth polar-orbiting satellite can perform multi-angle, multi-spectral photopolarimetric measurements of top-of-atmosphere radiances. Because of wide swath (about 1600 km cross-track for PARASOL), it allows nearly global coverage every two days, providing great opportunities for both Earth atmosphere and surface characterization [2]. PARASOL measurements cover different geometries (including the backscattering and specular reflection regions) and different type of surfaces (soil, vegetation, desert surfaces etc.). This makes them specifically useful for testing different models of BRM, which can be applied both for terrestrial and extraterrestrial surfaces.

Here we will present the results of the retrieval [3] of aerosol/surface parameters obtained from PARASOL multi-angle, multi-spectral photopolarimetric measurements and discuss the main issues of surface reflection modeling for satellite remote sensing in visible and infrared ranges of solar spectrum.

**References:**

1. P. Litvinov, O. Hasekamp, O.Dubovik, B. Cairns. Model for land surface reflectance treatment: Physical derivation, application for bare soil and evalusation on airborne and satellite measurements. JQSRT, 1113, 2023-2039, 2012.

2. D. Tanré, F. M. Bréon, J. L. Deuzé, O. Dubovik et al. Remote sensing of aerosols within the A-Train: the PARASOL mission, Atmos. Meas. Tech., 4, 1383-1395, 2011.

3. O. Dubovik, Herman M., Holdak A., Lapyonok_T., Tanré D., Deuzé J.L., et al. Statistically optimized inversion algorithm for enhanced retrieval of aerosol properties from spectral multi-angle polarimetric satellite observations. Atmos. Meas. Tech., 4:975 - 1018, 2011.

# Spectro-Polarimetry as a potentially powerful tool for asteroid studies

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The first pioneering studies of the dependence of the degree of linear polarization of asteroid light as a function of wavelength (Belskaya et al., Icarus 109, 97, 2009), based on polarimetric observations in different colors at visible wavelengths, suggest that one single spectro-polarimetric measurement might possibly be sufficient to distinguish between bodies belonging to different albedo ranges. This would be a tremendous improvement, because traditionally obtaining asteroid albedos via broadband polarimetric measurements would require several observations at different phase-angles. We have recently submitted an observing proposal to ESO in order to carry out a VLT campaign to extend and refine preliminary inferences coming from multi-color asteroid polarimetry, by carrying out the first program of spectro-polarimetric observations of asteroids. This has to be considered as a pilot project, and is aimed at obtaining accurate spectro-polarimetric measurements of a limited number of selected targets belonging to very different spectral and albedo classes. The proposal has been accepted, and observations will be hopefully carried out in the next semester. This suggests that laboratory experiments of spectro-polarimetry of samples of meteorites and other materials of astrophysical interest for Solar System studies can become soon very timely and important.

# Spectropolarimetry, Biosignatures, and the Search for Chirality

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The Polarimetry Laboratory at the University of Hertfordshire has been engaged for several years in performing high-sensitivity Stokes spectropolarimetric measurements on a variety of biological and inorganic materials. The aim of the work is to gather information in the laboratory that could indicate possible routes to the detection of life on solar system planets and moons, and exoplanets by the direct detection of optical biosignatures. Prominent in our experiments was attention to the characteristic spectral signature of chlorophyll in biomaterials and the possibility of remotely detecting the circular polarisation scattering arising from the chirality of this complex molecule. We assume that convergent evolution may produce similar molecules on Earth-like exoplanets . The evaluation of the remote detection of scattered light containing the spectropolarimetric signatures of biological material is the goal of this work. We will present a summary of the recent results of measurements on biological materials including extensions to earlier work on leaves, blue-green algae, and amino acids. The experimental techniques required to measure Stokes scattering coefficients to a level of ±0.0005 across visible wavelengths will be described and conclusions will be presented addressing remote sensing of light scattering biosignatures via spectropolarimetry.

# Multiple scattering of light in planetary regoliths

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Scattering of light in planetary regoliths constitutes an open problem in planetary astrophysics. The regoliths, such as the surfaces of asteroids and many atmosphere-less Solar System objects, are considered to be complex scattering and absorbing media composed of close-packed irregular and inhomogeneous particles. No exact electromagnetic solutions based on the Maxwell equations exist for such a scattering problem. A review is offered on multiple-scattering methods capable of approximately solving the scattering problem. These methods account for the so-called radiative-transfer and coherent-backscattering contributions. The methods are applied to interpret polarimetric phase curves of asteroids and transneptunian objects.

# Characterizing Mueller matrices in Polarimetry

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Polarimetry and ellipsometry are commonly formulated either in terms of the Jones vector/Jones matrix formalism or the more general Stokes vector/Mueller matrix formalism.

In the former formalism, which only applies to fully polarized light and non-depolarizing media, the transversal polarization of a plane wave of coherent light is represented by a complex 2 component Jones vector, which elements are the complexified transversal electric field components. The polarization altering properties of a material medium or a surface are represented by a complex 2x2 Jones matrix. A general Jones matrix is the product of a real scalar matrix and a complex matrix with determinant 1.
In the latter formalism, the transversal polarization of a plane wave of partial coherent light is represented by a real 4 component Stokes vector, with the elements now being quadratic forms of the transversal electric field components. The polarization altering properties of a material medium or a surface are represented by a real 4x4 Mueller matrix.
For fully polarized light and non-depolarizing media, both formalisms are equivalent.

A Mueller matrix is a matrix which by definition maps any Stokes vector again in a Stokes vector. Stokes vectors satisfy two conditions: (i) non-negative intensity and (ii) the degree of polarization is in [0,1]. This implies that a Mueller matrix also must satisfy certain conditions to ensure that it always produces a Stokes vector and thus represents a physical system. The effect of a Mueller matrix on an input Stokes vector however is difficult to understand in terms of how each element changes the input polarization into the output polarization. No simple analytical characterization of Mueller matrices is known at present. So far, we only have a numerical test to check if a measured matrix is physically valid [Givens and Kostinski, J. Mod. Opt., 1993]. This test is stated in terms of certain conditions on the eigenvalues and eigenvectors of an associated matrix.

The goal in polarimetry and ellipsometry is often to measure the Mueller matrix that represents the medium or surface under study. Primary difficulties in obtaining accurate polarization measurements are the systematic errors due to non-ideal polarization elements, such as misalignment, de-polarization, and uncertainties on the retardation of the polarimetric components. This results in error bars on the Mueller matrix elements.

A central issue in the determination of the Mueller matrix is to ensure that it is a valid representation of the underlying physical system. When the available numerical test is applied to a measured matrix with uncertainties, it is difficult, if not impossible, to propagate the errors through the eigenvalue calculation. Hence, the presence of error bars on the matrix elements may render a numerical test to be impractical or inconclusive. For these reasons, it would be more helpful to have a simpler and more direct test that could be run on the measured matrix elements themselves. The latter could be achieved if we had an analytical necessary and sufficient condition stated on the matrix elements, that assures whether a given real 4x4 matrix is a Mueller matrix.

I will present some results in this direction that I have obtained recently. I will address the following:

- A classification of Mueller matrices.
- A sufficient condition for a real 4x4 matrix to be/not to be a Mueller matrix.
- Necessary conditions satisfied by a Mueller matrix in general.
- A necessary and sufficient condition for some special subsets of Mueller matrices.

# Investigations on the influence of particle geometry and surface properties on the linear polarisation of scattered light

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In this contribution, we present computations to assist the interpretations of linear polarisation and depolarisation measurements, respectively, during two different types of experiments:

Computations of phase functions and degree of linear polarisation for light scattering by roughened ellipsoids were carried out to support single scattering measurements at Saharan dust grains. Particle models comprised of large numbers of facets have been constructed to resemble the levitated particles. Utilizing Gaussian random sphere methods, different levels of roughness have been added to the surfaces of these models. A Geometric Optics model and a related model, Ray Tracing with Diffraction on Facets, have been modified to calculate scattering on these particle reconstructions. Scattering calculations were performed on each of these reconstructions using a range of refractive indices to fit the experimental results.

To assist the interpretation of linear depolarisation measurements during mixed phase cloud experiment at the AIDA chamber, geometric optics calculations for randomly oriented hexagonal prisms of a range of aspect ratios were carried out. Raypaths, which strongly contribute to linear depolarisation, have been identified.

# Light scattering by feldspar particles: Modeling laboratory measurements

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Using the discrete dipole approximation (DDA), we model light scattering by a sample of feldspar particles and compare the results against laboratory measured light-scattering properties at two visible wavelengths. The shape of feldspar particles is approximated with the so-called agglomerated debris particles [see, e.g., Zubko et al., 2009, J. Quant. Spectr. Rad. Trans. 110, 1741–1749]. These model particles have irregularly shaped, agglomerate morphology with material packing density being 0.236. We consider a large number of sample particles (500+) that makes our computational results statistically reliable. The refractive index is assumed to be m = 1.5 + 0i and nearly coincides with what was measured in experimental feldspar samples. The light-scattering response is computed over a wide range of particle sizes spanning the range from 0.14 to 4.5 micron. We compare the non-zero light-scattering Mueller-matrix elements of agglomerated debris particles with those of well-characterized experimentally measured feldspar samples at blue (0.442 microns) and red (0.633 microns) wavelengths [Volten et al., 2001, JGR 106, 17375–17401]. It is important to stress that we also account for the polydispersity of feldspar particles, adapting the size distribution measured by Volten et al. The only meaningful free parameter in our comparisons is the small-size cut-off of the sample, which was not known.

In Figure 1, we present results of our modelling vs. laboratory measurements by Volten et al. (2001). The significance is that both the light scattering and the measured properties of model and real particles agree very well at both blue and red wavelengths simultaneously. While some tweaking of the particle parameters could achieve some improvement, the fits are remarkably good. We suggest that the reason for the good fits is not that the agglomerated debris particles exactly represent those of the sample particles, but rather that both sets of particles belong to a class of highly irregular particles, whose high degree of irregularity dominates the resulting scattering behaviour, suppressing the effect of any characteristic morphological features. The ability to replicate the light-scattering Mueller matrix elements at two wavelengths using particles having the same physical properties as those of the experimental sample is the primary advantage of using the agglomerated debris particles over more regularly shaped particles.

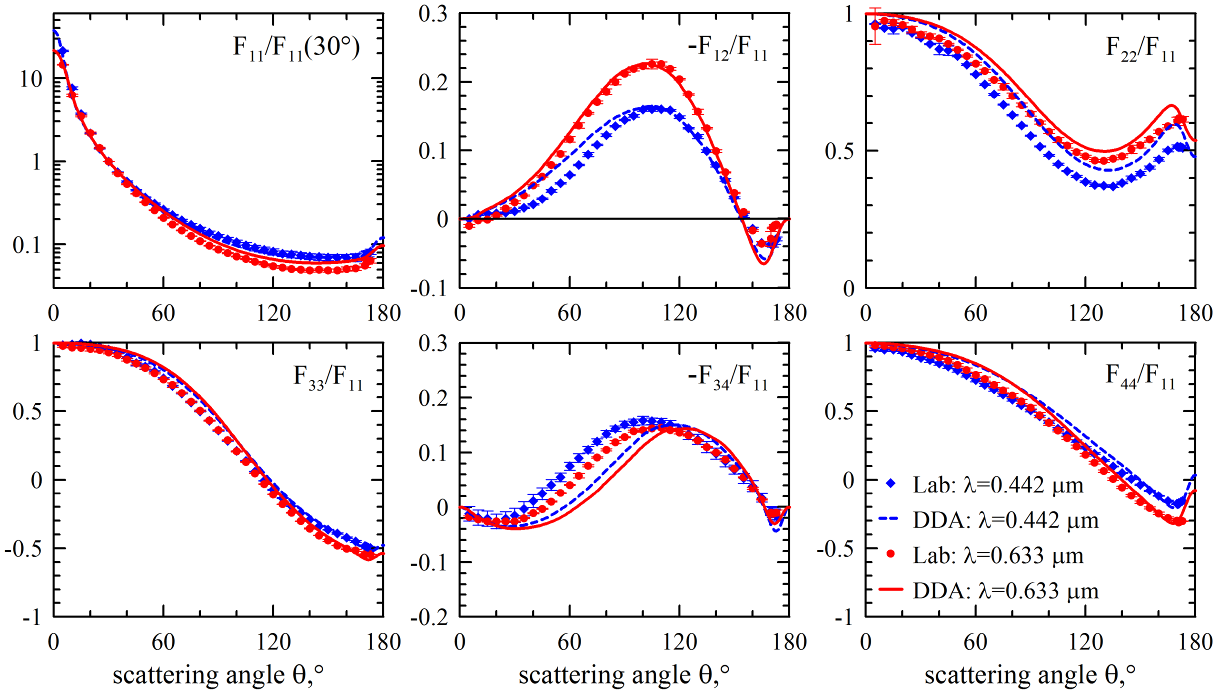


*Figure 1: Comparison of light-scattering Mueller-matrix elements of feldspar particles (diamonds and points) with agglomerated debris particles at refractive index m = 1.5 +0i and size distribution* $r^{-2.9}$ *(dashed and solid lines)*

# Polarisation of vegetation

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Vegetation polarises light, as many other objects. The reflectance polarisation might be a good indicator of something, but is yet too unknown to be used widely in remote sensing of land surfaces.

We have measured reflectance and linear polarisation of several samples using FIGIFIGO. Usually, the strongest signals are at moderate forward angles, around 110 degrees phase angle. The second interesting regime is some 10 degrees around the opposition. In measurements we can see up to 50% forward polarisation, and 1-5% backward polarisation, and clear differences between targets. We can separate wax covered leaves from smooth leaves, different growing phases of crops, note differences in dryness. For most of these signals, there are usually cheaper and more accurate alternatives, e.g. spectrometry or simple photography. However, there are some spectral polarisation signals that might tell something new. But optimum use of polarisation requires deep understanding of the phenomena, and much stronger physical modelling than easier techniques.

More information about the meeting is available at
http://www.polarisation.eu/index.php/meetings/spectropolarimetricexperiments