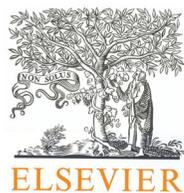


Book of Abstracts

Seventeenth Conference on Electromagnetic & Light Scattering

Texas A&M University, College Station, TX, USA
4–9 March 2018



Edited by

Nadia Zakharova

SciSpace, LLC
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OBJECTIVE

The 17th Electromagnetic and Light Scattering Conference (ELS-XVII) took place in the Texas A&M University, College Station, TX, USA from 4–9 March 2018. It built on the remarkable success of the previous ELS conferences held in Amsterdam, Helsinki (twice), New York, Vigo, Halifax, Gainesville, Bremen, Salobreña, St. Petersburg, Bodrum, Hatfield, Taormina, Lille, Leipzig, and College Park. The main objective of the



conference was to bring together scientists and engineers studying various aspects of light scattering and to provide a relaxed atmosphere for in-depth discussions of theoretical advances, measurements, and applications.

ELS-XVII was held in parallel with the 11th International Conference on Laser-light and Interactions with Particles (LIP2018).

SCOPE

The specific topics covered by ELS-XVII included (but were not limited to) the following:

- new theoretical developments, numerical simulations, and laboratory measurements of light scattering by nonspherical and morphologically complex particles and particle groups
- detection and characterization of atmospheric particulates using laboratory, in situ, and remote sensing techniques
- scattering of light by terrestrial aerosols and clouds
- scattering of light by oceanic particulates
- scattering of light by solar system objects, exoplanets, and exoplanetary environments
- scattering of light by various astrophysical objects
- applications of light scattering methods in biology and biomedicine
- light scattering in densely packed particulate media
- near-field and coherent effects in light scattering, optical trapping, and manipulation
- light scattering methods to control material properties and technological applications

PLENARY TUTORIAL LECTURES

- B. Cairns *et al.*, *A polarized view of the world*
- O. Dubovik *et al.*, *Solving inverse problems of light scattering: sensitivity tendencies in remote sensing of atmospheric aerosols*
- M. Francoeur, *Fluctuational electrodynamics and near-field thermal radiation*
- P. H. Jones and O. M. Maragó, *Optical forces and applications*
- M. Scully, *Remote detection from black mold to black holes*
- A. V. Sokolov, *Coherent light scattering by molecular vibrations*
- L. Tsang, *Van de Hulst lecture*
- J. J. Wang *et al.*, *Structured light interaction with small particles: GLMT and EBCM theoretical treatments*

- L. V. Wang, *Photoacoustic tomography: omniscale imaging in scattering media from organelles to patients*

INVITED REVIEWS

- L. Bi, *The invariant imbedding principle applied to light scattering by nonspherical particles: a review*
- A. Egel *et al.*, *Efficiency and validity of the superposition T-matrix method: recent advances*
- J. Markkanen *et al.*, *Light scattering by dense discrete random media of small particles: exact and approximate numerical solutions*
- M. I. Mishchenko *et al.*, *Scattering by particles in an absorbing medium*
- Zh. Zhang, *Plasmonics in nanoparticles for solar energy conversion and thermal transport*

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Plenary Tutorial Lectures

Ordered alphabetically according to the first author's last name

A polarized view of the world

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Until recently there were few polarized observations of the atmosphere of the Earth and the spectral range and accuracy of the available observations was somewhat limited. Over the last two decades new instruments that make highly accurate polarimetric observations over a wide spectral and angular range have been developed. Although the primary impetus for this development was to reduce uncertainties in the radiative properties of aerosols such measurements can also be applied to the remote sensing of clouds. For example, polarized observations can be used to estimate the droplet size distributions of water clouds and determine the shape and roughness of the crystals in ice clouds. By making polarimetric observations in closely spaced spectral bands, with and without absorption, assumptions required in deriving cloud macrophysical properties, such as the number concentration and physical thickness of clouds can be eliminated. While historically aerosol and cloud retrievals from satellite have been applied to separate pixels where either aerosols, or clouds dominated the observed signal, more recently the importance of detecting and characterizing aerosols above clouds has been recognized. As our understanding of the information contained in polarimetric observations improves it is clear that the use of such observations for characterizing aerosols under thin cirrus clouds and in the gaps between clouds will also become part of our repertoire for the passive remote sensing of aerosols and clouds. In this talk we summarize these developments and point to new approaches for combining active and passive measurements to extend the capabilities for remotely sensing the Earth from space.

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Solving inverse problems of light scattering: sensitivity tendencies in remote sensing of atmospheric aerosols

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Progress in the understanding of interactions of electromagnetic radiation with small particles has stipulated the development of a new class of optical diagnostics and remote sensing applications. The necessity of data inversion, i.e., the derivation of information about properties of natural objects from the results of interactions of electromagnetic radiation with the objects, is an inherent feature of these applications. Even if the direct simulation of interactions of the light with the objects is fully known, the inversion requires additional analysis. For instance, there is a wide variety of remote sensing observations developed for monitoring properties of tropospheric aerosols. They include satellite and ground-based observations, both passive and active (lidar), spectral and multi-directional measurements, recording of only the intensity or also polarimetric properties, etc. Evidently, the scope and the accuracy of the aerosol information retrieved from these observations are very different, as are the assumptions and constraints used. This aspect always requires thorough considerations. In this study, we propose an assessment of the fundamental tendencies in sensitivities of aerosol light scattering which is expected to be of help for understanding of the full potential and limitations of aerosol remote sensing. To this end, a special “hierarchical” concept of the test evolution has been developed. The tests start from only single-scattering observations. Indeed, most of the aerosol remote sensing approaches rely on the manifestation of angular and spectral features in aerosol scattering properties determined by the aerosol scattering matrix, extinction, and absorption. Thus, if some retrieval limitations exist in the single scattering regime, then they most likely remain with some modifications in the presence of multiple scattering effects in the atmosphere. At the same time, the numerical tests only with single-scattering properties is much simpler and logistically easier than the tests with full modeling of atmospheric radiances including multiple scattering effects. Specifically, the importance of multi-angular and polarimetric observations, the possibilities to determine aerosol type and other important aspects were studied.

The tendencies established with single-scattering tests are used for the analysis of limitations of some real ground-based and satellite retrieval approaches. The conclusions are illustrated both by the numerical tests with full account of multiple scattering and by analyses of real observations. The tests use the unique retrieval algorithm GRASP (Generalized Retrieval of Aerosol and Surface Properties, see Dubovik et al. (2014)) available as an open source software (<http://www.grasp-open.com/>).

Fluctuational electrodynamics and near-field thermal radiation

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The classical theory of thermal radiation is based on the blackbody concept. In this framework, transport is treated as incoherent and thermal emission is conceptualized as a surface process. The blackbody concept is, however, based on the assumption that all characteristic lengths, which include the size of the bodies and their separation distance, are larger than the wavelength [1]. When the size of the bodies and/or their separation distance is comparable to or smaller than the wavelength, the wave characteristic of the energy carriers must be taken into account. In addition to these coherence effects, radiation heat transfer between bodies separated by subwavelength separation gaps may exceed by a few orders of magnitude the blackbody prediction due to tunneling of evanescent modes. Finally, when the size of a heat source is comparable to or smaller than the wavelength, thermal emission may experience size effect.

Coherence effects, emission and tunneling of evanescent modes, and volumetric thermal emission that are important in the near-field regime of thermal radiation (i.e., when the characteristic lengths are smaller than the wavelength) are modeled via fluctuational electrodynamics [2]. The fluctuational electrodynamics framework is based on Maxwell's equations into which fluctuating currents representing thermal emission are added. The link between the fluctuating currents and the local temperature of a heat source is provided by the fluctuation-dissipation theorem, which is valid under the assumption of local thermodynamic equilibrium.

In this talk, the basics of fluctuational electrodynamics applied to near-field thermal radiation will be reviewed. Recent experimental measurements demonstrating the validity of fluctuational electrodynamics will be overviewed [3]. Finally, the limit of validity of fluctuational electrodynamics in the extreme near-field regime (i.e., sub-10 nm separation gaps) will be discussed.

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Optical forces and applications

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Mechanical effects of light stem from conservation laws in light scattering. Optical tweezers (OT) [1], tools based on strongly focused light, enables optical trapping and manipulation of a wide range of microscopic and nanoscopic materials, as well as their characterization [2]. In the limiting cases of spherical particles either much smaller (dipole approximation) or much larger (ray optics) than the trapping wavelength, the force in OT separates into different contributions: a conservative *gradient force*, proportional to the light intensity gradient, responsible for trapping, and a non-conservative *scattering force*, proportional to the light intensity that generally is detrimental for trapping, but fundamental for optical manipulation and laser cooling. However, for non-spherical particles or at intermediate (meso)scale the situation is more complex and this traditional identification of gradient and scattering force is more elusive [1]. Moreover, shape and composition can have dramatic consequences for optically trapped particle dynamics.

Here, after an introduction to optical forces with a focus on the role of shape, aggregation, and composition, we give an overview of current applications to material science, plasmonics, soft-matter, and present some results on optical trapping, optical binding, and characterization of 1D and 2D materials, surface-enhanced spectroscopies in OT, and chiral particles.

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Coherent light scattering by molecular vibrations

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Atomic or molecular coherence is the central feature of multiple techniques; high degree of coherence can lead to astonishing results. The term “coherence” refers to a situation when all molecules/atoms in a macroscopic sample oscillate in unison, or, in the language of quantum mechanics, to a situation where a molecular/atomic ensemble is prepared in a vibrational superposition state. Atomic coherence has earlier been used in electromagnetically induced transparency, ultraslow light propagation, and lasing without inversion. Increased and cleverly manipulated molecular coherence has found important applications in coherent Raman spectroscopic detection and sensing [1]. Coherence yields the famous N^2 signal enhancement, compared to spontaneous Raman spectroscopy. Another remarkable example of an application of molecular coherence is a technique termed molecular modulation, which allows ultrafast laser pulse shaping and non-sinusoidal field synthesis via broadband (multi-sideband) coherent Raman generation [2]. An additional dimension to the laser field engineering is added, within the molecular modulation technique, by using spatial light modulators to shape the transverse beam profiles, taking us toward production of space- and time-tailored sub-cycle optical fields – possibly coupled to plasmonic nano-antennas for single-molecule spectroscopy with nano-structured light. These ideas open intriguing opportunities for molecular spectroscopic studies [3–5].

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Structured light interaction with small particles: GLMT and EBCM theoretical treatments

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With the enhancement of techniques in manipulating optical fields, various structured beams with brand new properties, e.g., non-diffractive Bessel beams, Laguerre–Gaussian beams with orbital angular momentum, self-accelerating Airy beams, and others, are generated by manipulating the amplitude, phase, and polarization of a basic Gaussian beam or a plane wave. Novel applications in optical manipulations, super-resolution imaging technique, biological detection, and other fields are extended significantly, which brings a promising research in the investigation of structured beam interactions with small particles [1].

From a theoretical perspective, great efforts have been devoted to deal with the scattering of structured beams by small particles in the past decades. The Lorenz–Mie theory (LMT), which provides a rigorous way to describe the interaction between a linearly polarized plane wave and a homogeneous spherical particle, was greatly developed and extended after the name of generalized Lorenz–Mie theory (GLMT) mainly from two aspects: (i) from plane wave to arbitrary structured beams, and (ii) from homogeneous sphere to various regular shaped/structured particles [2]. The GLMT is now a well-known and widely used tool in the structured beams scattering by regular particles. Although only regular particles can be handled by the GLMT since this analytical method is implemented based on the separation of variables, the expansion description of arbitrary structured beams in GLMT can be combined with the Extended Boundary Condition Method (EBCM), or the Null-Field Method (NFM) [3] to construct a synthetic T-matrix solution for the structured beams scattering by arbitrary shaped particles [4]. This technique is of great interest and much favorable in several research fields since the advantage of T-matrix: “The elements of T-matrix are independent of the incident field ..., so that the T-matrix needs to be computed only once and then can be used in computations for any directions of light incidence and scattering” [5] holds, and fruitful results for the expansion description of arbitrary structured beams in the GLMT can be directly used.

In this talk, most recent developments in the theoretical treatments of structured light interactions with spherical/nonspherical particles are briefly reviewed. Description and expansion of structured beam [6,7], evaluation of beam shape coefficients (BSCs) for use in the GLMT and EBCM [8, 9], the synthesis between the GLMT and EBCM [4], and some results concerning the far-field, internal, and near-surface field distributions will be discussed.

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Photoacoustic tomography: omniscale imaging in scattering media from organelles to patients

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Photoacoustic tomography has been developed for in vivo functional, metabolic, molecular, and histologic imaging by physically combining optical and ultrasonic waves. Broad applications include early-cancer detection and brain imaging. High-resolution optical imaging—such as confocal microscopy, two-photon microscopy, and optical coherence tomography—is limited to superficial imaging within the optical diffusion limit (~1 mm in the skin) of the surface of a scattering tissue. By synergistically combining light and sound, photoacoustic tomography in the form of either photoacoustic computed tomography or photoacoustic microscopy provides deep penetration at high ultrasonic resolution and high optical contrast. The annual conference on photoacoustic tomography has become the largest in SPIE's 20,000-attendee Photonics West since 2010.

In photoacoustic computed tomography, a pulsed broad laser beam illuminates the biological tissue to generate a small but rapid temperature rise, which leads to emission of ultrasonic waves due to thermoelastic expansion. The unscattered pulsed ultrasonic waves are then detected by ultrasonic transducers. High-resolution tomographic images of optical contrast are then formed through image reconstruction. Endogenous optical contrast can be used to quantify the concentration of total hemoglobin, the oxygen saturation of hemoglobin, and the concentration of melanin. Exogenous optical contrast can be used to provide molecular imaging and reporter gene imaging as well as glucose-uptake imaging.

In photoacoustic microscopy, a pulsed laser beam is delivered into the biological tissue to generate ultrasonic waves, which are then detected with a focused ultrasonic transducer to form a depth resolved 1D image. Raster scanning yields 3D high-resolution tomographic images. Super-depths beyond the optical diffusion limit have been reached with high spatial resolution.

Wavefront engineering and compressed ultrafast photography will be touched upon.

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Invited Reviews

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The invariant imbedding principle applied to light scattering by nonspherical particles: a review

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Although the invariant imbedding principle had gained popularity in radiative transfer and computational mathematics a long time ago, the concept's power in light scattering by nonspherical particles has only been explored in recent years. Unlike solving Maxwell's equation in conjunction with boundary conditions, this principle transforms the boundary value problem into an initial value problem in the framework of an electromagnetic volume integral equation. In this talk, I will summarize the invariant imbedding principle for the solution of the T-matrix equations as well as Debye's series of nonspherical particles [1–4], and discuss current modeling capabilities of the aforementioned techniques. The invariant imbedding T-matrix method computes the optical properties of nonspherical (inhomogeneous) particles. Debye's series helps understand the scattering mechanism and, in particular, the semi-classical scattering effect beyond geometric-optics or physical-optics approaches. Moreover, I will illustrate the use of Debye's series to determine an optimized high frequency extinction formula for spheroids in the context of the complex angular momentum theory pioneered by Nussenzveig and Wiscombe [5] for a homogeneous sphere. Finally, I will report on representative calculations for nonspherical particles, including ice crystals, aerosols, red blood cells, and coccolithophores, and also highlight relevant downstream applications in both particle characterization and remote sensing.

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Efficiency and validity of the superposition T -matrix method: recent advances

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With growing computing hardware capabilities, full-wave simulations of light propagation in macroscopic aggregated media like powders, paint, or scattering layers in optoelectronic thin-film devices are becoming feasible [1]. To this end, half-spaces or laterally infinite slabs of discrete random media are approximated with scattering samples comprising finite, but very large, numbers of particles [2]. This approach poses substantial challenges to current implementations of the superposition T -matrix method (STMM), as the numerical effort grows rapidly with the particle number.

Another challenge for the STMM is the adaption to a broader range of scattering configurations, including densely packed non-spherical particles as well as flattened particles close to infinite interfaces. Here, care has to be taken with respect to the validity of the employed field representations in the near-field zone of the particles [3].

After an introduction to the general formalism, this talk will focus on the computational bottlenecks, and review strategies for efficient implementations of the STMM. We will also cover recent approaches to extend the validity of multiple-scattering calculations to configurations where the circumscribing sphere of a particle is intersected by either another particle or by a planar interface [4,5].

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Light scattering by dense discrete random media of small particles: exact and approximate numerical solutions

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Electromagnetic scattering and absorption in a macroscopic particulate medium composed of densely-packed microscopic particles constitute an open computational problem. This results in the absence of quantitative inverse methods to interpret various spectroscopic, photometric, and polarimetric remote sensing observations.

In this talk, we will discuss the applicability of the exact and approximate numerical methods to model scattering and absorption by dense discrete random media. The exact numerical methods such as the superposition T-matrix, integral-equation, and finite-difference methods, give rise to the full wave numerical solution [1]. The required computation time, however, limits the size of the entire random medium and prevents the analysis of macroscopic medium consisting of billions of particles. The approximate methods, for example the radiative transfer and coherent backscattering (RT–CB), can address large media but the accuracy of the solution is questionable, particularly for the systems of close-packed particles. Recently, a numerical technique has been developed for the dense discrete random media of spherical particles entitled as the radiative transfer with reciprocal transactions R2T2 [2,3]. By comparing the exact and approximate solutions, we show that the R2T2 and its extension to non-spherical particles can be applied for the microscopic as well as the macroscopic dense discrete random media. Further, we discuss the approximations of the R2T2 that allow for efficient spectroscopic, photometric, and polarimetric analyses of planetary regolith.

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Scattering by particles in an absorbing medium

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In this talk we review the recently developed first-principles approach to electromagnetic scattering by particles immersed in an unbounded absorbing host medium [1]. This formalism enables one to solve the following two important problems: (i) simulate theoretically the (polarized) reading of a remote well-collimated radiometer measuring electromagnetic scattering by an individual particle or a small random group of particles; and (ii) compute the single-scattering parameters that enter the vector radiative transfer equation derived directly from the Maxwell equations [2]. We then introduce an actual computational tool in the form of a public-domain FORTRAN program [3] for the calculation of pertinent far-field optical observables in the context of the classical Lorenz–Mie theory of electromagnetic scattering by homogeneous spherical particles [4].

We apply this program to a limited yet representative set of problems [5,6]. We identify and analyze the remarkable phenomenon of negative extinction and provide voluminous evidence in favor of its interference origin (cf. [7]). We study the main effects of increasing the width of the size distribution on the ensemble-averaged extinction efficiency factor and show that negative extinction can be eradicated by averaging over a very narrow size distribution. We also analyze the effects of absorption inside the host medium and ensemble averaging on the phase function and other elements of the Stokes scattering matrix. It is shown in particular that increasing absorption can result in a dramatic expansion of the areas of positive polarization, while the phase functions at larger effective size parameters can develop a very deep minimum at side-scattering angles bracketed by a strong diffraction peak in the forward direction and a pronounced backscattering maximum.

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Plasmonics in nanoparticles for solar energy conversion and thermal transport

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When absorbing particles (such as metallic nanoparticles) whose dimensions are much smaller than the electromagnetic wavelength, localized surface plasmon resonance (LSPR) can be excited, giving rise to enhanced scattering and absorption cross sections. One way to increase the efficiency of solar thermal conversion is by dispersing nanoparticles in liquids to create highly absorbing liquid, i.e., “black” liquid. Photothermal effects can enable steam generation using solar radiation or a laser source. For solar thermal systems, increasing the absorption peak and broadening the absorption band are both important, since the ultimate goal is to achieve high total power absorption. For this reason, we propose to combine a carbon-core and gold-shell to boost the total solar absorption efficiency factor (SAEF) of nanoparticles [1]. Further, we study the effects of geometry, material, as well as the surrounding on the SAEF [2]. The wavelength range of consideration is from ultraviolet (300 nm) to near-infrared 1100 nm, since water is highly absorbing beyond 1100 nm. We have identified carbon-core gold-shell [1] as well as star-shaped gold nanostructures [2] as promising systems that can boost SAEF by exciting plasmonic resonances. The effect of graphene-coated nanoparticles on light absorption will also be investigated.

Dielectric materials can support surface phonon polaritons (SPhPs). In an array of nanoparticles, such as SiC or SiO₂, localized SPhPs can be coupled between neighboring structures, resulting in substantial energy transfer via propagating SPhPs that could contribute more to heat conduction than phonon transport in the system. We have illustrated that the near-field emission spectrum from ordered nanoparticle arrays is dictated by the density of states of propagating SPhPs when they are present [3]. Moreover, we will employ the coupled dipole method as well as the dispersion-based analysis of propagating surface modes to calculate the thermal conductivity of a chain of SiC nanoparticles.

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Regular Presentations

Ordered alphabetically according to the first author's last name

Effects of particle agglomerate deposits on the radiative response of heterogeneous coatings

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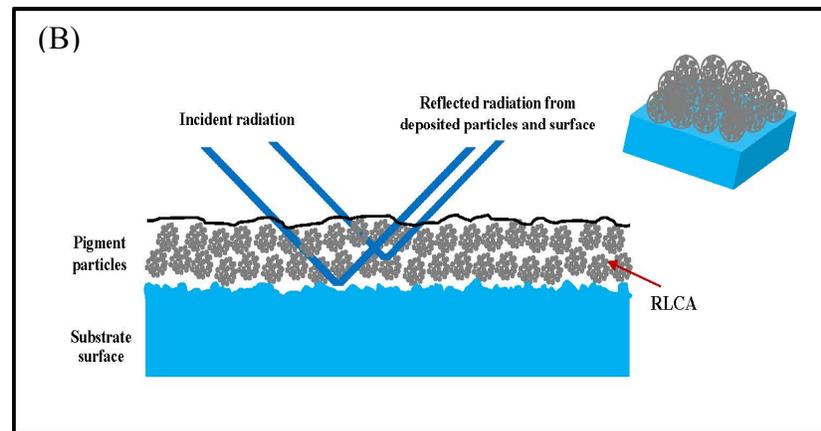
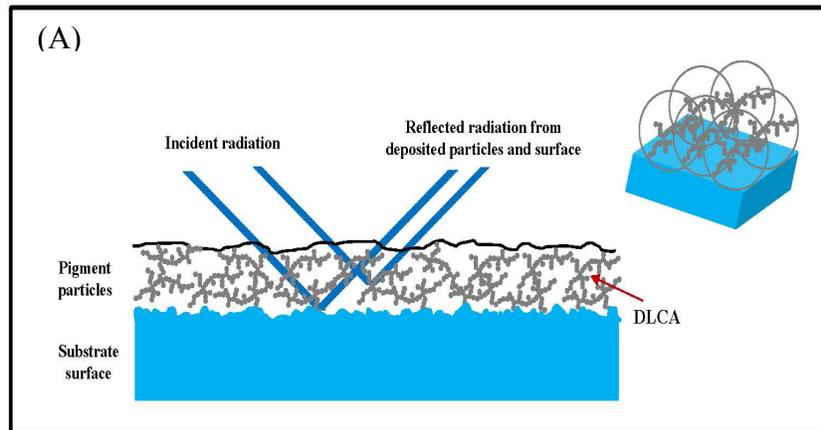
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The optical and radiative properties of surfaces need to be designed for a variety engineering and industrial applications, such as electric power generation, solar energy harvesting systems, for innovative chemical processes, and building radiative cooling applications, among others. Many of these coatings are comprised of packed particles and their agglomerates, rather than homogeneous layers. The particulate deposits affect the radiative properties of surfaces not only because of their intrinsic optical properties, but also due to the structures of individual particles and their agglomerates [1]. Consequently, the reflection on the substrate and the upper interface of particulate deposits become more complicated, altering the radiative properties of surfaces as well [2].

The main objective of this study is to investigate the effects of the different characteristics of particle agglomerates and their optical properties on the radiative properties of heterogeneous particulate deposits on surfaces. The ultimate aim is to have optimized particle shapes and structures for specific applications. For this purpose, the radiative properties of different particle agglomerate structures are determined using the discrete dipole approximation (DDA and DDA-SI) techniques. The performances of different coatings to be evaluated in terms of their reflection and scattering behaviors. In addition, these radiative properties are to be used in the solution of the radiative transfer



Heterogeneous particulate deposits: (A) linear particle agglomerate shapes, and (B) compact particle agglomerate shapes.

equation (RTE), to determine the radiative behavior particulate deposits as a function a series of parameters, including optical depths of deposits and the substrate properties.

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Preferred mode of presentation: Oral

Aerosol retrievals from proposed satellite bistatic lidar observations: accuracy and information content

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Accurate aerosol retrievals from space remain quite challenging and typically involve solving a severely ill-posed inverse scattering problem. We suggested to address this ill-posedness by flying a bistatic lidar system. Such a system would consist of formation flying constellation of a primary satellite equipped with a conventional monostatic (backscattering) lidar and an additional platform hosting a receiver of the scattered laser light [1,2]. If successfully implemented, this concept would combine the measurement capabilities of a passive multi-angle multi-spectral polarimeter with the vertical profiling capability of a lidar. Thus, bistatic lidar observations will be free of deficiencies affecting both monostatic lidar measurements (caused by the highly limited information content) and passive photopolarimetric measurements (caused by vertical integration and surface reflection).

We present an accuracy assessment study for a bistatic lidar system consisting of a high spectral resolution lidar (HSRL) and an additional receiver flown in formation with it at a scattering angle of 165° . This study uses synthetic data generated using Mie-theory computations. The model/retrieval parameters in our tests were the effective radius and variance of the aerosol size distribution, complex refractive index of the particles, and their number concentration. Both mono- and bimodal aerosol mixtures were considered. Definitive evaluation of error propagation from measurements to retrievals was performed using a Monte Carlo technique, which involves random distortion of the observations and statistical characterization of the resulting retrieval errors. Our tests demonstrated that supplementing a conventional monostatic HSRL with an additional receiver dramatically increases the information content of the measurements and allows for a sufficiently accurate characterization of tropospheric aerosols.

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Preferred mode of presentation: Oral

Digital holographic imaging of rough surfaces

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This presentation is focused on explaining a technique that will provide insight on the structure of rough surfaces. We have constructed what is essentially a Michelson interferometer; one arm illuminates the surface and collects the back-scattered light, and the other arm provides the reference beam. Both beams then interfere and create the hologram, which is recorded on a CCD. Some surfaces we have measured include a window with ragweed pollen, a cluster of fiberglass, and deposited salt crystals on a slide. Thus far, we have successfully generated two dimensional images of these surfaces with a resolution on the order of $\sim 3\text{--}4$ micrometers. The goal is to extend this by generating a three dimensional model of the surface in question.

Preferred mode of presentation: Oral

Using linear electrodynamic quadrupole trap for drop pattern formation and nanoparticle aggregates production from drying colloidal microdroplets of suspension

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Electrodynamic quadrupole trapping of microparticles provides a contactless approach for optical measurements of microdroplets of different compositions, aerosols, and dust grains [1,2]. The use of the linear electrodynamic quadrupole trap (LEQT) [3] can provide unsupported solvent drying, well-defined aggregate morphology evolutions from colloidal droplets of suspension as well the possibility to deposit (“soft-landing”) the final dry microproducts on a substrate and analyze them offline by scanning electron microscopy (SEM) [4,5].

In this presentation, we will demonstrate advancements in the use of the LEQT to produce various nanoparticle aggregates of interesting structural properties from drying microdroplets of colloidal suspension. The final products were carefully deposited on a substrate and analyzed offline with scanning electron microscopy. Highly-ordered aggregates of silica nanoparticles, aggregates of gold and silica as well as aggregates of silica with crystallized sodium dodecylsulfate (SDS) will be presented. Additionally, we will present SEM analysis of intermediate drying drop deposits and the manner in which SDS alter these deposits/patterns with time and SDS concentration. Our ability to deposit intermediate drop patterns and complex dry aggregates of different morphologies with unique properties using the LEQT and offline SEM analysis is desirable in many applications.

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Preferred mode of presentation: Oral/Poster

Radiation pressure forces and blowout sizes for particles in debris disks

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Debris disks are a type of circumstellar disk that contain dust generated by collisions and disruptions of protoplanets and/or planetesimals. To interpret scattered light observations of debris disks, it is useful to compare modeled grain size distributions to radiation pressure blowout sizes. The ratio of radiation pressure to gravitational forces (β) acting on a dust grain depends on grain composition, size, and structure. Typically, β is calculated using the assumption of compact, spherical particles or accounting for porosity via the Maxwell-Garnett mixing rule (e.g., [1]). Calculations of radiation pressure balance for porous, irregular dust grains have been carried out for a handful of cases [2–4] using the discrete dipole approximation (DDA) method [5]. However, due to computational considerations, these focused on submicron particles that only require a small number of dipoles ($N \leq 2048$), but may be below the blowout size of some systems.

Here we present comparisons between Mie, Maxwell-Garnett, and DDA calculations of β for micron-sized grains using different stellar luminosities and grain compositions. The grain shapes and DDA implementation used to generate scattering and absorption efficiencies are similar to [6]. Stellar properties were chosen to correspond to stars known to host debris disks.

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Preferred mode of presentation: Oral/Poster

Comparison of local absorption of core-shell nanoparticles with different core size and shell thickness

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The noble metals supporting surface plasmon polariton modes in the near-field regime introduced the possibility of utilizing surface plasmon resonance (SPR) of these materials in many applications. The spectral position of localized SPR of the nanoparticles depends on their size, shape, and surrounding medium. In some biomedical and sensing applications, optimum field enhancement is aimed; however, tuning the SPR position may not be guaranteed with single component nanoparticles due to impurities, and/or difficulties in creating certain shape and sizes. Hence, the idea of using alloys as well as different core and shell materials in nanoparticle compositions draw great interest [1]. The aim of using core-shell nanoparticle is to optimize the LSPR behavior of the particles with increasing field enhancement. Possible nanoparticle combinations can be considered as metal-metal, metal-dielectric, and dielectric-metal core-shell structures. Dielectric core and metal shell study showed that uniform field distribution can be achieved over the metal shell of the nanoparticles, and introducing an AFM tip results in near-field coupling with field enhancement [2].

In this study, we will focus on metal-metal core-shell nanoparticles with well-known noble metals such as gold, silver, and copper that are placed over dielectric substrate under surface evanescent illumination caused by total internal reflection. The variations of core and shell materials will be investigated with different core diameters and shell thicknesses to find an optimum size ratio, which is called as filling factor [3]. The aim is to provide a good insight for a selection of metal pairs regarding their effect on each other's absorption spectra. Tuning the plasmon resonance wavelength for chosen metal pairs will be further investigated with an AFM tip placed over the core-shell nanoparticle. For this purpose, the spectral absorption efficiency of the nanoparticles with different filling factors are determined using the discrete dipole approximation with surface interaction (DDA-SI).

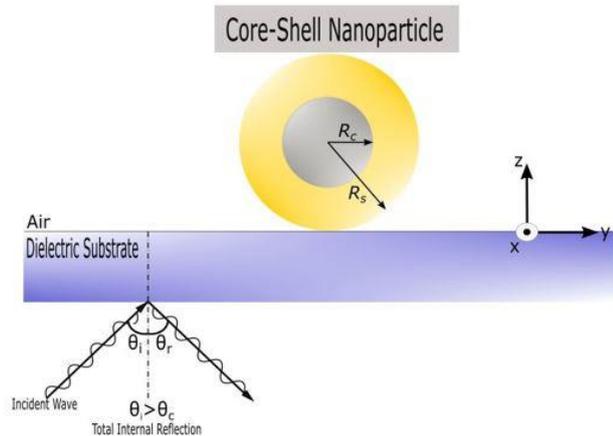


Figure 1 A cross-sectional schematic of the configuration.

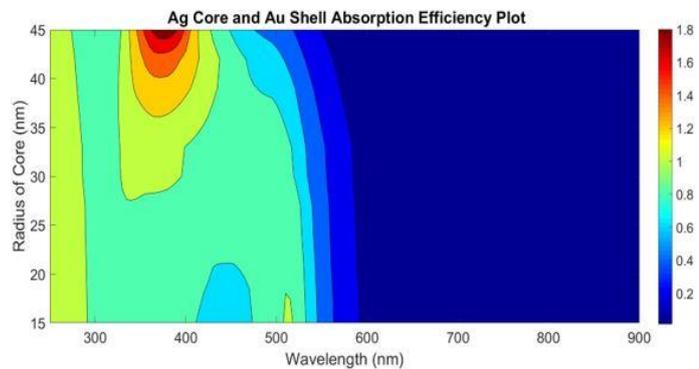


Figure 2 Absorption efficiency patterns for 50 nm diameter of silver-gold core-shell nanoparticle.

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Preferred mode of presentation: Oral

The challenge of sub-millimetre-wave scattering

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Scattering by atmospheric ice in the mm-wave and sub-mm-wave spectral regions presents a challenge to the cloud microphysics and light scattering communities. This is because scattering by atmospheric ice, at these frequencies, not only depends on ice crystal shape, orientation and size, but also on how its mass or density evolves with size, and on the shape of the size spectrum. As there is no universal density-size relationship or representation of the size spectrum this makes interpretation of mm-wave and sub-mm-wave observations problematic.

In this talk, the methodologies proposed in [1,2] will be applied to state-of-the-art mm-wave and sub-mm-wave airborne observations of ice cloud that occurred around the United Kingdom [3]. Furthermore, these observations also consisted of state-of-the-art detailed microphysics measurements. From the latter observations, and using the geometric optics approximation to estimate the volume extinction coefficient, ice mass-extinction relationships were previously derived by [4]. The three-component models presented in [2] are applied to predict the geometric-based relationships and these models are then used to simulate the observations in the microwave using a generalized state-of-the-art line-by-line radiative transfer model [5]. The results of these analyzes will be presented and discussed in relation to the scattering challenge.

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Preferred mode of presentation: Oral

Determination of the optical constants of the active layer of a suspended particle device smart window with multilayer structure, at the clear and dark states, with and without applied voltage

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Smart windows based on suspended particle devices (SPD) are able to switch optically from dark to clear visual appearance when applying an AC electrical signal. This effect is due to light absorbing nanoparticles that get aligned by the applied voltage. The sandwich structure of a SPD consist of several layers and includes two outer glass substrates, each one covered on its inwards-facing side with a transparent conducting thin layer surrounding the centrally positioned SPD active layer. A knowledge of the optical constants of each layer—i.e., the complex refractive index, including its real and imaginary (absorption) parts—is a key in the design of the visual appearance of the SPD window and is a useful tool to determine the optimum thickness of the active layer.

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Preferred mode of presentation: Poster

Application of submillimeter- and thermal-infrared measurements to retrieve ice cloud properties

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Ice clouds have a profound impact on the Earth's energy budget through their contribution to radiative warming, emission of infrared radiation, and cooling from reflection and absorption of solar short-wave radiation. These contributions, coupled with the variable structure and high spatial and temporal coverage of ice clouds, impose difficulties in quantifying their radiative characteristics, and thus limit our understanding of the current climate and potential future changes [1]. A principal difficulty in quantifying these radiative effects is the number of degrees of freedom affecting radiative forcing, such as ice water content and cloud microphysical properties [2]. To simplify calculations in general circulation models, many cloud properties are parameterized. Thus, to improve the representation of clouds in the models, a validation of these parameterizations with cloud property retrievals is essential. Successful retrievals of cloud properties from satellite based measurements is dependent on the ability to relate observed radiances to a unique set of desired cloud properties, and the most useful measurements are those that exhibit the greatest sensitivity to small perturbations in cloud microphysical properties. The potential of submillimeter radiometers has been recently explored to improve cirrus ice water content retrievals, and our previous results show good sensitivity for submillimeter and thermal infrared measurements to retrieve ice water content and particle diameter.

In this work we summarize these recent developments and present results of simulated retrievals of cirrus ice water path and particle effective diameter. We also discuss the inclusion of polarimetric measurements in these bands, and the possibility of retrieving cloud microphysical properties such as particle shape and size distributions.

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Preferred mode of presentation: Poster

Diffraction, shadows, and scattering in electrodynamics: a new view

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Diffraction is the spreading of waves of any kind. The mechanism of diffraction, however, can be quite different for different types of waves.

We show that for electromagnetic waves such as light the diffracted wave of an object is the Ewald–Oseen extinction wave in the far field. The intensity distribution of this wave yields what is commonly called the diffraction pattern. This is the same Ewald–Oseen extinction wave that extinguished the incident wave in the object and thereafter continued to do so immediately behind the object to create a shadow. The object can be an isolated particle or a screen with a hole; in the former case the Ewald–Oseen extinction wave is radiated from the particle, in the latter case it is radiated from the screen. This point of view explains Babinet’s principle. If the object is an isolated, non-absorbing particle, nearly half the scattering cross section is in the Ewald–Oseen extinction wave; if the particle has significant absorption, nearly all the scattering cross section is contained there.

Unlike other common waves, such as sound and water waves, electromagnetic waves do not require a material medium in which to propagate. Thus a material object cannot block electromagnetic waves. Hence, light shadows do not form by blocking the light; light does not bend around the edges of the blocking object.

Preferred mode of presentation: Oral

Internal fields in soot fractal aggregates

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Light scattering from carbonaceous-soot fractal aggregates is commonly described with the Rayleigh–Debye–Gans (RDG) approximation [1]. Based upon the assumption that the monomers of an aggregate are within the Rayleigh regime, this approximation treats scattering from the aggregate as if each monomer scatters the incident field only. That is, the RDG approximation neglects “internal multiple scattering” between the monomers of an aggregate. While many of the physical characteristics of soot aggregates appear to justify use of the RDG approximation, its range of validity for this purpose has long been in debate [2].

In this presentation, we investigate light scattering from simulated soot fractal aggregates using the Maxwell volume integral equation combined with the discrete dipole approximation (DDA). The fields present within the aggregate’s monomers are then compared to the analogs given by the RDG approximation. Through this comparison, new aspects to our understanding of how these aggregates scatter light is uncovered.

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Preferred mode of presentation: Oral

Interstellar dust analogue mixture of graphite and fayalite: computational and experimental light scattering properties

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Interstellar graphite and silicate dust analogue samples are of utmost importance for laboratory simulations to interpret astrophysical data obtained through space and ground based observatories. The light scattering properties of a graphite and silicate dust analogue laboratory model is studied in this work. The shape and size averaged values of scattering parameters phase functions and polarizations are calculated using Discrete Dipole Approximation (DDA) based computations at three incident wavelengths 543.5, 594.5, and 632.8 nm respectively. The calculated results are then compared with the experimentally measured scattering parameters [1–3]. Two modeling approaches are used for a comparative study to fit the theoretical and experimentally acquired data considering a size distribution of 0.3 to 5 μm . The effects of modeling parameters: percentage composition, number of dipoles and number of random orientation directions are studied and other important findings are presented in this paper.

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Preferred mode of presentation: Oral

Experimental boundary conditions for frequency domain PDW spectroscopy – a Monte Carlo study

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To characterize the optical properties of strongly light scattering materials, like polymer dispersions, paint, food, or cosmetics, different experimental techniques can be used, e.g. spatially or time-resolved reflectance or transmission measurements or Photon Density Wave (PDW) spectroscopy in the frequency domain. Here, the radiative transfer equation is often applied in data analysis to determine the absorption (μ_a) and reduced scattering coefficient (μ_s') from the measured signals. Additionally, the diffusion approximation (DA) with appropriate boundary conditions is widely used due to the simplicity of the solution. However, the DA restricts the data analysis to samples with an absorption coefficient that is small compared to the reduced scattering coefficient ($\mu_a \ll \mu_s'$) and too small modulation frequencies. Especially because of the latter condition the solution of the radiative transfer equation in the P1-approximation for an infinite medium has been used for PDW spectroscopy quite extensively and has been applied successfully to determine the optical properties and subsequently particle sizes with high precision and accuracy [1–2]. However, the boundary conditions used to derive the P1-approximation include an infinite sample volume and an isotropic point-like light source and detector which can only be achieved to a certain extent experimentally.

To study the influence of the above mentioned conditions and further experimental influences on the results of PDW spectroscopy Monte Carlo (MC) simulations are carried out to simulate the light expansion in the sample. The simulated amplitude and phase of the PDW are compared directly to the P1-approximation to identify major influences. Additionally, the simulated MC data are analyzed via the P1-model and the influence of different experimental parameters including sample volume, range of relative and absolute fiber positions as well as modulation frequencies and fiber parameters on the resulting optical coefficients is evaluated with respect to the accuracy of the latter. In case of the above mentioned materials, the infinite medium is well approached by sample volumes typically ranging from 50 mL – 1 L depending on the optical properties and a not too small absorption coefficient (to reduce loss of light at the sample boundaries). The isotropy and point-like dimension of the light source and the detector can be approximated by using optical fibers with high numerical aperture and small fiber core to couple light into or out of the sample. Depending on the optical parameters and fiber properties, data analysis should be carried out excluding e.g. too small distances between emission and detection fiber to obtain results with high accuracy and precision.

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Preferred mode of presentation: Oral

Lidar depolarization ratio of soot fractal aggregates: spectral dependence over the visible-to-infrared spectrum

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The global warming and environmental issues imply the study of anthropogenic airborne particulate matter (PM), such as carbonaceous or soot aerosols, emitted by several sources. Carbonaceous particulate matter emitted by aircraft engines is due to incomplete fuel combustion. These particles can have long residence times in the upper troposphere and lower stratosphere and affects the global radiative budget. Soot particles are considered to influence ice and liquid water cloud droplet activation as they could be important centers of ice-particle nucleation and would promote ice formation involved in contrails formation for instance. The understanding of ice-forming activity of soot particles is closely related to the knowledge of their microphysical properties. The primary soot particles, with size distribution in the nanoscale range, form large and robust complex-shaped cluster of particles such as fractal aggregates. Lidar measurements are useful in deriving the radiative properties of scattering media from backscattered light at several wavelengths. Polarization-sensitive lidar measures the total lidar depolarization ratio which can be separated into the molecular and aerosol depolarization ratio. The determination of the latter over the visible-to-infrared spectrum is expected to improve the determination of aerosol types present in the atmosphere. We propose to study the spectral dependence of lidar depolarization ratio for several soot fractal aggregates generated by diffusion-limited cluster-aggregation (DLCA). Our Spectral Discrete Dipole Approximation (SDDA) [1,2] model is used to accurately simulate the lidar depolarization ratio over the visible-to-infrared spectrum. Results from the SDDA method will be presented and compared with the lidar depolarization ratio measured by our instruments.

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Preferred mode of presentation: Oral

Effects of atmospheric photo-oxidation on brown carbon aerosol spectral optical properties

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Light absorbing organic aerosols, optically defined as brown carbon (BrC), have been shown to strongly absorb short visible solar wavelengths and significantly impact earth's radiative energy balance. There currently exists a knowledge gap regarding the potential impacts of atmospheric processing on the optical properties of such particles. Climate models and satellite retrieval algorithms parameterize the optical properties of BrC aerosols as unchanging throughout their atmospheric lifecycle. Here, using integrated photoacoustic-nephelometer spectrometers, we investigated the effects of multiple-day photochemical oxidation on the spectral (375–1047 nm) optical properties of primary BrC aerosols emitted from boreal and Indonesian peatlands. Emitted particles were “aged” to timescales ranging from one to several days using an oxidation flow reactor under the combined influence of OH, O₃, and UV light. We found the largest effects of oxidation in the near-UV wavelengths, with the 375 nm imaginary refractive index (κ) and absorption coefficients of BrC particles decreasing by ~36% and 46%, respectively, and an increase in their single scattering albedo from 0.847 to 0.898. The spectral variability of κ follows the Kramers–Kronig dispersion relation for a damped harmonic oscillator. Direct radiative forcing efficiency calculations show the effects of aging on atmospheric warming attributed to BrC aerosols, which could be significant over snow and other bright surfaces.

Preferred mode of presentation: Oral

Validation of cloud optical parameters from passive remote sensing in the arctic by using aircraft measurements

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Cloud Optical Parameters (COPs; e.g., cloud optical thickness, thermodynamic phase, and cloud effective radius) and surface albedo are the most important inputs for determining the shortwave Cloud Radiative Effect (CRE). In the Arctic, the COPs derived from passive remote sensing, such as from the Moderate Resolution Imaging Spectroradiometer (MODIS), are difficult to obtain with adequate accuracy, owing not only to insufficient knowledge about the snow/ice surface but also to the common occurrence of thin clouds. This study aims at evaluating the broadband and spectral irradiances calculated from MODIS-derived COPs in the Arctic with aircraft measurements collected during the Arctic Radiation-IceBridge Sea and Ice Experiment (ARISE) based in Fairbanks, Alaska. During ARISE, the Solar Spectral Flux Radiometer (SSFR) and the Broadband Radiometer system (BBR) provided upwelling and downwelling shortwave spectral and broadband irradiance, respectively. In the first step, the spectral snow surface albedo was derived from the collective irradiance measurements, accounting for partially snow-covered scenes by the snow fraction estimated from aircraft camera imagery. In the second step, we used a radiative transfer model (RTM) to calculate the upwelling and downwelling spectral irradiance at flight level, incorporating the MODIS-derived COPs and SSFR-derived spectral surface albedo for “pure snow” as inputs. The calculated irradiances were then compared with the measured broadband and spectral irradiance pixel by pixel for all suitable aircraft underpasses of the satellites.

We found that although MODIS provides reasonable COPs for thick clouds, it cannot detect optically thin clouds with cloud optical thickness less than around 7. Because thin clouds occur so frequently in the Arctic, undetected clouds may be the dominating error source of fluxes and CRE derived from passive imagery. Future work needs to focus on (a) obtaining systematic aircraft or surface-based observations of fluxes, surface albedo, and COPs and (b) on new methods to enable passive imagery based retrievals even for thin clouds. We will discuss possible avenues for both.

Preferred mode of presentation: Oral/Poster

Modeling of spectral snow emissivity over the entire longwave band

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Surface emissivity is defined as the ratio of actual surface emission to the blackbody radiation at the same temperature. It can vary with frequency and with the viewing solid angle. While there have been extensive measurements of surface spectral emissivity for a variety of surface types, such as the Spectral Library for the Advanced Spaceborne Thermal Emission and Reflection Radiometer [1], such measurements only cover the middle IR ($> 650 \text{ cm}^{-1}$). There have been no systematic compilations of far-IR ($< 650 \text{ cm}^{-1}$) spectral emissivity of surface types nor any systematic measurements of far-IR emissivity of snow or ice surfaces. Snow surface spectral emissivity is an important parameter for the energy budget and climate over high-elevation polar continents where the dry and cold atmosphere is not opaque in the far IR [2,3].

We modeled the spectral emissivity of snow surfaces for different snow grain sizes using the refractive indices of ice [4] and the Mie theory [5]. Wald [6] pointed out that the single-scattering albedo and the asymmetry parameter computed by the Mie theory cannot be directly used in radiative transfer models of closely packed grains. A “static structure factor correction” proposed by Mishchenko [7] and Mishchenko and Macke [8], which is based on solving Maxwell’s equations and statistical mechanics for dense packing, is used to modify the optical properties derived from the Mie scattering theory. The corrected single-scattering parameters are then fed into the Hapke emissivity model [9] to simulate snow emissivity at all spectral frequencies in the longwave. The modeled snow spectral emissivities agree reasonably well with measurements by Hori *et al.* [10] in the middle-IR for different viewing angles and different snow grain sizes, validating our snow spectral emissivity model in the mid-IR. The modeled snow far-IR spectral emissivities are then used to do sensitivity tests of their effect on TOA and surface energy budget during a winter month over the Antarctic Plateau. Details are described in Chen *et al.* [2]. Following this study, spectral emissivities of more surface types are then simulated in Huang *et al.* [11].

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Preferred mode of presentation: Oral

Influence of surface longwave emissivity and ice clouds longwave scattering on climate simulations

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In reality, surface longwave (LW) emissivity varies with wavelength and surface types, and ice clouds can scatter LW photons. These features, however, are usually ignored in general circulation models, which assume the surface as blackbody and non-scattering ice clouds in LW region, thus suggesting a need to quantify the climate simulation errors related to these assumptions.

In this study we incorporate the surface LW emissivity and ice clouds LW scattering effects into the NCAR CESM, namely, (1) a global surface LW emissivity dataset [1]; (2) an updated LW radiation scheme, RRTMG_LW, with a two-stream solver; (3) a state-of-the-art ice optical parameterization [2]. Both the modified and standard CESM are carried out 10-year simulations with prescribed sea surface temperatures. By comparing these two simulated results, we intend to quantify the influence of the surface emissivity along with ice clouds LW scattering on climate variables such as radiative energy budget and surface temperature. We also put a particular focus on the polar regions, where is a hot spot of human-induced climate changes and previous studies suggest that both surface emissivity and ice clouds LW scattering can play a role in energy budget in these regions [3].

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Preferred mode of presentation: Oral/Poster

Using radiometric and polarimetric sensitivities of sub-mm/mm and infrared wavelengths to provide information on simultaneous ice water path and effective diameter retrieval

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Radiometric and polarimetric calculations of simulated ice clouds composed entirely of aggregate particles are conducted for several wavelengths in the Infrared (IR) and Sub-millimeter/Millimeter (sub-mm/mm) ranges as part of NASA's SWIRP (Compact Submm-Wave and LWIR Polarimeters for Cirrus Ice Properties) project. The scattering/absorption/polarization properties of the aggregates that were calculated at the selected bands before this study are incorporated into a radiative transfer model, ARTS (Atmospheric Radiative Transfer Model) [1] in order to explore ice cloud characteristics in 1D spherical atmospheres.

This study focuses on simulating cirrus clouds using the wavelengths of 441 μm (680 GHz), 1363 μm (220 GHz), 8.6 μm , 11 μm , and 12 μm . The simulated cirrus clouds are made to be composed of a single ice particle habit of 8-column aggregates with a gamma distribution of particle sizes. Simulations are performed for combinations of ice water path (IWP), effective particle diameters (D_{eff}), visible optical thickness, and certain viewing zenith angles with ambient temperatures and pressure levels corresponding to a typical tropical atmosphere. The sensitivity analyses for these cases will focus on the creation of plots that display isolines of IWP and D_{eff} with brightness temperature parameters representing the axes for a combination of two or three wavelengths [2,3]. The brightness temperature parameters being used for this study are polarization difference for microwave wavelengths [4], brightness temperature depression from a cloud-free atmosphere [5], and IR split-window brightness temperature differences [6] that are based on the computed radiances from the ARTS calculations. The results can provide information on the possibility of simultaneously retrieving IWP and D_{eff} using a combination of sub-mm, mm, and IR wavelengths and brightness temperature parameters.

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Preferred mode of presentation: Poster

Generalized radiative transfer models for subpixel spatial & spectral variabilities in optically thin scattering media: application to aerosol profiling with the Oxygen A-band

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Generalized radiative transfer (GRT) theory was originally developed as a rigorous formalism for predicting spatial/ensemble average radiances and fluxes in stochastic 3D optical media dominated by scattering using a new homogenization [1,2]. Phenomenological precursors of GRT explained a slew of real-world observations of the cloudy atmosphere from the ground up (Ref. [3], and references therein). In parallel, the basic tenet of GRT, namely, substitution of the standard exponential (a.k.a. Beer's) direct transmission function with a power-law form, was proposed to address the perennial problem of efficient spectral integration across molecular absorption bands where cross-sections vary over many orders-of-magnitude [4]. We recently unified these two applications of GRT [5], established the validity of the spectral version from first physical principles [6], and illustrated the two purposes with analytical solutions for media that are optically thin as far as the scattering goes.

We will survey these recent developments in GRT theory and dual applications, and tie them to a current problem in aerosol profiling from space-based using passive imaging sensors that exploit the unique properties of the O₂ A-band (759–772 nm), as opposed to active lidar sensors that may have exquisite vertical resolution but no swath—only a “curtain” of data is provided. NASA's upcoming PACE mission and MAIA investigation will benefit from this new capability.

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Preferred mode of presentation: Poster

Spectral and spatial near-field radiative transfer analysis in nature-inspired golden spiral nanostructures

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In the near-field regime of radiative transfer (NFRT), where the physical dimensions and separation spaces between geometries become less than or comparable to the thermal wavelength of emission, the evanescent surface waves become the dominant carriers of electromagnetic modes. In the close proximity of objects, these evanescent waves, which are confined to the surfaces, can transport thermal energy to a degree that exceeds the classical predictions [1–3]. In recent years, a significant amount of research has been devoted to theoretical, numerical and experimental investigations of radiative transfer in the near-field regime with various applications such as energy harvesting and radiative cooling, among others. In this work, we investigate NFRT in a golden spiral nanostructure. The golden spiral is a nature-inspired, mathematically defined geometry which can be found in galaxies, animals, and human fingerprint, to name only a few. Here, we present a computational work, based on finite difference time domain method and evaluated by the NF-RT-FDTD algorithm [4] where we investigate the spectral and spatial behavior of the local density of states and near-field radiative heat flux in a SiC golden spiral nanostructure. The results show that additional spectral peaks occur within the *reststrahlen* band of SiC. This observation suggests that the spatial position of the source of excitation as well as the local point where the fields are obtained are factors that could be tuned to achieve desired spectral functionality in quasi-periodic or aperiodic structures which may find applications in nano-scale energy harvesting.

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Preferred mode of presentation: Oral

Dust aerosol optical depth and particle size retrieval using spaceborne lidar

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Spaceborne lidar such as the Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) on the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite provides global observation of aerosol backscatter properties [1]. Light scattering and radiative transfer computations show that in the size range of dust aerosol, both the lidar integrated depolarization ratio (IDR) and integrated color ratio (ICR) are sensitive to the effective particle size and optical depth. The IDR is the ratio of attenuated backscatter in two orthogonal polarization directions, and the ICR is the ratio of attenuated backscatter in 1064 and 532 nm wavelengths.

We develop a retrieval algorithm to simultaneously infer the dust aerosol optical depth and particle size from CALIOP IDR and ICR data. A look-up table (LUT) is built to map the IDR and ICR onto the effective particle size and optical depth. The LUT is computed by a Monte Carlo lidar simulator [2] with the input of dust aerosol single-scattering properties, optical thickness, and atmospheric profile. A hexahedron ensemble model is assumed for dust shape. The two-dimensional cubic spline interpolation and an iteration method are utilized to find an optimal solution in the LUT by matching CALIOP IDR and ICR data with the simulated counterparts.

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Preferred mode of presentation: Oral

Retrieval of microphysical characteristics of particles in atmospheres of distant comets from ground-based polarimetry

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We summarize unique aperture data on the degree of linear polarization observed for distant comets C/2010 S1, C/2010 R1, C/2011 KP36, C/2012 J1, C/2013 V4, and C/2014 A4 with heliocentric distances exceeding 3 AU. Observations have been carried out at the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (Nizhnij Arkhyz, Russia) during the period from 2011 to 2016. The measured negative polarization proves to be significantly larger in absolute value than what is typically observed for comets close to the Sun. We compare the new observational data with the results of numerical modeling performed with the T -matrix and superposition T -matrix methods. In our computer simulations, we assume the cometary coma to be an optically thin cloud containing particles in the form of spheroids, fractal aggregates composed of spherical monomers, and mixtures of spheroids and aggregate particles. We obtain a good semi-quantitative agreement between all polarimetric data for the observed distant comets and the results of numerical modeling for the following models of the cometary dust: (i) a mixture of submicrometer water-ice oblate spheroids with aggregates composed of submicrometer silicate monomers; and (ii) a mixture of submicrometer water-ice oblate spheroids and aggregates consisting of both silicate and organic monomers. The microphysical parameters of these models are presented and discussed.

Preferred mode of presentation: Oral

Fast method for computing the scattered radiation in the O₂A-band using the predictor–corrector approach

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Reflected spectra of solar radiation in the O₂A-band (750–780 nm) are used to retrieve cloud and aerosol parameters such as cloud/aerosol optical thickness and top height [1]. Calculations of hyper-spectral data with full-multiple scattering treatment are computationally expensive. Usually, accurate simulations of the measurements in this spectral region require up to several thousands of monochromatic computations. Recently, the dimensionality reduction techniques have been proposed for speeding up radiation transfer computations [2,3]. Essentially, by capturing the most significant information from the spectrum they allow to use the fast two-stream model instead of the multi-stream model without significant loss in accuracy, yet enhancing the performance by several orders of magnitude. The drawback of this approach is that the dimensionality reduction procedure introduces an additional performance bottleneck in the satellite data processing chain [4]. To further accelerate the computations, new approaches are required.

In this talk we summarize recent developments in hyper-spectral computations and present a new approach relying on the predictor-corrector procedure. Essentially, a predictor is computed by using fast approximate radiative transfer models, and then, by means of machine learning, a mapping between the approximate solution and the exact multiple scattering solution is derived. This method is also extended for weighting function computations required by cloud/aerosol retrieval algorithms. The performance of this approach is analyzed for real hyper-spectral instruments and compared against dimensionality reduction techniques.

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Preferred mode of presentation: Oral

The role of absorption in retrievals of aerosol optical and microphysical properties from measurements of absolute and polarized phase function

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In this work, the Generalized Retrieval of Aerosol and Surface Properties (GRASP) algorithm is applied to airborne, in situ measurements made by a novel polar nephelometer. This instrument, the Polarized Imaging Nephelometer (PI-Neph), can make field measurements of absolute phase function and the scattering matrix element F_{12} , at three visible wavelengths, over a wide angular range of 3° to 177° . The resulting retrieved products include size distribution, complex refractive index and fraction of spherical particles. This presentation will focus primarily on GRASP's ability to retrieve absorption from PI-Neph scattering measurements alone as well as on the possibility of improving the inversion's accuracy by incorporating an independent measurement of the aerosol absorption coefficient. The retrieval technique is applied to over 2300 aerosol measurements made aboard the NASA DC-8 aircraft during the Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC⁴RS) and the Deep Convection Clouds and Chemistry (DC3) field experiments. The resulting samples represent desert dust, biomass burning, urban, and biogenic emissions as well as a wide array of aerosols that have been influenced by convective systems. The inversion results are compared with absorption measurements made in parallel by a Particle Soot/Absorption Photometer (PSAP). When GRASP is applied to PI-Neph light scattering measurements alone a correlation ($R^2 \approx 0.4$) is found between the measured and retrieved absorption coefficients but the retrieved values are biased high by more than a factor of two. The PSAP measurements are then used, in conjunction with the PI-Neph data, as an input to the retrieval and, as is expected, the retrieved absorption values decrease markedly. Additionally, the inclusion of an absorption measurement is found to significantly influence the retrieved fraction of spherical particles and real refractive index (RRI). The spherical fraction is decreased on average by 20% and shows a meaningful reduction in the variability between neighboring samples. The retrieved RRI values also show a small decrease in variability and are generally found to increase by ~ 0.02 when absorption is included as an input to the retrieval. The interdependence among these three parameters is expected theoretically, as Mie and T-matrix computations show that, in the size and refractive index regimes spanned by these particles, changes in RRI, imaginary refractive index and spherical fraction all produce roughly similar changes in F_{11} and F_{12} .

Preferred mode of presentation: Poster

Properties of haze particles in the atmospheres of Pluto and Titan from recent space missions

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On July 14th, 2015, New Horizons performed its historic close approach of Pluto, giving humanity unprecedented observations of the dwarf planet. One of the amazing features seen was the multi-layered haze in its atmosphere [1]. The haze was detected both at visible wavelengths by the Long Range Reconnaissance Imager (LORRI) from direct imaging and in the ultraviolet by the Alice spectrograph from solar occultations. Preliminary analysis using simplified models showed that neither spherical nor 2-dimensional aggregate particles could satisfy both sets of observations [2,3]. In this work, we present a joint retrieval of haze particle properties from both LORRI and Alice data. Due to the similarity between the atmospheres of Pluto and Titan, we assumed that the haze particles have optical properties similar to those of Titan's tholins [4]. We will study the aerosol particles' shapes, sizes, and number densities and investigate their phase functions by using both forward scattering and UV extinction observations. With the combination of these two approaches, the haze particle properties can be constrained.

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Preferred mode of presentation: Oral

Numerically efficient direct solver-based full-wave model for EM scattering from complex-geometry particles

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Accurate and numerically efficient modeling of electromagnetic scattering from precipitation particles represents a crucial tool for a better analysis of weather radar/radiometer observations. In particular, the averaging of the scattering properties over different random orientations combined with a realistic complex geometry modeling, enables a better representation of the EM behavior of precipitation particle. In this context, the discrete dipole approximation (DDA) is one of the main approaches that has been used in the past as a geometry-flexible and numerically low-cost technique for computing scattering and absorption by snow particles. The open source code DDScat has been proven to be a numerically high efficient implementation of the DDA. However, since the code is based on iterative solvers, the major drawback of DDScat comes from the fact that if orientation averages are needed then computationally demanding linear equations must be solved repeatedly.

To overcome this limitation, we have chosen to apply a direct solver-based method, known as the characteristic basis function method (CBFM) [1], to the modeling of scattering by randomly oriented and complex-shaped snow particles, in a context of the Method of Moments (MoM) with a volumetric integral equation formulation. This domain decomposition technique is based on the generation of a new set of basis function adapted to the geometry of the scatterer, in order to significantly reduce the numerical size of the EM problem. This enables us to use a direct solver for the resolution of the final compressed system of linear equations, which is better adapted for multiple excitation problems. When applied to numerically medium snow particles, our CBFM based model for Coherent Scattering from Complex Hydrometeors (NESCoP) has been shown to yield good results [2], which compare well with those obtained with DDScat, while providing a significant gain in CPU time.

In this talk, we summarize the overview of NESCoP, prove its computational superiority over DDScat particularly for electrically large particles, and discuss how this work could help stimulate increased interest in solving problems involving larger complex-geometry particles, with higher number of orientations for a better understanding of the EM behavior of ice particles.

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Preferred mode of presentation: Oral

Classification of riming extent in the Arctic with the Multi-Angle Snowflake Camera

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The Rayleigh–Gans approximation (RGA) is often invoked as a simplified model for the scattering of radar energy by low-density aggregate snowflakes [1–3]. Aggregates tend to exhibit negligible riming and thus allow for an assumption of non-interference. Implicit in the use of this approximation is the assumption that such low-density aggregates comprise a significant portion of the distribution of snowflake types being observed and detected by weather radar. In order to gain a better understanding of the properties of solid hydrometeors in the Arctic, millions of ice particles in freefall have been captured by the surface-based Multi-Angle Snowflake Camera (MASC) at the Department of Energy’s Atmospheric Radiation Measurement (ARM) Mobile Facility at Oliktok Point, Alaska.

A subset of approximately 40,000 frozen hydrometeors collected between June 2016 and July 2017 have been analyzed. As a proxy for riming extent, a “complexity” variable was calculated for each particle based on inter-pixel variability and the degree of departure from sphericity, which were themselves determined using simple algorithms involving OpenCV image processing software. This riming proxy was then used to classify the particles according to riming extent. Of the total, 25% were classified as graupel (low complexity), 48% as rimed aggregates, and 27% as aggregates (high complexity). However, many of those in the latter category still exhibited some degree of riming, and the portion of those exhibiting negligible riming was less than 5% of all particles. Therefore, riming appears to be quite common. Based on prior work, this suggests that the RGA may have limited applicability, even at colder temperatures characteristic of the Arctic.

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Preferred mode of presentation: Oral/Poster

Integrating cavities and UV water absorption

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One of the most sensitive techniques for measuring a very weak spectral absorption is based on an integrating cavity. An integrating cavity is a closed container whose wall is a diffuse (Lambertian) reflector with a very high reflectivity. When a sample is placed in an integrating cavity, the result of the multiple reflections of the light from the cavity walls is that the light makes many transits through the sample, i.e., the effective path length through the sample far exceeds the dimensions of the sample. For example, the effective path length through a sample that fills a spherical cavity of radius 7.5 cm is about 100 meters if the wall reflectivity is 99.9%. The result is a very high sensitivity to a very weak absorption. In addition, since the diffuse reflecting walls of the cavity produce an isotropic illumination of the sample, absorption measurements are not affected by light scattering in the sample.

We have developed a new diffuse reflecting material that has significantly higher diffuse reflectivity in the visible than that of the best previous existing material known as Spectralon (e.g., we have obtained a 99.92% diffuse reflectivity at 532 nm versus 99.4% for Spectralon). In addition, this new diffuse reflector has a reflectivity that exceeds 99.6% at wavelengths down to 250 nm. This new material is opening new research vistas by providing very sensitive and accurate direct spectral absorption measurements of both a sample and any particulates suspended in it. As important examples we have obtained the first accurate measurements of pure water absorption in the near UV [1], and we have demonstrated the capability to measure for the first time the very weak spectral absorption of highly scattering biological samples [2].

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Some considerations on the design of micro-fabricated photovoltaics

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Planar Si substrates typically reflect about 35% of incident solar irradiance. The theory of scattering and absorption of light by Si microspheres and by Si-dielectric microsphere dimers shows that they can significantly reduce reflection losses and thereby potentially enhance the harnessing of solar power. Calculations indicate that the flux-weighted, band-averaged absorption of an array of Si microspheres can be on the order of 60% greater than that for Si thin films of equal mass. It is seen that an over layer of dielectric microspheres can also reduce reflectance losses and, in addition, concentrate energy into specific regions of the Si photodiodes. Numerical results will be presented, as will suggestions for the design of more efficient solar panels.

Preferred mode of presentation: Oral

Joint retrieval of aerosol optical properties and water leaving reflectance over coastal waters based on multi-angle polarimetric observations

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Ocean color remote sensing is an important tool to monitor water quality and biogeochemical conditions of ocean. Atmospheric correction, which obtains water leaving radiance from the total radiance measured from satellite-borne or airborne sensors, remains a challenging task over coastal waters due to the complex optical properties of aerosols and waters. The suspended sediment particles as well as the colored dissolved organic matter (CDOM) in coastal waters usually vary independently over wide range in time and space, and may share similar absorption spectrum with the absorbing aerosols in deep blue and UV. The strong backscattering over turbid waters may also contribute to non-zero water leaving signals in near infrared bands.

In this talk we report an atmospheric correction algorithm over coastal waters through the joint retrieval of aerosol optical properties and water leaving reflectance using polarized radiance measurements at multiple viewing angles and multiple wavelengths. We implement the vector radiative transfer model for a coupled atmosphere and ocean system as the forward model and generalize the bio-optical model to account for the absorption and scattering of phytoplankton, CDOM and non-algal particles (NAP). The ocean bio-optical model parameters and the aerosol refractive indices and size distributions are retrieved using the Levenberg–Marquardt optimization algorithm, and then used to calculate the atmospheric path radiance. The atmospheric correction is conducted by subtracting the atmospheric path radiance from the total radiance measured at the top of atmosphere. The retrieval algorithm is validated by synthetic Research Scanning Polarimeter (RSP) measurements. The algorithm will improve the current atmospheric correction algorithm by enabling the retrieval of ocean color under optically-complex atmospheric and oceanic conditions.

Preferred mode of presentation: Oral

Progress on an AERONET aerosol Opto-Physical Typology: defining the variable space and determination of a reference basis to produce a global aerosol climatology

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We present an aerosol classification based upon AERONET level 2.0 almucantar retrieval products from the period 1993 to 2012. We opto-physically identified five major types of Bulk Columnar Aerosol (BCA) – based solely upon intensive optical properties of spectral *Single Scattering Albedo* (SSA), spectral *Indices of Refraction* (real – RRI and imaginary – IRI), and two *Angstrom Exponents* (extinction – EAE and absorption – AAE). These BCA we classified as *Maritime Aerosol*, *Dust Aerosol*, *Urban Industrial Aerosol*, *Biomass Burning Aerosol*, and *Mixed Aerosol*. The classification of a particular aerosol observation as one of these aerosol types is determined by its five-dimensional Mahalanobis distance to each reference cluster (itself a 5-D *hyperellipsoid*). Studies with higher dimensional spaces by including other AERONET retrieved quantities, reduced the size of the global database – as not all properties were retrieved at as many sites throughout the record history. To retain a greater number of AERONET sites in the study, we kept the variable space to 5-D. We have calculated the fractional aerosol type distribution at 190 AERONET sites, as well as the monthly variation in aerosol type at those locations. The results are presented on a global map. Our aerosol typing is based on recognizing that different geographic regions exhibit characteristic aerosol types. To generate reference clusters we only keep data points that lie within a Mahalanobis distance of 2 from the data centroid. Our aerosol characterization is based on the AERONET retrieved quantities, therefore it does not include low optical depth values. The analysis is based on “point sources” (the AERONET sites) rather than globally distributed values. The classifications obtained will be useful in interpreting aerosol retrievals from satellite borne instruments and as input for regional climate models. It is evidenced that each of these five aerosol types can be further discriminated into specific *aerosol sub-types* by this same classification scheme. The application of further optical discrimination into *sub-types* of the *Biomass Burning* aerosol may provide insight into complicated *absorbing aerosol* problems.

Spectrally and angle resolved light scattering properties of graphite and expanded graphite particles

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Carbonaceous particles (amorphous carbon, graphite, carbonates, nanodiamonds, etc.) of highly irregular shapes are a major constituent of the interstellar dust and planetary regolith layers. Depending on their origin, they can be compact or fluffy aggregates of sub-micrometer to micrometer sized grains with large values of the real and imaginary parts of the refractive index and can be sometimes embedded in an absorbing mantle or in the form of composite grains. The proper study and analysis of the light scattered by interstellar dust particles is very important as such results help in remote detection and retrieval of information about their physical properties. In this context laboratory research on the properties of terrestrial interstellar dust analogues are of great astronomical importance as their properties are found to be similar to the properties of planetary regoliths, cometary dust, etc. [1].

Graphite and expanded graphite particles, which can be considered as potential candidates of interstellar carbonaceous dust analogues, are chosen as samples for our investigation. Importantly, graphite can transform into expanded graphite at suitable environmental conditions (e.g., chemical, thermal, etc.) with abrupt changes in their optical, electrochemical and mechanical properties. The knowledge of the scattering properties of such particles is essential for deducing their physical and optical properties, which in turn may give clues for understanding earlier events like formation of comets, planets, etc.

In this contribution, we report measurements of the spectrally and angle resolved light scattering properties of graphite and expanded graphite particles in the 396–625 nm optical spectrum by using a laboratory based goniometric setup. The instrument is capable of measuring the scattered light signals at scattering angles from 25° to 155° in steps of 1°. The accuracy and the reliability of the setup were verified by conducting light scattering measurements on spherical water droplets and comparing the results with theoretical Mie calculations. The experimental errors were reduced by taking the average of a large number of scattering measurements on the same set of samples. Comparisons of the experimental results with theoretical calculations will also be presented.

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Preferred mode of presentation: Oral

Biological tissue quality assessment by using light scattering goniometry and oblique incidence reflectometry

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Recent years showed a considerable interest in monitoring food quality due to an increased recognition of the risk of encountering a biological, chemical, or physical agent in the food due to adulteration or spoilage with potential adverse health effects. Notably, the biochemical composition and concentration of cells and tissues get altered due to denaturation and enzymatic degradation at different time scales resulting in a change in their light scattering properties. Thus, proper determination and interpretation of time dependent light scattering properties of biological tissues would provide valuable information for discriminating between healthy and damaged food products or for monitoring changes in their biophysical properties due to the microbial infection, stimuli, etc. [1,2].

In this contribution, we report the design and fabrication of a compact and efficient optical metrology system with the combined capability to perform both scattering and reflectance measurements to determine the scattering, absorption, and reduced scattering coefficients (μ_s , μ_a and μ'_s respectively), phase function, $P(\theta)$, and anisotropy factor, g of biological tissues at broadband (396–625 nm) incident wavelengths. Preliminary results including look-up tables which contain the measured scattering properties as a function of time dependent degree of spoilage of different food products (e.g., vegetables and fruits) will be presented. Significant differences in the values of scattering parameters were observed for healthy and rotten tissues at different measurement wavelengths. This study will be useful in the development of portable devices for efficient food quality assessment.

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Preferred mode of presentation: Oral

Measuring physical properties and heterogeneous chemistry of single airborne particles concurrently using optical trapping–Raman spectroscopy (OT–RS)

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Our current understanding of airborne particles, for example, aerosols, ice nuclei, etc., is mainly based on measurements of particle ensembles, and their fundamental physical and chemical properties are not yet completely clear. Measuring a single particle can reveal the fundamental properties of the target sample as well as view the dynamic evolving processes. Among various single-particle techniques for airborne particles, optical trapping has unique advantages: no interferences from substrates or liquid solution, no mechanical contacts, no requirement of charge, and so on. With recent developments, the optical trapping technique can trap both transparent and absorbing particles in air using a universal optical trap (UOT) based on counter-propagating hollow beams. A wide variety of particles ranging from spherical silica microspheres and droplets to irregularly shaped carbon nanotubes and bioaerosols can be stably trapped in the UOT. Both physical and chemical properties can be resolved and monitored by a microscopy imaging system and Raman spectroscopy (RS). We demonstrate the analytical capabilities of the OT-RS system in three different scenarios, 1) unchanged, 2) partially degraded, and 3) fragmented particles in the optical trap. The evolution processes of different cases are also temporally resolved. This new technique enables the studies of single particle's microphysical properties as well as heterogeneous chemistry. Furthermore, the effective fluorescence bleaching phenomenon is observed in the trapped particle, which facilitates Raman spectroscopic studies of single biological particles without fluorescence interferences.

Preferred mode of presentation: Oral

Application of the multiple-scattering modeling pipeline for spectroscopy, polarimetry, and photometry

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We present the application of a newly developed data-processing and analysis pipeline (Penttilä et al., this meeting) to analyze the reflectance spectra and photometric and polarimetric phase curves of close-packed random media. In the software suite, light-scattering characteristics of the sample are modeled using novel multiple scattering methods for close-packed random media, such as a geometric optics method SIRIS4 [1] and the radiative transfer with reciprocal transactions R^2T^2 [2]. The R^2T^2 method solves the ensemble-averaged Foldy–Lax equation involving the ladder and maximally crossed diagrams as well as the near field corrections. The near field corrections are implemented in terms of the incoherent volume element containing all the scattering diagrams that do not cancel out in the near-zone [2]. The incoherent scattering parameters of the volume elements are solved exactly by the fast superposition T-matrix method [3]. The latter enables us to extend the applicability of the radiative transfer to close-packed random media [2].

Application of the software suite to the defined close-packed random media is followed by comparison with experimental results. Among suitable planetary analog samples for the experimental study are, for example, macroscopic agglomerates formed by ballistic hit-and-stick deposition [4]. The agglomerates consist of monodisperse SiO_2 spheres and their light-scattering characteristics are thoroughly measured with the new scatterometer setup [5,6].

This work is supported by the European Research Council Advanced Grant project No. 320733, SAEMPL: “Scattering and absorption of electromagnetic waves in particulate media”.

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Preferred mode of presentation: Poster

Simulation of light scattering from compact irregular particles in a wide range of sizes

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We apply computer modeling to study light scattering properties of compact irregular particles in a wide range of size parameters from $X = 10$ to 150. As model shapes, we use faceted Gaussian Random Field Particles [1]. To solve the light scattering problem we apply the Discontinuous Galerkin Time Domain method [2]. It allows optimal spatial discretization based on unstructured meshing and excellent parallel scalability that is critical for large-scale simulations.

With such systematic variation of sizes we are able to track qualitative changes in the angular dependencies of intensity and linear polarization degree. The observed evolution of the scattering angle curves with increasing size parameter can be expected taking into account the decreasing role of light diffraction on edges and facets. Interestingly, all main linear polarization features are preserved in the entire size range. At $X = 150$ we approach the geometrical optics regime where we can apply ray trajectory analysis. This gives us insights into the light scattering mechanisms that work at smaller sizes.

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Preferred mode of presentation: Oral

Improvements to the fast parameterization of atmospheric transmittances in RRTMG

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RRTMG (the Rapid Radiative Transfer Model for GCM Applications) is one widely used broadband radiative transfer model, which currently utilizes the correlated-k distribution (CKD) approach to calculate fluxes and cooling rates. However, the accuracy and speed of CKD may not be sufficient for current climate models. In this study, we develop the transmittance equations with linearly parameterized optical depths determined from a least squares regression to improve accuracy and efficiency for atmospheric absorption simulations. We compare fluxes and cooling rates calculated by the new and original RRTMG with rigorous LBLRTM (Line-By-Line Radiative Transfer Model) calculations. In total, 6 US standard atmospheric profiles and 42 atmospheric profiles from Atmospheric and Environmental Research (AER) are used to evaluate the performance of the new RRTMG against LBLRTM simulations from wavenumber 0 to 3250 cm⁻¹.

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Preferred mode of presentation: Poster

Resolving size distribution of black carbon internally mixed with snow: impact on snow optical properties and albedo

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We develop a stochastic aerosol-snow albedo model that explicitly resolves the size distribution of aerosols internally mixed with various snow grains, based on a geometric-optics surface-wave (GOS) approach. We use the model to quantify effects of black carbon (BC) size distribution on snow albedo and optical properties for BC-snow internal mixing. Results show that BC-induced snow single-scattering coefficient enhancement and albedo reduction decrease by a factor of 2–3 with increasing BC effective radii from 0.05 to 0.25 μm , while polydisperse BC results in up to 40% smaller visible single-scattering coefficient enhancement and albedo reduction, compared to monodisperse BC with equivalent effective radii. We further develop parameterizations for BC size effects for application to climate models. Compared with a realistic polydisperse assumption and observed shifts to larger BC sizes in snow, respectively, assuming monodisperse BC and typical atmospheric BC effective radii inside snow grains could lead to overestimates of ~24% and ~40% in BC-snow albedo forcing averaged over different BC and snow conditions.

Preferred mode of presentation: Oral

Light absorption properties of coated black carbon aggregates with increasing fractal dimension

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Soot Aggregates (SAs) in the atmosphere significantly influence the earth's radiation balance, visibility, and public health. They are formed from high-temperature, incomplete combustion of fossil and biomass fuels via diffusion-limited cluster aggregation (DLCA) of spherical monomers. SAs can contain a significant amount of surface coatings of organic compounds which may alter their native fractal morphology through capillary and surface tension forces. Depending on the strength of these restructuring forces, the morphologies of SAs can be parameterized with increasing fractal dimension (D) with values ranging from $D = 1.8$ to 3.0 . We used three aggregation mechanisms—DLCA, Percolation, and Face-centered cubic stacking – to generate aggregates with $D = 1.8$, 2.5 , and 3 , respectively. This range of D closely mimics the different morphologies of real-world SAs: bare ($D = 1.8$); partially collapsed ($D = 2.5$), and fully collapsed ($D = 3$). Next, we coated these numerical aggregates with non-refractory materials using a custom-made algorithm and calculated their numerically-exact optical properties using the discrete dipole approximation (DDA) algorithm. In many climate models, SAs are approximated by an equivalent-mass core-shell spherical model due to the ease of calculating optical properties using Lorentz–Mie theory. Keeping this in mind, we computed the optical properties of core-shell spheres equivalent in mass to our coated SAs. Comparisons of the core–shell spheres with the coated aggregates showed that the mass absorption cross-sections (MAC) were significantly underestimated in the core-shell approximation with increasing particle size. Due to their porous nature, the monomers of the aggregates are entirely illuminated by the incident light while the optical skin depths of the equivalent core-shell spheres prevent the black carbon core from participating in light absorption.

Preferred mode of presentation: Oral

Light scattering measurements enabled by acoustic levitation with 3D orientation control

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We present newly developed acoustic levitation system with remote orientation control for reliable manipulation of mm-sized particles. The system allows conducting comprehensive measurements of light scattered by the sample held in place by sound. The absence of interfering sample holder in the setup (enabled by levitation) allows non-destructive measurements of the sample in all orientations [1]. The obtained measurement data, in turn, provide a more complete presentation of the Mueller matrices of the studied scatterers.

The main goal of this presentation is to explain how the choice and stability of the position, as well as orientation of the levitated samples are achieved in the course of the experiment, and how this knowledge was integrated in the levitator system.

This study is supported by the European Research Council Advanced Grant project No. 320733, SAEMPL: “Scattering and absorption of electromagnetic waves in particulate media”.

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Preferred mode of presentation: Poster

Scattering dynamics of dust in the interstellar medium

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In recent works [1,2], we have presented a full solution to the scattering problem of non-spherical particles and the corresponding dynamical problem in a numerically exact manner. The solution provides a means of studying how cosmic dust particles spin under radiative torques. In this work, we extend the previously developed dynamical integrator to take into account some dynamical effects affecting interstellar dust particles.

Several effects affecting the alignment of interstellar dust have been identified and studied [3]. In this work, we evaluate some previously applied approximations about the dynamics of spinning dust particles and the limits of the precise dynamical integration under the extreme time scale differences between scattering and magnetic field coupling effects. From this analysis, a new integration scheme is implemented and presented.

The resulting integration scheme has two parts. First, the plane of most stable spinning is identified by explicit integration methods. Second, the alignment is studied by combining the results of the first integration with the gradually aligning larger-time-scale effects. The dynamics and alignment of an ensemble of Gaussian random ellipsoids [4] modeling interstellar dust and resulting polarization are presented.

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Preferred mode of presentation: Oral

Spectrally and microphysically consistent ice particle model for application in the terrestrial troposphere

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Suspended ice particles in the terrestrial atmosphere mostly occur in the troposphere as ice clouds. The size and shape of ice cloud particles are diverse and thus their corresponding single scattering properties (e.g. single scattering albedo and phase function) since the single scattering properties are highly dependent on the particle shape, size, and internal structure. The reflection and emission by clouds are determined by the geometric structure of clouds as well as scattering properties of such diverse populations of particles.

For applications such as remote sensing and climate modeling, ice cloud particle models that represent this diverse population are indispensable. Aircraft measurements show that natural clouds cannot be modeled with particles of a single fixed shape because of the complex relation between independently measured particle volume (i.e. ice water content) and particle size. Also, multi-spectral satellite measurements indicate that the retrieved cloud optical thickness from the shortwave technique and the longwave technique are not always consistent and depend on ice particle models. These findings are strong drives for the development of a simple ice particle model that is microphysically and spectrally consistent w.r.t. these measurements.

In this study, we introduce a two-habit model that consists of roughened hexagonal column particles and ensemble of distorted column-aggregate particles. An aggregate particle consists of 20 randomly distorted hexagonal column particles. The mixing ratio of single column particles (habit 1) and the ensemble of aggregate particles (habit 2) are adjusted so that the model is consistent with the in-situ aircraft measurements. We also present the results of validation efforts on the spectral consistency to compare with other ice particle models, including the models used in the production of the Moderate-resolution Imaging Spectroradiometer (MODIS) Collection 6 cloud products and the Cloud and the Earth's Radiant Energy System (CERES) products.

Preferred mode of presentation: Oral/Poster

Development of a common framework for handling particle scattering data

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There are now many published datasets on the scattering properties of realistically shaped snow and aerosol particles. These datasets represent increasingly sophisticated attempts to match the variability and detail of particles found in nature. This wide variability has caused several problems. When constructing a scattering database, scattering formulations make various approximations in their solutions of the electromagnetic equations. They require different types of input information and output different parameters. Database creators also make varied assumptions regarding polarization, particle orientation and dielectric parameters. Their databases frequently have different conventions for reporting basic quantities such as particle length, volume, fractal dimension and aspect ratio. There is no common format for storing and distributing structural and scattering data. These issues accumulate and introduce significant challenges when validating and comparing results and, also, when incorporating results into operational algorithms [1].

To address these issues, we propose a standard specification for storing particle structural and scattering data in NetCDF. We provide a set of high-level reference libraries in C and C++ to manipulate data in this format, and invite feedback from the community. Many potential uses are foreseen. We will briefly discuss some of these, including: cross-comparisons of particle models, matching modeled snowflake structures to field campaign images, and converting between volume-based and surface contour-based representations of particle structure.

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Preferred mode of presentation: Oral

Multiple scattering of closely packed nonspherical objects using vector spheroidal waves and vector addition theorem

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Multiple scattering by spherical particles has been extensively studied and well established, where vector spherical waves are used [1,2]. However, many real-life objects are nonspherical such as dust, ice particles, and vegetation elements (e.g., branches, leaves and trunks). In this paper, we develop a hybrid method to calculate the multiple scattering of closely packed arbitrary-shaped objects, based on the rigorous solutions of Maxwell equations in the form of Foldy–Lax multiple scattering equations (FL). This method is a hybrid of the off-the-shelf techniques (e.g., HFSS) and newly developed techniques. The newly developed techniques are the three key steps of the hybrid method: (1) extracting the T matrix of each single object using vector spheroidal waves, (2) vector spheroidal wave transformations, and (3) solving FL for all the objects, which are detailed below.

The T matrix relates the incident fields to the scattered fields for an arbitrarily-shaped scatterer [1,3]. Previously, vector spherical wave expansions were used for T matrix [1, 3]. However, when the objects are closely packed, it is impractical to enclose each object by a spherical surface without overlap. In general, spheroidal surfaces are more compact to enclose closely packed objects such as clustered vegetation elements. Thus, vector spheroidal wave expansions are used here, which are more complex than the spherical waves. To extract the T matrix for an arbitrary-shaped object, we use the off-the-shelf technique HFSS which is a 3D full wave electromagnetic field simulation tool. HFSS allows the simulations of complicated structures that exist in a single object. To extract the T matrix of the single object from HFSS, we first define a spheroidal surface (∂S) which encloses the object. Then, we excite the object using incident plane waves at different incident angles and polarizations in HFSS. By numerical integration of the scattered fields from HFSS with the vector spheroidal waves over ∂S , the vector spheroidal wave expansion coefficients of the scattered waves are obtained. Since the expansion coefficients of the incident plane waves are known [3,4], the T matrix is extracted. It is noted that the T matrix extraction method works for arbitrary-shaped objects, including those required a spheroidal surface with a large aspect ratio (e.g., branches with leaves). The second step is vector spheroidal wave transformations. To find the scattered fields from object a to object b , the outgoing spheroidal waves centered at object a need to be transformed to incoming spheroidal waves centered at object b , which is also called translation addition theorem. We develop robust numerical methods to perform wave transformations for vector spheroidal waves. Finally, the extracted T matrices for the single objects are substituted to FL, and the FL is solved utilizing the numerical wave transformations. In solving FL, the coherent wave interactions among the objects are considered and the multiple scattering of all the objects is calculated. The hybrid method using vector spheroidal waves has applications such as full wave simulations of trees which can be decomposed into single nonspherical objects (e.g., trunks and branches with leaves).

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Preferred mode of presentation: Oral

Radiative-transfer modeling of spectra of planetary regoliths using cluster-based dense packing modifications

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Over the last several decades, a wealth of remote sensing data has been collected for various solar system objects. However, the development of analysis techniques that lead to quantitative interpretations of such datasets has been comparably deficient, especially for regoliths with particle sizes on the order of or smaller than wavelength of light utilized for remote sensing. Radiative transfer theory has often been applied to the study of densely packed particulate media like planetary regoliths, but with difficulty, and here we continue to investigate radiative transfer modeling of spectra of densely packed particulate media. We use the superposition T-matrix method to compute scattering properties of clusters of particles and capture the near-field effects important for dense packing. Then, these scattering parameters are modified with the static structure factor correction, accounting for the dense packing of the clusters themselves. Using the corrected scattering parameters, reflectance (or emissivity via Kirchhoff's Law) is computed via the invariant imbedding solution to the scalar radiative transfer equation. We modeled the emissivity spectrum of the 3.3 μm particle size fraction of enstatite, representing a common regolith component, in the mid-infrared ($\sim 5\text{--}50 \mu\text{m}$). The use of the static structure factor correction coupled with the superposition T-matrix method produced better agreement with the corresponding laboratory spectrum than the sole use of the T-matrix method. This work demonstrates the importance of proper treatment of the packing effects of the clusters themselves when modeling semi-infinite densely packed particulate media using finite, cluster-based light scattering models.

Preferred mode of presentation: Oral

Status and development of the Community Radiative Transfer Model (CRTM)

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The Community Radiative Transfer Model (CRTM) is a fast, 1-D radiative transfer model designed to simulate top-of-the-atmosphere radiances consistent with a wide variety of satellite-based sensors [1]. The CRTM was primarily developed by JCSDA-funded scientists with essential contributions from NOAA/STAR and NOAA/EMC scientists. The primary goal of CRTM is to provide fast, accurate satellite radiance simulations and associated Jacobian calculations under all weather and surface conditions. CRTM supports all current operational and many research passive sensors, covering wavelengths ranging from the visible through the microwave. The model has undergone substantial improvement and expansion, since the first version in 2004. The CRTM has been used in the NOAA/NCEP and U.S. Navy operational data assimilation systems and by many other JCSDA partners such as NOAA/NESDIS/STAR, NOAA/OAR, NASA/GMAO, Naval Research Laboratory, Air Force Weather, and within multiple university environments. Over the past 14 years, both external research groups and operational centers alike have made essential contributions to the continued development and growth of CRTM.

A major goal of the CRTM core team is to ensure that CRTM becomes a true community radiative transfer model for all users. The CRTM official baseline code is developed and maintained based on internal and community-wide inputs, consisting of both improvements and externally contributed codes.

This presentation will briefly review the scientific and technical basis of CRTM, including its many strengths and limitations. There will also be an overview of the current status of the recently released CRTM version 2.3.0; and the future planned release of CRTM version 3.0.0 – which will represent a major milestone in CRTM’s development and capabilities.

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Preferred mode of presentation: Oral

Active-subspace analysis of speckle patterns

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Laser speckle measurements have been used to optically characterize samples such as rough surfaces [1] and ensembles of particles [2–4]. The approach relies on linking, theoretically or heuristically, certain statistical properties of the measured speckle pattern with the macroscopic properties of the sample. For example, the mean speckle intensity and the width of the speckle autocorrelation function (the characteristic ‘size’ of the speckle) may be related with the refractive index and concentration of particles in an aerosol.

In this talk we present an active-subspace analysis [5] of some statistical parameters of the speckle pattern for laser light transmitted through a water suspension of microparticles. Such analysis can yield directions in the space of macroscopic sample parameters along which the speckle measurements are the most or the least sensitive. This, in turn, can qualify the obtained estimates of sample parameters in the presence of uncertainty. Our analysis is non-asymptotic, and can therefore also account for suspensions of electrically large particles.

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Preferred mode of presentation: Oral

Light scattering by ultrasonically levitated particles: system design

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We present the design of a scatterometer for accurate measuring of the full angular Mueller matrix profile of mm- to μm -sized samples held in place by sound. The aim of this project is to enable research on single particles of highly valuable materials in a non-contact and controlled manner. The scatterometer comprises a tunable multimode Argon-krypton laser, with 12 wavelengths in visible range, linear polarizers, a reference photomultiplier tube (PMT) for monitoring the laser beam intensity, and one or 14 PMTs mounted radially towards the sample at an adjustable radius. The measurement angle is controlled by a motor-driven rotational stage with an accuracy of 15' [1]. The system is entirely implemented using LabVIEW, including the FPGA-based data acquisition and the instrument's user interface. The built-in FPGA allows for data transfer as well as efficient data processing in the case of using multiple channels, which is our next step.

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Preferred mode of presentation: Oral

In-situ atmospheric particle imaging with a portable digital holography instrument

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Digital holography is a contact-free imaging method that does not require trapping or otherwise preparing the imaged particle prior to the measurement. We have designed and are currently manufacturing a proof-of-concept model for a lightweight digital holography instrument that can capture holograms of freely flowing particles, sizes ranging from tens of micrometers up to millimeters, in the atmosphere, and developed the necessary algorithms to automatically reconstruct the particles' two-dimensional silhouettes, with additional limited three-dimensional information [1].

The current estimate for the mass of the instrument is approximately 5 kg with batteries, light enough to be flown on an off-the-shelf Unmanned Aerial System (drone), with approximately 20–30 minutes of flight and measurement time between landings. The current material cost estimate for one model is roughly \$10K, not including the platform, such as a drone.

The instrument concept, if proven successful in the upcoming test campaign, will allow imaging large atmospheric particles almost anywhere in the lower boundary layer with minimal set-up required, and with very low operational costs. We expect the instrument will greatly add to the knowledge of coarse-mode aerosol particle morphology by providing statistically significant amount of measurements that have been slow, costly, and in some cases impossible to perform thus far.

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Preferred mode of presentation: Oral

Spatial and temporal distribution of cloud properties observed by MODIS

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Cloud properties have been retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) over 18 years of continuous observations from Terra and nearly 16 years from Aqua. A comprehensive set of operational algorithms for the retrieval of cloud physical and optical properties (optical thickness, effective particle radius, water path, thermodynamic phase) have been updated using the new ‘Collection 6.1’ processing stream and are publically available through the MODIS Adaptive Processing System (MODAPS) at NASA GSFC [1]. The archived products from these algorithms include 1 km pixel-level (Level-2) and global gridded Level-3 products. The cloud products have applications in climate change studies, climate modeling, numerical weather prediction, as well as fundamental atmospheric research. In this talk, we will summarize the available Level-3 cloud properties and their associated statistical data sets, and show Terra and Aqua results from the available Collection 6.1 reprocessing effort. Results include the latitudinal and spatial distribution of cloud optical and radiative properties for both liquid water and ice clouds, as well as joint histograms of cloud optical thickness and effective radius for selected geographical locations around the world.

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Preferred mode of presentation: Oral

Conjugated random Gaussian particles model and its application for interpretation of cometary polarimetric observations

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Cometary dust consists of particles of complex composition, shape and structure. Rigorous modeling of light scattering by such particles is very computer time and memory consuming. Moreover, an adequate shape of irregular particles is often hard to be mathematically described. Often cometary dust particles are described as random Gaussian spheres [1]. Based on this approach, we are presenting a model of conjugated random Gaussian particles. This model combines the advantages of random Gaussian spheres of different types since it has a rough surface, both on large and small scales, which makes it convenient for simulations of irregular particles.

A computer simulation of the polarimetric properties of such particles was carried out using the *Sh*-matrix technique [2]. This method is based on the T-matrix technique [3] and was developed after it had been found that the shape-dependent factors could be separated from the size- and refractive-index-dependent factors and presented as a shape matrix, or *Sh*-matrix. Size and refractive index dependences are incorporated through analytical operations on the *Sh*-matrix to produce the elements of the T-matrix. We survey the angular and spectral dependencies of the intensity and polarization resulting from light scattering by such particles, studying how they depend on the particle shape, size, and composition. Polarimetric observations of comets were interpreted, their possible physical and chemical characteristics were inferred, and the range of their variations within which the model is capable to describe the observed data was determined.

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Preferred mode of presentation: Poster

Light scattering by complex ice crystals using the Boundary Element Method

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The Boundary Element Method (BEM), also known as the Method of Moments, or Surface Integral Equation Method, has recently been shown to be a competitive computational method for simulating light scattering problems [1,2]. BEM is a flexible tool offering accurate simulations even for complex scatterer configurations. BEM involves reformulating the Maxwell's equations into integral equations on the boundary of the scatterer(s). This requires the solution of large linear systems on the boundary and then extension of the solution to the interior and exterior of the scatterer via the Stratton-Chu representation formulae.

In recent years, certain strategies have been investigated to try to speed up the iterative solution of such large linear systems, including Calderón preconditioning [3] and the use of novel basis functions [4]. In this talk, we will discuss recent developments in the solution of dielectric scattering problems using BEM, the extension of these ideas to scattering by multiple dielectric objects, and their implementation in the software library Bempp [5]. Bempp is an open source library offering fast and accurate simulation of electrostatic, acoustic and electromagnetic scattering problems.

Of particular interest to us are cases of light scattering by ice crystals found in cirrus clouds [6,7]. We will demonstrate how one can use the above theory and the Bempp library to efficiently solve examples of light scattering by single and multiple ice crystals of complex shape.

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Preferred mode of presentation: Oral

Atmospheric correction with polarization

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Atmospheric correction removes the effects of the atmosphere from the top of atmosphere (TOA) signal and reveals the surface. The adding-doubling, matrix operator, and similar methods detach the atmospheric effects (path radiance, diffuse reflectance, and transmittance) from the surface reflectance [1]. At the expense of a 1% error in the TOA signal, we neglect the radiation bouncing at the atmosphere–surface boundary. Thus, the TOA signal becomes directly proportional to the surface reflectance. The linear least squares method readily gives the coefficients for linear parameterization of the surface reflectance.

In our algorithm, we use three surface models. The Ross Thick – Li Sparse (RTLS) model [2] simulates the scalar reflection in the surface Mueller matrix. For other elements, we use a linear combination of the vegetation and bare soil models [3]. When the atmosphere is removed, we retrieve weights at the vegetation and soil using the PARASOL data, the RTLS, and aerosol parameters from MAIAC [4], and the aerosol optical thickness from AERONET. Our discrete ordinates radiative transfer code IPOL (Intensity & POLarization), thoroughly tested in [5], simulates diffuse atmospheric transmittance and the path radiance. IPOL decouples the atmosphere and surface using the matrix operator method.

To prove the concept, we will demonstrate the error analysis for thin and moderately thick atmospheres as well as the results of the inversion.

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Preferred mode of presentation: Oral

Inherent uncertainties in radiation simulations of the influence of clouds on the climate

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The energy equilibrium between solar and terrestrial radiation defines the state of the climate. When the energy absorbed from incoming radiation is larger than the energy lost through outgoing radiation, the global average temperature rises, and temperature declines in the reverse case. To study the influence of radiation on the climate, the commonly applied method is to use GCMs (General Circulation Models) to simulate the results of a current or future scenario. However, the methods to calculate the radiation field, especially where clouds exist, cause different uncertainties in the flux and heating rate simulations. Due to the highly anisotropic scattering properties of clouds, accurate flux and heating rate calculations are time consuming. Therefore, GCMs use approximations [1,2] as a compromise between accuracy and efficiency of radiation calculations.

In this study, we quantify the uncertainties in the flux and heating rate calculations by using different radiation simulation methods in both visible and infrared spectral bands. Moreover, the potential impacts on climate projections due to radiation simulation uncertainties will be presented by using the cloud microphysical and optical properties obtained from MODIS (Moderate Resolution Imaging Spectroradiometer) retrieval products.

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Preferred mode of presentation: Poster

A model for analysis of fractal aggregate aerosols

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Our knowledge in aerosols in planetary atmospheres comes mostly from remote sensing and radiative transfer modeling. Accurately constraining physical properties of aerosols requires accurate radiative transfer modeling which requires accurately obtaining scattering properties of aerosols. There are many different methods to calculate the scattering properties. However, for non-spherical aerosols, such as the Titan's haze, this is a challenging problem [1]. Some methods provide high accuracy, at the expense of high computational cost; others usually lack high precision while providing fast calculations. Previously a fast, physically based semi-empirical model for fractal shape aerosols was used to calculate Titan's aerosols particle [2]. Although this model is promising in terms of both accuracy and computational cost, it has not been tested for particles with monomer numbers (N) larger than a few hundred. Still, it has been used to estimate scattering properties of particles with several thousand monomers [2,3].

In this project, we tested this model for fractal aerosols with N up to 1024 for a number of choices of refractive indices, size parameters (α), and aggregate shapes. For the validation, we created a database of scattering properties with 25 realizations for each choice using multi sphere T-matrix model (MSTM) [4]. With the available testing so far, we concluded that the parameterization requires some modifications. For example, in most cases as one of the variable increases errors also increase especially when matching with larger α . Phase functions usually fit well with small error except for small phase angles coinciding with the occurrence of coherent backscattering effect which is not modeled in the initial version of this model. Absorption modeled well, but parameterization quickly fails to calculate valid scattering efficiencies for larger parameters.

In this talk, we will discuss this model and its validation with our T-matrix database. We will also discuss our future plans in the extension of the validation, modification in the parameterization and the possible applications of this model and our extensive T-matrix database for planetary aerosols studies.

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Preferred mode of presentation: Oral

Using MSTM to model geometrically complex space weathered particles

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Space weathering can be defined as the gradual changes experienced by the surfaces of airless planetary bodies due to exposure to the vacuum of space, radiation, and micrometeoroid bombardment [1]. Characteristic visible/near-IR spectral changes due to space weathering include a decrease in albedo and a general “reddening” of spectra (increasing reflectance with increasing wavelength). Apollo-returned lunar soils contain grains hosting amorphous rims with nanophase metallic-iron particles (npFe⁰) dispersed throughout. Absorbing particles of this scale (tens of nm) have very strong optical effects relative to their abundance. The size of the npFe⁰ particles determines the amount of reddening observed with smaller particles being associated with redder spectra than larger particles. In laboratory data, a transition occurs at a particle size of ~30–50 nm, above which the spectra darken without reddening. Previous modeling work has failed to robustly reproduce this transition at the observed iron particle size, instead requiring larger particles [2].

We present work using the Multiple Sphere T-Matrix method [3] to model space weathered olivine particles. We construct each particle out of a host grain of olivine, a thin (tens to hundreds of nm) amorphous silica rim, and a number of iron particle inclusions outside the host, but within the rim. We then explore the dependence of the modeled reflectance on the abundance and size of iron nanoparticles. Additionally, we construct small clusters of these grains in order to model more realistic multiple scattering cases that are more comparable to remote sensing and laboratory data.

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Preferred mode of presentation: Oral

Retrieval of ice cloud properties from HIMAWARI-8 satellite measurements with Voronoi light scattering model

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Single-scattering properties of the Voronoi habit model are calculated by a combination of the finite-difference time-domain (FDTD) method, Geometric Optics Integral Equation (GOIE) technique, and geometric optics method (GOM) for use in ice-cloud remote sensing [1,2]. A Voronoi scattering database is implemented in the forward radiative transfer model (RTM) to develop a look-up table for the cloud property retrievals.

The CAPCOM algorithm [3] is improved to retrieve ice cloud properties from MODIS and HIMAWARI-8/AHI satellite measurements. Ice cloud properties from the AHI measurements are compared to MODIS collection-6 ice cloud products for characterizing the retrieval accuracy of the Voronoi model. Furthermore, downward shortwave radiative flux in cloudy sky is calculated by the implemented RTM model.

In this presentation, we will introduce the scattering properties of the Voronoi model and retrieval accuracy of the ice cloud parameters from the AHI data.

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Preferred mode of presentation: Oral

Use of non-spherical aerosol models within the Dark Target aerosol retrieval over ocean

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The Dark-target (DT) aerosol retrieval has been running operationally on Moderate-resolution Imaging Spectrometer (MODIS) since 2000 (Terra) and 2002 (Aqua), creating a time series of spectral aerosol optical depth (AOD) over land and ocean. Recently, DT is also running on Visible Infrared Imaging Radiometer Suite (VIIRS) aboard Suomi-NPP. Over the ocean, the DT algorithm is known to provide biased retrievals of AOD, Angstrom Exponent (AE) and fine mode weighting (FMW), especially in scenes known to be dust of African or Asian origin. We believe that these biases arise from not using appropriate dust optical models, which in the current algorithm are assumed to be spherical. This leads to wrong phase functions which leads to AOD and AE biases which are dependent on angles. We have been experimenting with a two-step process for retrieving dust aerosol: (i) detection of dust using combined deep-blue, visible and IR radiances, then (ii) using lookup tables (LUTs) derived from non-spherical models for the retrieval. What optical properties should we be using to create the LUTs in step (ii)? Here, we generated ensembles of LUTs using different dust shapes (spheres, spheroids, ellipsoids) from different codes (GRASP and earlier versions) and databases (Texas A&M), each time characterizing the retrieval sensitivity on size, shape, refractive indices, and volume vs surface area equivalency assumptions. We have tested on sample MODIS granules and show how the different models/assumptions affect the retrieval of AOD and AE as a function of solar/observing geometry.

Preferred mode of presentation: Oral or Poster

A systematic comparison of the optical properties of spheroids and super-ellipsoids with implications in optical modeling of dust aerosols

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Atmospheric dust particles are known to have diverse irregular morphologies. In order to account for the non-sphericity, the spheroidal model with a distribution of aspect ratios has been extensively used for modeling the optical properties of dust aerosols. The spheroidal model is superior to the spherical shape assumption but still has shortcomings. For example, the aspect ratio distribution is unrealistic or even suffer spectral inconsistency. Due to additional degrees of morphology freedom, the super-ellipsoidal model can mimic the aspect ratio, roundness and concavity characteristics of realistic dust aerosols. Note that the super-ellipsoids are non-spherical at the aspect ratio of unity. This study presents a comprehensive comparison of the optical properties of spheroids and super-ellipsoids. The invariant imbedding T-matrix method (II-TM) [1–3] is employed to compute the single-scattering properties of super-ellipsoids with a number of roundness/concavity parameters. Then we assess the applicability of spheroidal model and super-ellipsoidal model for simulating the optical properties of different dust samples from the Amsterdam-Granada Light Scattering Database [4]. It is found that extreme aspect ratios for spheroids in reproducing the measurements are unnecessary if super-ellipsoids are employed. Specifically, we will highlight the use of a newly defined shape index (SI) of super-ellipsoids ($SI = 3V / [4\pi(S/\pi)^{3/2}]$, where V is the volume and S is the average projected area, $SI = 1$ for a sphere) in conjunction with the aspect ratio to characterize the non-sphericity of aerosol samples. Different non-spherical particles with close shape index are found to have strong optical similarity.

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Preferred mode of presentation: Poster

Ray optics for absorbing particles with application to NIR scattering by ice crystals

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Light scattering by particles large compared to the wavelength of incident light is traditionally solved using ray optics which considers absorption inside the particle approximately. To study the effects arising from this simplification, we have updated the ray-optics code SIRIS [1–3] to take into account the propagation of light as inhomogeneous plane waves inside an absorbing particle following the methodology presented in [4]. We investigate the impact of this correction on traditional ray-optics computations in the example case of light scattering by ice crystals through the extended near-infrared (NIR) wavelength regime, where the refractive index of ice has a high spectral dependence.

We show that the correction for inhomogeneous waves systematically increases the single-scattering albedo throughout the NIR spectrum for both randomly-oriented, column-like hexagonal crystals and ice crystals shaped like Gaussian random spheres. We also present results for the scattering-matrix elements that show generally minor differences. We evaluate the correction for inhomogeneous waves through comparisons against the discrete exterior calculus (DEC) method [5], and our comparisons at two NIR wavelengths agree that the consideration of the inhomogeneous waves brings the ray-optics solution generally closer to the exact result.

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Preferred mode of presentation: Poster

The scattering and absorption properties of black carbon aggregates: from numerical aspect

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This study focuses on the scattering and absorption properties of black carbon (BC) aerosols, and presents the capabilities of numerical modeling on understanding BC optical properties. The effects of particle non-sphericity and inhomogeneity on BC optical properties are extensively discussed. Realistic BC particles can be well represented using the fractal aggregates, and various numerical models (e.g. RDG, MSTM, DDA, and et al.) with quite different accuracies are capable to simulate their corresponding optical properties. Those models used for light scattering properties of BC aggregates are systematically compared, and, by considering both the efficiency and accuracy, the MSTM shows great performances. The geometries of fractal aggregates are improved to account for particles minor structures (such as coating, different-sized monomers, monomer necking and overlapping) on the optical properties, and a simple numerical model is developed to consider the effects of non-absorption coating. Our results indicate that the non-sphericity and inhomogeneity of BC particles should be considered for further applications such as BC measurement and radiative transfer, whereas the minor structures are not as important as previously demonstrated.

Preferred mode of presentation: Oral/Poster

Sensitivity study of the radiance to optical and microphysical properties of nonspherical dust aerosols

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Aerosols influence the atmospheric radiation balance not only through directly absorbing and scattering solar radiation, but also altering the radiation properties of clouds by acting as cloud condensation nuclei. Tropospheric aerosols have been considered the most uncertain part of the climate forcing [1]. For a cloud-free and dusty pixel, the radiance measured by the airborne instrument is affected by the optical depth and single-scattering properties. Single-scattering properties are mainly determined by particle size, complex refractive index and particle aspect ratio [2].

To understand and quantify how much these parameters affect the visible and infrared radiance measured by the Airborne Multiangle SpectroPolarimetric Imager (AirMSPI), the sensitivities of the radiance to the optical and microphysical properties (i.e., particle size, complex refractive index and particle aspect ratio) of nonspherical aerosol were studied at the wavelengths of AirMSPI's bands with polarization (i.e., 470, 660, and 865 nm) [3]. An existing tri-axial ellipsoidal mineral dust aerosol database was employed to carry out this study [4,5]. This study will benefit the development of aerosol retrieval algorithm with polarization and multi-angle AirMSPI data.

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Preferred mode of presentation: Poster

Negative extinction in one-dimensional scattering

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It has recently been shown [1] that negative extinction can occur for scattering of an electromagnetic plane wave by a dielectric spherical particle in an absorbing medium. This result can be interpreted as more energy per second leaving the scattering volume than enters it. The same effect is shown to occur when an electromagnetic plane wave in an absorbing medium is normally incident on a plane-parallel dielectric slab. This one-dimensional geometry has the advantages that the scattered wave consists only of transmission and reflection, and that it is exactly analytically solvable. The transmitted plus reflected fraction of the incident energy per second exceeds 100% for certain slab thicknesses. This is because the phase of a wave reflected at an interface between dielectric and absorbing materials is shifted from its value for reflection at an interface between two dielectric materials. This leads to the maxima and minima of the composite reflected intensity being phase shifted with respect to the minima and maxima of the composite transmitted intensity, thus causing the illusion of excess energy. The amount by which energy conservation is seemingly violated is exactly compensated by the contribution to the Poynting vector describing incident/reflected wave interference. This contribution vanishes when the medium is dielectric, and is non-zero only when the medium is absorbing. It results from the phase shift of the magnetic field of the waves in the absorbing medium with respect to their electric field.

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Preferred mode of presentation: Oral

Humblet's angular momentum decomposition applied to terahertz radiation torque on metallic spheres in the Hagen–Rubens approximation

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When circularly polarized light is scattered by isotropic spheres, Humblet's decomposition [1] is helpful for understanding why the axial projection of "spin-related" scattered angular momentum transport gives incomplete information concerning the total radiated angular momentum [2,3]. Some of the radiated angular momentum is found to be "orbital-related." This application of Mie scattering gives insight into why classical electromagnetic radiation torques are proportional to absorbed power for isotropic spheres [4]. It also reveals the direct measurability (from Stokes parameters) of the contributions to the radiated angular momentum. The relative angular momentum components [2,3] were also derived by others [5] and applied to dielectric spheres.

This talk considers metallic spheres illuminated by circularly polarized light modeled with Mie theory in the Hagen–Rubens approximation (HRA) in which the real and imaginary components of the sphere's refractive index are equal in magnitude [6]. (The HRA was anticipated by Maxwell's suggestion to neglect displacement currents to give a diffusion equation for the vector potential in metals. It is useful for some non-magnetic metals for terahertz and lower frequencies provided the Drude collision rate and plasma frequency are sufficiently large.) It was found helpful to compare the "spin efficiency factor" Q_{spin} introduced in [2,3] with the canonical scattering efficiency factor Q_{sca} for varying sphere sizes at a fixed frequency. A small-size limiting case [2,3] is recovered while novel structure for larger sizes is revealed. The limiting case for small sizes is associated with a common classical interpretation of dipole-related torque [2,4].

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Preferred mode of presentation: Oral

Spectroscopic, photometric, and polarimetric modeling of asteroid (4) Vesta

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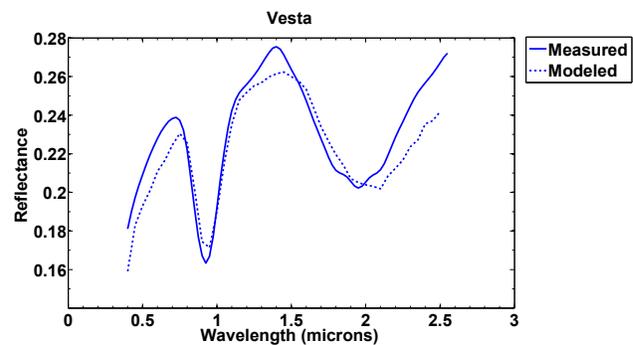
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We present a novel simulation framework for modeling the spectroscopy, photometry, and polarimetry of asteroid (4) Vesta. The spectral modeling is carried out by utilizing a SIRIS4 – a code that takes inhomogeneous waves into account and simulates light scattering by Gaussian-random-sphere particles large compared to the wavelength of the incident light [1,2]. The code uses incoherent input and computes phase matrices by utilizing incoherent scattering matrices [3,4]. In order to model Vesta's reflectance spectrum, we first derive the complex refractive indices of howardite mineral abundant on Vesta's surface. The derived values are then further utilized in SIRIS4 with a specific particle size distribution to obtain the final spectrum. We also model Vesta's photometric phase curve and, with the same model, explain the observed opposition effect and negative linear polarization.

This research is funded by the ERC Advanced Grant No. 320773 (SAEMPL).



The measured and modeled reflectance spectrum of (4) Vesta at 15-degree phase angle.

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Preferred mode of presentation: Oral

A 2D demo of adjoint methods for 3D remote sensing

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We are developing multi-dimensional retrievals to improve the performance of remote sensing technologies near horizontal cloud edges. In earlier work, we derived the adjoint method as a computationally efficient path to three-dimensional (3D) retrievals [1]. In this talk we will show a proof-of-concept of the adjoint method using new two-dimensional (2D) radiative transfer calculation [2]. We call this simplified 2D radiative transfer code the Fourier Series Discrete Ordinate Method (FSDOM).

Using FSDOM, we generated multi-directional measurements for several synthetic cloud fields and then retrieved the cloud optical density as a 2D function of the horizontal and vertical coordinates. The retrieval algorithm minimizes the measurement misfit function with a gradient-based, quasi-Newton approach. The use of a gradient-based retrieval algorithm is important because adjoint methods allow us to compute the gradient of the misfit function with only two calls to FSDOM, regardless of the number of measurements and unknowns.

Our synthetic retrievals verify that adjoint methods are scalable to retrieval problems with many measurements and unknowns. In all cases, the vertically-integrated optical depth is recovered as a function of the horizontal coordinate. In cases where the clouds are separated by clear regions, it is possible to also retrieve the vertical profile of the cloud near its edge. In some sense, it is the horizontal heterogeneity of the cloud that enables us to retrieve its vertical profile. So, using 2D radiative transfer (relative to 1D radiative transfer) actually increases the amount of information that is available for retrieving the vertical profile.

These synthetic retrievals show that adjoint methods can efficiently compute the gradient of the misfit function, and encourage our ongoing efforts to develop 3D radiative transfer codes with adjoint derivative calculations.

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Preferred mode of presentation: Oral

Approximation to the diffraction limit of three-dimensional shapes using the scaling approach

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A scaling approach for understanding features such as power laws and cross over points of the light scattered in the diffraction or $m \rightarrow 1$ limit, where m is the relative index of refraction, is presented. The scaling approach is a semi-quantitative approach to describing the behavior of the structure factor of an arbitrary collection of scatterers, be it a dense three-dimensional particle, fractal aggregate or a collection of scatterers within a scattering volume [1,2]. The focus here will be on single three-dimensional orientationally averaged homogenous particles. In the scaling approach instead of considering the particle itself as being rotated, it is instead the scattering wave vector q that can take on all possible directions. Instead of being a vector, q can be thought of as a spherical region with radius q^{-1} . We show that for three-dimensional shapes such as hexagonal columns, spheroids, cylinders, and square columns the average behavior, power laws, and cross over points of the structure factor can be described by a single parameter ϵ which is the aspect ratio of the shape.

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Preferred mode of presentation: Oral/Poster

Single scattering albedo of homogeneous, spherical particles in the transition region

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The aerosol single scattering albedo (SSA) is the dominant intensive particle parameter determining the aerosols radiative forcing in the earth's atmosphere [1–3]. We use Mie theory to examine the behavior of SSA as a function of size parameter x and complex refractive index m for homogeneous spherical particles. Previously, we investigated the limiting cases of the small particle limit ($x \ll 1$) and the large particle limit ($x \gg 1$), where SSA is proportional to x^3 and independent of the size parameter x , respectively [4]. In between these cases lies the transition (or peak) region, where SSA transitions from the small to the large particle regime and, for sufficiently small imaginary parts of the refractive index, shows one or more peaks.

Here, we investigate the behavior of SSA in the transition region including conditions on the complex refractive index for peak formation, peak location, and general properties of SSA as function of size parameter.

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Preferred mode of presentation: Oral/Poster

Single scattering albedo of agglomerated debris particles and homogeneous spheres: a comparison

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The aerosol single scattering albedo (SSA) is the dominant intensive particle parameter determining aerosol radiative forcing in the earth's atmosphere [1–3]. We build on previous work that used Mie theory to examine the behavior of SSA as a function of size parameter x and complex refractive index m for homogeneous spherical particles [4,5].

Here, we investigate the behavior of SSA as a function of size parameter x for agglomerated debris particles [6] that are a much more realistic model for atmospheric mineral dust particles than homogeneous spheres. We use discrete dipole approximation (DDA) calculations to obtain SSA as function of size parameter and imaginary part of the refractive index. These results are compared with Mie theory results for homogeneous spherical particles and we show that SSAs for agglomerated debris particles and homogeneous spheres converge in the small particle and geometric optics regimes if complex refractive indices are adjusted properly using effective medium theory [7]. However, in the intermediate transition regime there are substantial differences in the SSAs of these two types of particles that greatly affect their radiative forcing.

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Preferred mode of presentation: Oral

Multiple scattering in discrete random media using incoherent interactions

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We consider scattering and absorption of light in discrete random media of densely packed spherical particles. The particle size is assumed to be of the order of the wavelength. First, we extend the numerical Monte Carlo method of radiative transfer and coherent backscattering (RT-CB, [1]) to the case of dense packing of particles [2]. We adopt the ensemble-averaged first-order incoherent extinction, scattering, and absorption characteristics of a volume element of particles as input for the RT-CB. The volume element must be larger than the wavelength but smaller than the mean free path length of incoherent extinction. In the RT part, at each absorption and scattering process, we account for absorption with the help of the single-scattering albedo and peel off the Stokes parameters of radiation emerging from the medium in predefined scattering angles. We then generate a new scattering direction using the joint probability density for the local polar and azimuthal scattering angles. In the CB part, we utilize amplitude scattering matrices along the RT path and the reciprocal path, and utilize the reciprocity of electromagnetic waves to verify the computation. Second, in what we term radiative transfer with reciprocal transactions (R^2T^2 , [3]), we derive the volume-element scattering and absorption characteristics using the Superposition T -Matrix Method (STMM, e.g., [4]), and compute its incoherent volume-element scattering characteristics. Using an order-of-scattering approach (resembling that in RT-CB), we then compute a numerical Monte Carlo solution for the scattering problem with an exact treatment of the interaction between two volume elements. We compute both the direct and reciprocal contributions along a sequence of volume elements, allowing us to evaluate the coherent-backscattering effects. Finally, we show that the dense-medium RT-CB and R^2T^2 solutions are in agreement with the exact STMM solutions for large finite systems of densely packed spherical particles [2,3]. We study the effect of the finite volume-element size on the computation of the incoherent scattering and absorption characteristics for the elements themselves as well as for the entire discrete random media.

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Preferred mode of presentation: Oral

Hierarchical clustering of the precomputed signals database to solve the parametric inverse light-scattering problem

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Light scattering is a powerful proxy for non-invasive characterization of single particles through the solution of the inverse light-scattering (ILS) problem. In most cases one a priori specifies the particle model with several free parameters, which are determined by non-linear regression, i.e. by fitting an experimental signal (typically, a light-scattering pattern – LSP) with the simulated ones. Finding a global minimum of the residual in the space of particle parameters may require thousands of simulations, making direct fit unrealistic.

This computational bottleneck is alleviated by preliminary computing a database of theoretical signals, using a super-computer, for specific class of particles. The ILS problem then boils down to finding the nearest neighbor in this database. A by-product of the direct search is the distances between an experimental signal and all entries in the database. They are further used in a statistical analysis to estimate not only the best-fit parameters, but also their confidence ranges (uncertainties) [1]. This approach has been successfully used to characterize several classes of biological cells in a flow using the LSPs measured with a scanning flow cytometer [1,2]. These cells were described by 4–5 parameters and databases had up to 6×10^5 entries. The processing of each experimental LSP took about 1 second on a desktop, which is still far from real-time, considering measuring speed of 100 particles per second.

The goal of this work is to further decrease the processing time by hierarchically clustering the precomputed database in the form of a binary tree. Knowing the radius of each cluster, i.e. the maximum distance between its element and a center, we can rigorously discard some of the clusters entirely during the nearest-neighbor search. First results show at least ten-fold decrease of number of distance calculations, and hence, of the processing time. Importantly, this reduced number of distances is sufficient for the above-mentioned statistical analysis, approximating the missing distances by that to the center of the corresponding discarded cluster. Overall, the clustering decreases the computational complexity of ILS solution down to almost logarithmic in the database size, which potentially allows much larger databases (hence, better accuracy) with small extra computational costs (apart from one-time investment for the database itself).

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Preferred mode of presentation: Oral/Poster

Regional variations of ice microphysical properties near the tops of deep convective cores implied by the GPM dual frequency radar observations

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Using three-year GPM dual frequency radar observations, precipitation systems are defined by grouping the contiguous pixels with surface precipitation detected by radar. Then radar reflectivity profiles are selected at the location with the tallest radar echo top in each individual precipitation systems. The properties of these profiles above 10 km are examined, focusing on the Dual Frequency Ratio (DFR) between Ku and Ka band radar reflectivity. DFRs near the top of continental convection are found larger than those over ocean in general. This implies larger ice particles in the convective cores over land. To validate this, simple ice particle size distribution retrieval lookup tables are created using simulations of reflectivity at Ka and Ku band with idealized gamma size distributions. Applying these lookup tables to the GPM observed reflectivity profiles, the properties of ice particle size distributions at the top of deep convective cores are derived. Then, the global geographical distribution of the mass median ice particles in the deep convection are constructed. Under a same and simple PSD assumption, larger ice particles are found near the top of deep convection over land than over ocean. The size of the ice particles increases in deep convection with stronger convective intensities indicated by higher echo top height of 30 dBZ. The distributions of number concentration of ice particles and ice water contents retrievals are also presented and discussed.

Preferred mode of presentation: Oral/Poster

Internal traveling waves, energy trapping, and energy release in time domain simulations of incident Gaussian-pulse scattering by single particles

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Time-domain simulations of single particle scattering involve cpu intensive near-field calculations. When the incident electromagnetic energy is in the form of a time-localized burst, the question of how long the simulations must be run becomes one of how long it takes for near-field amplitudes to decay to a negligible level. Examination of near-field decay of electromagnetic energy in pseudo-spectral time-domain simulations of Gaussian-pulse interactions with single particles shows presence of intermittent episodic bursts of amplitude. These bursts have been traced to the release of electromagnetic energy transiently trapped within the particles. The trapped energy is organized in the form of waves continually traveling within the particles. The waves have amplitudes that are generally maximal near but inside particle boundaries, and the observed near field episodic bursts appear to be results of either interactions between separate traveling maxima, or entrance of individual maxima into boundary regions of increased curvature. We present some examples of the interactions in the case of simple particle shapes and present a simple mathematical model in which factors determining the location of traveling wave amplitude maxima and the speed of propagation can be understood.

Preferred mode of presentation: Oral

Validating polarization implementations in 3D MCRT codes

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In astronomy, Monte Carlo Radiative transfer codes (MCRT) are often used to disentangle the interplay of the optical properties and the spatial distribution of cosmic dust. The majority of these codes are not able to calculate any polarization maps.

I will present the codes SKIRT and MC3D, in which we implemented the polarization of light due to scattering and extinction by dust. Our codes are capable of calculating the full Stokes vector (I, Q, U, V) for scattering of light by spherical grains, electrons, as well as scattering and extinction by aligned spheroids. In contrast to the implementations of other MCRT codes, ours uses co-moving reference frames that rely solely on the physical processes. This reduces the number of calculations and avoids certain numerical instabilities.

I will discuss analytical test cases that we developed to verify our implementations. These can be used in addition or instead of benchmarks comparisons with other codes, where the true solution is often unknown [1].

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Preferred mode of presentation: Oral/Poster

3D radiative transfer code for polarized scattered light with aligned grains

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Polarized scattered light has been observed in cometary comae [1] and in circumstellar disks [2]. It carries information about the grains from which the light scattered. However, modelling polarized scattered light is a complicated problem. So far, most scattering codes consider either optically thin cases, where radiative transfer is not necessary, or only do one-dimensional (1D) radiative transfer. Three-dimensional (3D) radiative transfer is mainly focused on unpolarized radiation, which is easier to calculate.

We are working on a 3D Monte Carlo radiative transfer code, based on the unpolarized CRT code [3,4], which incorporates hierarchical grid structure (octree) and the full Stokes vector for both the incoming radiation and the radiation scattered by dust grains. The dust model will be able to include different populations of dust, differing in composition, size distribution, shapes, and orientation. The non-spherical dust grains can be randomly aligned, or a fraction of them can be aligned with the magnetic fields (in particular, by the radiation field via radiative torques). However, the inclusion of the non-spherical, aligned grains is a complicated and time consuming task. The final code will be a valuable tool in studying polarized scattered light from cometary comae in the solar system and from protoplanetary disks in the exoplanetary context.

We summarize the current state of the code, presenting comparison tests with the radiative-transfer coherent-backscattering code (RT-CB, [5]) and a simple model of a protoplanetary disk.

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Preferred mode of presentation: Poster

Multiple scattering modeling pipeline for spectroscopy, polarimetry, and photometry

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We are combining a set of numerical tools to analyze the reflectance spectra of granular materials, i.e., close-packed random media. Our motivation for this study comes from the present lack of such tools when it comes to intimate mixing of materials, including space-weathering effects with nano- or micron-sized inclusions in the host matrix. The current common practice is to apply a semi-physical approximate model such as some variation of the Hapke models (e.g., [1]) or the Shkuratov model [2]. These models are expressed in a closed form so that they are relatively fast to apply. They are based on simplifications to the radiative transfer theory. The problem is that the validity of a model is not always guaranteed, and the derived physical properties related to particle scattering properties can be unrealistic [3]. The Hapke space-weathering model does not include a correct size dependence for the nanophase iron inclusions [4].

Our numerical tool consists of individual scattering simulation codes and a main program that chains them together, calling the codes and converting the output of one code into the input for the next code. The chain for analyzing a macroscopic target with space-weathered mineral would go as follows: (1) Exact methods such as FaSTMM [5] solving the Maxwell equations of the small inclusions in the system. (2) Scattering by a single regolith grain is solved using a geometrical optics method SIRIS4 [6] accounting for surface reflections, internal absorption, and possibly the internal diffuse scattering. (3) The radiative transfer simulation R^2T^2 ([7] and Markkanen, Väisänen, and Muinonen, this meeting) is executed inputting the regolith grains from the previous step as the basic scatterers in a macroscopic planar volume element.

The tools in the proposed chain already exist, and the practical task for us is to tie these together into an easy-to-use public toolchain, i.e., a pipeline for spectroscopy, polarimetry, and photometry.

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Preferred mode of presentation: Oral

Deep Learning for optical characterization of individual laser-trapped particles

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The inverse problem in light scattering theory (i.e., the characterization of particles from optical signals) constitutes one of its most important applications. High accuracy measurements and models are needed to accurately infer physical and/or chemical particle properties from optical signals (e.g., phase function, polarization, Raman scattering). Inferring physical characteristics (e.g., size, refractive index, type) of light-scattering particles can be extremely difficult (or sometimes impossible) if the inversion solution is not unique or if an appropriate model is not available. Here we investigate the inverse problem for Raman and elastic scattering and fluorescence data without the use of light scattering models.

The U.S. Army Research Laboratory has developed a laser trap for absorbing as well as non-absorbing particles. Trapped particles can be optically interrogated and an amalgamation of optical data can be measured (e.g., extinction, degree of polarization, Raman scattering). Such optical data can be treated as points in a multi-dimensional mathematical space of all measured quantities.

Here, we address the following fundamental questions:

- 1) Can Deep Learning techniques infer physical and/or chemical particle properties without using light scattering models?
- 2) If particles are subject to aging due to ultraviolet radiation, is the method robust enough to identify these particles by properties unaltered by aging?
- 3) Can we identify the optical signal of a few particles in a background of many different other particles?

The answers to these questions have potential uses in aerosol detection, particularly relevant to early warning for chemical or biological agents.

Preferred mode of presentation: Poster

DDA/RTE hybrid method for predicting the scattering properties by densely packed media

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The increment of the particle density in a target significantly affect the interference between scattering fields by these particles, so the single scattering properties become questionable in densely packed media. Many geophysical materials, i.e., snow, bare soil and regolith surfaces are dense particulate matters and to retrieve their optical characteristic, an exact and fast methodology which applies to packed particle conditions is required.

Methods based on the direct simulation are the most accurate approaches to compute the directional scattering properties; however, such techniques become problematic for optically thick targets due to the large-scale computations. Radiative transfer theory (RTT), on the other hand, fails to model directional reflectance and transmittance characteristics of particulate media with volume fraction larger than 5% [1] due to the far-field assumption, e.g., particles are located in the far-field zone of each other.

In this work, a hybrid methodology composed of the exact and numerical radiative transfer equation is described and applied for particulate materials with large volume fraction. For exact method, a new plane wave plane parallel (PWPP) algorithm [2], based on the discrete dipole approximation, has been used to predict the reflection and transmission matrices for layer sufficiently thick to account for particle interaction effects. Then the optically thick properties are obtained by applying the adding and doubling method on the layer.

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Preferred mode of presentation: Oral

Infrared spectroscopic imaging of complex samples

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Morphology-dependent infrared (IR) spectral response of materials is of contemporary practical need in the analysis of biological and synthetic materials. While significant work has recently been reported in understanding the spectra of thin films [1] and single particles with well-defined geometries (such as spherical [2] and cylindrical [3]), we report here on samples that consist of collections of particles with various packing density from sparse to dense. Within the framework of the T-matrix methodology [4], we theoretically model the importance of multiple scattering effects and computationally predict the impact of local particles' environment on the recorded IR spectra of monodisperse and polydisperse particles clusters with various degree of packing. Fourier-transform IR (FT-IR) spectra of clusters of electromagnetically coupled polymethyl methacrylate (PMMA) spheres with wavelength-scale diameters were recorded and compared to simulated results. Measured spectra agreed well with those predicted. Of note, when PMMA spheres occupy a volume greater than 18% of the focal volume, the recorded IR spectrum becomes almost independent of the cluster's morphological changes. This threshold, where absorbance starts to dominate the signal, matches the percolation threshold for hard spheres and quantifies the transition between the single particle and bulk behavior. Our finding enables an understanding of the spectral response of structured samples and points to appropriate models for recovering accurate chemical information from IR microspectroscopy data. The universality of this conclusion is of crucial importance for FT-IR microspectroscopy: one could simply neglect the morphology of the target if the target is packed densely enough, or for thicker samples.

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Preferred mode of presentation: Oral

A spectral method to detect particle's non-sphericity from its light-scattering pattern

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Measuring angle-resolved light-scattering patterns (LSPs) of single particles is a powerful approach for their non-invasive characterization. However, most of the practical methods rely on the knowledge of particle shape model, applicability of which can be questionable in real applications. While some methods are resistant to small deviations from the ideal model [1], it is hard to control the smallness of this deviation and, hence, of the incurred error of the retrieved particle characteristics. We consider the simplest scenario – the deviation of particle morphology from a homogeneous sphere. While the brute-force fit of an experimental LSP with the simulated ones can provide estimation of non-sphericity, it is statistically rigorous only if an alternative shape model (e.g., a spheroid) is considered. The latter brings one to the original problem of extra prior assumptions.

Thus, it is fundamentally interesting and practically important to detect and even characterize nonsphericity directly from the LSP. Adhering to a simple ideology of direct calculations in contrast to fitting, we approach this problem through the Fourier spectrum of the LSP. Recently, we developed a method to determine size and refractive index of homogeneous spherical particles through the amplitude spectrum [1]. The amplitude spectrum is stable to small shape distortions, which is good for characterization, but bad for detection of non-sphericity. Thus, in present work we additionally considered the phase spectrum. The latter is rarely used in signal processing due to the lack of the reference point, but the LSP does have such point – an exact forward direction.

We developed a direct method to estimate the sphericity of individual particles from their LSPs, measured with the scanning flow cytometer. Specifically, in addition to two previously used parameters of the amplitude spectrum, the location of the non-zero peak and zero-frequency amplitude [1], we introduced a parameter of the phase spectrum – its value at the spectral peak. In the framework of the Rayleigh–Gans–Debye approximation, we derived the formulae relating this parameter to the aspect ratio of a spheroid. Due to their direct nature, they can also be used for other shapes to estimate the effective aspect ratio. In generalizing this approach to the Mie theory, we found a pronounced dependence on the refractive index, which need to be compensated. Alternatively, the phase can also be used to determine the refractive index of spheres with better accuracy or in a wider range.

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Preferred mode of presentation: Oral/Poster

Optical properties of dust in gassy comet 2P/Encke and in dusty comet 67P/Churyumov–Gerasimenko from observations and modeling

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Previously, from photometric and polarimetric observations of the dust-rich comet 67P/Churyumov–Gerasimenko at the 6-m telescope of the SAO RAS in 2015–2016, we revealed that the dust color (g-r)-sdss in the near-nucleus area was red, 0.84 ± 0.05^m , and then gradually became bluer, reaching $\sim 0.4^m$ at a distance of ~ 40000 km, while linear polarization initially sharply decreased within the first 5000 km from $\sim 8\%$ to $\sim 2\%$ and then gradually increased, reaching $\sim 7\%$ at 36000 km.

We present new results on the spatial variations of polarization and color of dust in the dust-poor comet 2P/Encke obtained at the 6-m telescope in January 2017. As in the case of comet 67P/C-G, we found that the near-nucleus area is redder and more polarized than the adjacent coma. The dust color BC(4429/36 Å)–RC(6835/83 Å) gradually changed from 1.0^m in the innermost coma to about 0.3^m in the outer coma. At the same time, the corrected for gas contamination radial profiles of polarization in the r-sdss filter showed that the polarization in the near-nucleus area was almost 12%, dropped sharply to 6% at the distance 3000 km, and then gradually increased with projected distance from the nucleus, reaching 12% at 12000 km.

Thus, the similar radial variations of polarization and color in both gassy comet Encke and dusty comet 67P/C-G suggest a change in particle properties and, hence, in the mean scattering properties on a time-of-flight timescale. To reveal the properties of scattering particles, the *Sh*-matrix method was used. We considered cometary dust as random Gaussian particles distributed over the cometary coma with the power law X^{-n} , where n depends on the projected distance from the nucleus. The main goal of this simulation was to find such parameters of model particles that would be in agreement with observational data. In the case of comet Encke, we considered the cometary dust to be a mixture of particles of three types: silicates, organic matter, and water ice. Our simulations allowed us to determine the microphysical parameters of these model particles which demonstrated a good agreement with observational data. On the other hand, in the case of comet 67P/C-G, the cometary dust was represented by particles of a single type which decayed with distance from the nucleus. Calculations showed that the physical decay of particles can also explain the spatial variations of polarization and color of dust in the comet.

Preferred mode of presentation: Oral

Light scattering tool to typify sub-micron particles in relevance to biomedical science

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Light scattering by small particles is one of the most prevailing and non-invasive tools for examining the properties of particulate systems. It has several applications in particle characterization and remote sensing of micron and sub-micron particles in the form of aerosols, interplanetary dust, nanoparticles, bacteria, biological cells etc. Experimental light scattering technique alone may not be sufficient to provide complete information about scattering properties of some sub-micron particles especially particles of biological origin. This calls for need to make use of theoretical approach and computer simulation based on the established theories as an additional tool for typifying such particles. The sub-micron particles including the bio-particles were so chosen because of their importance in biology and biomedical sciences. Light scattering investigation from homogenous sub-micron particles and bio-particles, both pathogenic and non-pathogenic types were carried out at different wavelength of incident light, by using an original designed and fabricated polar and azimuth-dependent light scattering setup. The most favourable cell density or concentration to which single scattering regime could be considered was found out before carrying out experimental investigation of such particles. Simulations of light scattering of these particles were also carried out using a novel Monte- Carlo simulation technique. The closeness of agreement or disagreement between experimental, theoretical and simulated result will be discussed in this paper. Our work is dedicated towards discussions mainly on the divergence found between the experimental and theoretical result, which provides a better insight into particle characterization. Furthermore, the results directs towards importance of inclusion of azimuthal dependency in conducting light scattering experiment.

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Preferred mode of presentation: Oral

Retrieval of optical thickness and droplet effective radius over vertically inhomogeneous water clouds

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Marine water clouds play an important role in the Earth-atmosphere system through their radiative effects and microphysical processes. Since scattering properties of spherical water droplets are well known through the Mie theory, we can infer cloud droplet effective radius (CDER) and cloud optical thickness (COT) from solar reflectivity at visible and near-infrared wavelengths (the so-called bispectral method [1]) through the radiative transfer equation using a simplified atmosphere-cloud model, i.e. the single-layer plane parallel homogeneous (PPH) cloud assumption. By using the method, satellite remote sensing techniques have provided a global picture of CDER as well as COT for a couple of decades. However, in general clouds are known as vertically inhomogeneous scattering media and strictly speaking, the PPH assumption is not applicable to water clouds in nature. In fact, several studies demonstrated that satellite CDER retrievals are affected by vertical inhomogeneity of CDERs [2].

In this study, we propose an improved retrieval method, which incorporates CDER vertical inhomogeneity, using the Moderate Resolution Imaging Spectroradiometer (MODIS) visible and two near-infrared reflectances/radiances and the CloudSat radar reflectivity profile. In this study, we will demonstrate radiative impacts and retrieval biases associated with CDER vertical inhomogeneity over the global open ocean.

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Preferred mode of presentation: Poster

Insight into power-law structure of scattering curve

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Electromagnetic scattering by small particles shows an overall power-law structure [1,2]. In this talk, we will present our work on the scattering patterns of wavelength-scale spheroidal particles. The scattering patterns were numerically simulated using Mie theory, T-matrix, and discrete dipole approximation (DDA) methods. Both far-field scattering patterns and internal fields were studied. We will have a deeper look into the reasons for the crossovers in the power-law structure. How the second crossover relates to the particle properties and the conditions for the second crossover to exist will be discussed.

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Preferred mode of presentation: Oral

Estimation of snow albedo reduction by light absorbing impurities using a Monte Carlo radiative transfer model

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Radiative forcing and climate change greatly depend on earth's surface albedo and its temporal and spatial variation. The surface albedo depends on the surface characteristics and ranges from 5-10% for calm ocean waters to 80% for some snow-covered areas. Clean and fresh snow surfaces have the highest albedo and are most sensitive to contamination with light absorbing impurities that can greatly reduce surface albedo and change overall radiative forcing estimates. Accurate estimation of snow albedo, as well as understanding of climate feedbacks from changes in snow-covered areas, is important for radiative forcing, snow energy balance, and predicting seasonal snowmelt and runoff rates. In particular, light absorbing particles from wildfires, if deposited onto snow surfaces, can greatly alter snow albedo and have been identified as a major contributor to regional climate forcing if seasonal snow cover is involved. However, uncertainty associated with quantification of albedo reduction by these light absorbing particles is high. Light absorbing particles can be mineral dust, black carbon (BC), brown carbon (BrC), or complex mixtures of them. So far, scientific work has focused on dust and BC and very little is known about the role of BrC.

We have applied a simple "Monte Carlo ray/photon tracing approach" to calculate the albedo of pure snow using fundamental optical constants [1]. Parametrization of single scattering parameters (i.e., single scattering albedo $\tilde{\omega}$ and asymmetry parameter g of pure snow was based on fractal, droxtal, and hollow column geometries along with spheres [2]. The single scattering parameters of impurities (from Siberian peat fire) were extracted from observation-based size distribution information and retrieved refractive index values from datasets obtained during laboratory combustion of biomass samples. Prior to any kind of multiple scattering calculation, Refractive indices of both snow and impurity were internally (using volume mixing rule of effective medium approximation) and externally mixed (where snow and smoke aerosols particles treated separately. In our Monte Carlo Approach, we have considered multiple scattering to be the "collection" of single scattering events. Using this approach, we vary the effective snow grain size and impurity concentrations to explore the snow albedo over a wide wavelength range (200–2000 nm). Results will be compared with those of the SNICAR two-stream model (<http://snow.engin.umich.edu/snicarcode>) for snow radiative transfer to better understand the differences in snow albedo computation between plane-parallel methods and statistical Monte Carlo methods.

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Preferred mode of presentation: Oral/Poster

Insights into atmospheric aerosol particle morphology from simulations of single-particle light scattering

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Characterizing the distribution of aerosol particles in Earth's atmosphere is a challenging endeavor. Traditionally, aerosol distributions are extracted from land-based and space-based measurements of light scattering. However, in order to invert light scattering data to characterize aerosol distributions, the light scattering properties of the constituent particles must be known. Although the scattering properties of homogenous spherical particles are well known, the same is not true for nonspherical particles. In this work, we explore different models of nonspherical aerosol particles and test our models using light scattering from real atmospheric aerosol particles. In particular, using an image autocorrelation method which was previously devised, we quantify features in the light scattering patterns from atmospheric aerosol particles. Using three different models for nonspherical particles (i.e., spheroids, Chebyshev, and inclusions) we calculated simulated light scattering patterns and performed the autocorrelation analysis on these simulated patterns. We then compared the results of the analysis of the simulated particles to that of the experimentally captured atmospheric aerosols particles. We found that the calculated light scattering patterns from simulated spheroids particles were the best match to the experimentally captured light scattering patterns from atmospheric aerosol particles.

Preferred mode of presentation: Poster

Light scattering and absorption by fractal aggregates including soot

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The problem of how fractal aggregates, and in particular soot fractal aggregates, scatter and absorb light is important in many applications ranging from in situ diagnostics of soot formation in flames to the radiative effects on the global environment. The foundational description for fractal aggregate scattering and absorption is the RDG fractal aggregate (RDGFA) theory which assumes that the light interacts with the aggregate so weakly that there is no internal coupling, or equivalently, no internal multiple scattering within the aggregate [1].

Here we address the question of how well the RDGFA describes fractal aggregate scattering and absorption. This has been addressed extensively in the past but never in a comprehensive, systematic manner which we provide here. We restrict our study to DLCA fractals with a fractal dimension of 1.8. Two monomer size parameters, 0.157 and 0.314, were studied and the number of monomers per aggregate ranged from 1 to 503. The optical properties studied were the forward scattering intensity, the angular scattering as parameterized by the scattering wave vector and the total absorption cross section. We find deviations from RDGFA of ca. 10% to 40% increasing with monomer size and monomer refractive index real part, decreasing with refractive index imaginary part, and fairly constant with aggregate size.

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Preferred mode of presentation: Oral

Snapshot imaging polarimeter for satellite aerosol remote sensing

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We discuss the development of a multispectral snapshot imager–polarimeter (MSIP) as one of the instruments intended for the Aerosol-UA space project with the main objective to study the global distribution and the physical properties of aerosol particles and clouds in the Earth’s atmosphere by measuring the polarization state and spectral characteristics of the scattered solar radiation [1]. The main requisite characteristics of the MSIP to meet the experiment purposes are discussed. The optical layout of the polarimeter’s channels is designed. It allows the determination of the linear polarization of the scattered radiation and performing photometric measurements. The polarimeter consists of three optical channels with a $60^\circ \times 60^\circ$ FOV across and along the satellite path at the Earth surface. The instrument measures Stokes parameters I , Q , and U at central wavelengths 410, 555, and 865 nm and with a spectral FWHM of 20 nm. The image-separation system of the MSIP provides the separation of the initial input image into four parallel equal images that are polarized by four sheet polarizers with azimuths 0° , 90° , 45° , and 135° . The MSIP spatial resolution is 6 km in the projection on the Earth surface, which corresponds to the instantaneous field of view of the ScanPol polarimeter. The number of scattering angles for measuring the single observation area is at least 15. The results of testing an experimental version of one of the MSIP optical channels are presented. A numerical polarimetric model for the multi-spectral imager–polarimeter MSIP is developed. The model allows determining the corrections for output signals of the MSIP to improve the quality of polarization measurements and provide orbital intercalibration of the ScanPol and MSIP polarimeters.

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Preferred mode of presentation: Oral/Poster

Near-field thermal radiation in many-body nanosystems with the discrete dipole approximation

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When two or more particles are separated by distances smaller than the characteristic thermal wavelength, the radiation exchange is said to be in the “near-field” regime and may exceed the blackbody limit by several orders of magnitude [1]. Several variations on the discrete dipole approximation (DDA), a well-known numerically exact method for calculating scattering by small particles [2], have recently been applied to predict near-field thermal emission and radiation heat transfer among particles [3–5]. If they are spheroidal, smaller than the characteristic wavelength, and separated by a distance greater than the effective radius, the particles may be represented as point dipoles and the radiation exchange is solved exactly with the many-body radiative transfer theory [3,4]. When these conditions are not met, the particles may be discretized into subvolumes to calculate the radiative heat transfer [5]. However, the stochastic nature of the interaction matrices when thermal sources are used imposes limitations on solution methodologies typically used with the DDA, which creates computational challenges for large particles, small separation distances, or many particles.

In this talk we review the application of the DDA to near-field thermal radiation among small particles, and we summarize solution methodologies and limitations for different size and separation distance regimes. We describe notable results for each case, and we discuss options moving forward to achieve computationally efficient solutions for near-field thermal radiation in many-body nanosystems.

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Preferred mode of presentation: Oral

T-matrix simulations of light scattering by densely packed nonspherical particles

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Combining the T-matrix method with the translation addition theorem for spherical vector wave functions (SVWFs), the superposition T-matrix method (STMM) [1, 2] offers excellent solutions to multiple-scattering problems, when light scattering by large ensembles of spherical particles or sparsely distributed nonspherical particles are considered. In fact, the STMM requires that adjacent particles' circumscribing spheres not intersect [3]. Hence, it is not suitable for clusters formed by densely packed nonspherical particles.

In this communication, we discuss an alternative formulation of the translation operator for SVWFs based on a plane wave expansion (PWE) [4]. In contrast to a spherical wave expansion (SWE), which is valid everywhere outside a particle's circumscribing sphere, a PWE can express the correct scattered electromagnetic field everywhere below or above a bounding plane of a particle. This holds true, even if it is constructed from the SWE [5]. Hereby the PWE enables to couple scattered fields of adjacent particles in close vicinity. The plane wave coupling formalism is integrated into the conventional superposition T-matrix scheme, allowing its utilization in large particle systems, whenever its use is necessary.

We demonstrate the suitability of our approach by comparing it to finite element method simulations of densely packed systems of arbitrary oriented, high aspect ratio particles. Finally, we discuss the method's suitability for far- and nearfield computations, for both dielectric and metallic particles of convex surface shape.

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Preferred mode of presentation: Oral

Advanced characterization of aerosol size properties from measurements of spectral optical depth using the GRASP algorithm

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This study evaluates the potential of using aerosol optical depth (τ_a) measurements to characterize the microphysical and optical properties of atmospheric aerosols. With this aim, we used the recently developed GRASP (Generalized Retrieval of Aerosol and Surface Properties) code for numerical testing of six different aerosol models with different aerosol loads. The direct numerical simulations (self-consistency tests) indicate that the GRASP-AOD retrieval provides modal aerosol optical depths (fine and coarse) to within 0.01 of the input values. The retrieval of the fine mode radius, width, and volume concentration is stable and precise if the real part of the refractive index is known. The coarse mode properties are less accurate, but they are significantly improved when additional a priori information is available. The tests with random simulated errors show that the uncertainty in the bimodal log-normal size distribution parameters increases as the aerosol load decreases. Similarly, the reduction of the spectral range diminishes the stability of the retrieved parameters. In addition to these numerical studies, we used optical depth observations at eight AERONET locations to validate our results with the standard AERONET inversion products. We found that bimodal log-normal size distributions serve as useful input assumptions, especially when the measurements have inadequate spectral coverage and/or limited accuracy, such as lunar photometry. Comparisons of the mode median radii between GRASP-AOD and AERONET indicate average differences of 0.013 μm for the fine mode and typical values of 0.2–0.3 μm for the coarse mode. The dominant mode (i.e., fine or coarse) indicates a 10 % difference in mode radii between the GRASP-AOD and AERONET inversions, and the average of the difference in volume concentration is around 17% for both modes. The retrieved values of the fine-mode $\tau_a(500)$ using GRASP-AOD are generally between those values obtained by the standard AERONET inversion and the values obtained by the AERONET Spectral Deconvolution Algorithm (SDA), with differences typically lower than 0.02 between GRASP-AOD and both algorithms. Finally, we present some examples of application of GRASP-AOD inversion using moon-photometry and the airborne PLASMA sun-photometer during ChArMEx summer 2013 campaign in the western Mediterranean.

Preferred mode of presentation: Oral/Poster

Detecting oriented dust with novel polarization lidar

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Dust orientation is an ongoing investigation in recent years [1]. Its potential proof will be a paradigm shift for dust remote sensing, invalidating the currently used simplifications of randomly-oriented particles. Dust orientation can be directly measured with a polarization lidar designed to target the off-diagonal elements of the backscattering matrix which are non-zero only when the particles are oriented [2]. Scattering calculations of realistic-shaped oriented dust particles are needed for designing this novel polarization lidar and further utilizing its measurements in advanced oriented-dust microphysical property retrievals. Currently there is no complete solution for calculating the scattering properties of the whole range of dust sizes, shapes and refractive indices. The Amsterdam Discrete Dipole Approximation (ADDA) [3] has been proven to adequately reproduce the backscattering properties for irregular-shaped dust particles with size parameters smaller than 20 [4]. For larger sizes ADDA calculations are challenging, due to high computational cost [3].

We present the preliminary design of our novel polarization lidar system based on first results of ADDA scattering calculations for irregular-shaped oriented dust particles with size parameters up to 50.

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Preferred mode of presentation: Oral/Poster

Comparison of geometric optics and radiative transfer in discrete random media

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We will simulate multiparticle media composed of Gaussian particles with geometric optics (GO), and with radiative transfer (RT). The RT assumes the medium to be ergodic, whereas in the GO, rays are traced inside a static mesh. The goal is to study the difference between the light-scattering characteristics from an ergodic medium and a mesh presenting a discrete random medium. The studied medium will be spherical, densely packed, and composed of Gaussian particles.

Preliminary results of this work will be presented. The GO part will be carried out with the extended version of SIRIS4 [1,2]. The current implementation supports only one Gaussian particle, so the code needs to be reworked to support arbitrary meshes. The RT part of the work will be done by simulating scattering by Gaussian particle with SIRIS4. The output is then used as an input for a RT simulation, which can be computed with the same code.

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Measuring single-particle absorption from elastic light scattering patterns of complex aggregates

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It is well known that elastic light scattering of aerosol particles depends upon particle morphology. However, for nonspherical atmospheric aerosol particles, the relationship between particle morphology and atmospheric light scattering is incredibly complicated. In this work, we explore a possible method for charactering an individual particle's absorption by analyzing the two-dimensional angularly-resolved optical scattering (TAOS) pattern of the particle. In particular, for a complex aggregate, the scattering cross-section of a particle is strongly dependent on the overall size of the aggregate as well as the absorptive properties of the particle. By performing an auto-correlation analysis of the TAOS pattern, we can estimate the size of the aggregate independent of its absorption. In addition, we can measure, within the constraints of our experimental geometry, an approximate scattering cross-section. With these two quantities (i.e. the scattering cross-section and nominal particle size) we can roughly estimate the absorption of the particle. This approach was tested by simulating the scattering from a cluster of spheres using the T-matrix method. We will present the results of this simulation showing how the technique works as well as some preliminary analysis of TAOS patterns collected from actual atmospheric aerosols.

Preferred mode of presentation: Poster

Response of aerosols toward drought: a view from climate–chemistry model

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Drought is a period of time when precipitation is below average in a given region, which affects not only agricultural activities but also air quality. Considering aerosols, drought can reduce wet scavenging and affect their chemical production. Previous study shows that surface PM_{2.5} concentrations increase 26% in the southern US during severe drought in 2011 and suggests that cloud process could be a key factor controlling PM_{2.5} concentration during drought period [1]. Furthermore, it was found that most climate-chemistry models underestimate sulfate during drought, which may be attributed to reduction of sulfate production in clouds during drought period [2]. In this presentation, a climate chemistry model, CESM CAM-Chem is used to capture the response of sulfate and SOA to drought, with a focus on in-cloud formation of aerosol species.

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Preferred mode of presentation: Poster

Best-fit degree of ice particle surface roughness based on the reflection and polarization properties of clouds

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As an important shape parameter in the ice particle model, ice particle surface roughness substantially affects single scattering properties of ice particles and remote sensing retrievals [1,2]. Current operational satellite retrieval algorithms commonly assume that ice cloud pixels are horizontally homogeneous with a fixed degree of roughness. The degree of roughness that best represents scattering properties from remote sensing measurements needs to be understood.

In this work, ice particle models are tested against reflectance as a function of scattering angle from multi-directional measurements. The Airborne Multiangle SpectroPolarimetric Imager (AirMSPI) is an airborne instrument to provide high-resolution multi-directional polarized reflectance measurements [3]. Various ice particle roughness models are applied to multi-directional total reflectance and polarized reflectance from AirMSPI to retrieve the best-fit degree of roughness. Moreover, to investigate the effect of considering polarization properties on retrievals, the best-fit roughness retrieved from polarized reflectance is compared with those from total reflectance.

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Preferred mode of presentation: Oral/Poster

Retrieving dust refractive index in the thermal infrared from AIRS and MODIS observations: information content analysis and case studies

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Mineral dust contributes over half of the total mass of atmospheric aerosols emitted from global continental sources, causing significant radiative impact in the infrared (IR) spectrum. Large uncertainty exists in the estimation of its IR radiative forcing due to limited knowledge of spectral refractive index. In this research, we quantify the information contained in observations as obtained from a paired combination of sounder and imager measurements, i.e., the Atmospheric Infrared Sounder (AIRS)'s hyperspectral IR radiance and Moderate resolution Imaging Spectroradiometer (MODIS) Aerosol Optical Depth (AOD). A variety of ancillary data are used to provide additional constraints towards a reliable retrieval, which include particle size distribution from the Aerosol Robotic Network (AERONET) and aerosol heights from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP). In addition, the Principal Component Analysis (PCA) is applied to the spectra of dust refractive index, which can effectively reduce the spectral redundancy. We found that five principal components are sufficient to explain more than 97% variance of real or imaginary part of refractive index in IR.

We apply UNL-VRM [1] (www.unl-vrtm.com) to simulate AIRS radiances and the Jacobians of AIRS radiances with respect to these PC's weighting coefficients which are in turn used for information content analysis. MODIS AOD is used as part of the observation vector, while AERONET particle size distribution and CALIOP aerosol height are used as model parameters for UNL-VRM and their uncertainties are considered in the information content analysis. These simulations cover an entire AIRS's spectral range of 3.7 – 15.4 μm . We then identify an optimal subset of AIRS channels for constraining dust spectral refractive index through sequential forward selection technique [2]. These results are theoretical basis for using paired sounder-imager observations to constrain dust spectral refractive index. Some preliminary results of using real data for a dust case in the mid-east will also be shown.

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Preferred mode of presentation: Oral

Coupled retrieval of water cloud and above-cloud aerosol properties using AirMSPI

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The Airborne Multiangle SpectroPolarimetric Imager (AirMSPI) has been flying aboard the NASA ER-2 high altitude aircraft since October 2010. AirMSPI acquires radiance and polarization data in bands centered at 355, 380, 445, 470*, 555, 660*, 865*, and 935 nm (the asterisk denotes polarimetric bands). In sweep mode, georectified images cover an area of 80–100 km (along track) by 10–25 km (across track) between $\pm 66^\circ$ off nadir, with a map-projected spatial resolution of 25 meters.

An optimization algorithm is developed to retrieve liquid water cloud properties including cloud optical depth (COD), droplet size distribution and cloud top height (CTH), and aerosol above cloud properties including aerosol optical depth (AOD), single scattering albedo and microphysical properties. The retrieval is composed of three major steps: (1) retrieval of an initial estimate of the mean droplet size distribution across the entire image of 80–100 km along-track by 10–25 km across-track from polarimetric cloudbow observations; (2) coupled retrieval of image-scale cloud and above-cloud aerosol properties by fitting the polarimetric data at all observation angles; and (3) iterative retrieval of pixel-scale COD and droplet size distribution by establishing relationships between COD and cloud droplet size and fitting the total radiance measurements. Our retrieval is tested using 134 AirMSPI datasets acquired during the NASA ORACLES field campaign in September 2016. The retrieved above-cloud AOD and CTH are compared to coincident HSRL-2 (NASA LaRC) data, and COD and droplet size distribution parameters (effective radius r_{eff} and effective variance v_{eff}) are compared to coincident RSP (NASA GISS) data. Mean absolute differences (MADs) between AirMSPI and HSRL-2 retrievals of above-cloud AOD at 532 nm and CTH are 0.03 and < 0.5 km, respectively. At RSP's footprint scale, MADs between RSP and AirMSPI retrievals of COD, r_{eff} and v_{eff} in the cloudbow area are 2.33, 0.69 μm and 0.020, respectively. Neglect of smoke aerosols above cloud leads to an underestimate of image-averaged COD by $\sim 15\%$.

Preferred mode of presentation: Oral

PCRTM-SOLAR model with multiple atmospheric scattering

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The top of atmosphere (TOA) reflected solar spectrum contains extensive information on the atmosphere and the Earth's surface. However, it is very difficult to calculate the TOA radiance spectra because (i) the radiance is highly azimuthal-angle-dependent, (ii) the multiple scattering of solar light by cloud particles and/or aerosol is complicated, and (iii) the Earth's surface has a non-Lambertian nature. A Principal Component-based Radiative Transfer Model (PCRTM-SOLAR) has been developed to simulate the reflected solar spectra for both clear sky and cloudy sky conditions [1,2].

In this talk we will summarize the recent advances in developing the PCRTM-SOLAR. We will discuss how the multiple scattering of the solar beam by the multilayer clouds and aerosols is calculated using a discrete ordinate radiative transfer scheme, how the calculation time is significantly shortened by using the principal component analysis, and how the calculation time is further reduced using a hybrid stream method. We will also discuss the accuracy of the fast PCRTM-SOLAR relative to other much slower radiative transfer models, such as MODTRAN. The results indicate that the hybrid stream PCRTM-SOLAR is very efficient and accurate in simulating thousands of reflected solar spectra under multilayer cloud and aerosol conditions for climate-change Observing System Simulation Experiment (OSSE) studies and other applications.

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Preferred mode of presentation: Oral/Poster

Similarity relations in radiative transfer

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Several quasi-invariant quantities in radiative transfer concerning multiple scattering, which were originally introduced by van de Hulst [1], can be derived from the equation of radiative transfer. Recently, it is shown that the aforesaid quasi-invariant quantities are useful in remote sensing of ice cloud properties from spaceborne radiometric observations [2]. Specifically, the overall performance of an ice cloud optical property model can be estimated without carrying out detailed retrieval implementation. In this presentation, we will review the radiative transfer similarity relations and some recent results. Furthermore, we will illustrate an application of the similarity relations to improvement of broadband radiative flux computation [3]. For example, the Rapid Radiative Transfer Model (RRTM) [4] does not consider multiple scattering in the longwave spectral regime (RRTMG-LW). It is shown that the similarity relations can be used to effectively improve the accuracy in computing radiative flux by incorporating the multiple scattering effect without an increase in computational effort.

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Preferred mode of presentation: Oral

Advanced topics related to the volume integral equation formulation of electromagnetic scattering

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The frequency-domain volume integral equation (VIE) for the electric field inside the scattering object has been known for more than 50 years. It has been intended to be a rigorous formulation of the electromagnetic-scattering problem equivalent to the more conventional one based on the differential Maxwell equations subject to appropriate boundary conditions. Moreover, the VIE has been used as the fundamental basis for a number of “numerically exact” computational methods to simulate electromagnetic scattering, the most popular one being the discrete dipole approximation. The latter has been successfully used for virtually all classes of scatterers, including those with sharp edges and internal interfaces.

Despite the vast existing literature on the subject, the theoretical understanding of the VIE remains incomplete and incommensurate to the domain of its actual practical applications. Indeed, the literature is largely grouped around the following two extremes: (i) accessible derivations with all complex issues swept under the rug with the intent to maximally shorten the path to practical computations, and (ii) mathematically rigorous yet practically limited treatises that commence with concepts such as Banach spaces, Hölder continuity, etc. and thus are hardly comprehensible to the applied scattering community. As a consequence, the publications from the first group tend to ignore fundamental issues such as the strong singularity of the integral kernel, which can potentially lead to ambiguities. And rigorous mathematical studies are typically based on simplified assumptions of smooth particle boundaries and continuous interiors, whereas sharp edges/vertices and internal interfaces are hardly mentioned. In addition, the current understanding of the conditions guarantying the existence and uniqueness of the VIE solution remains fragmentary, especially in the case of an absorbing host medium.

To fill these essential gaps, we present an accessible and general derivation of the VIE from the differential Maxwell equations, transmission boundary conditions, and locally-finite-energy condition with an explicit treatment of the kernel singularity. Our derivation applies to a representative type of scattering object such as a spatially finite group of multi-layered particles with piecewise smooth (intersecting) boundaries and internal interfaces (with a smooth refractive index in between) immersed in a passive unbounded host medium. We also generalize the results of existing mathematical analyses of the VIE and formulate a conjecture about sufficient conditions ensuring the existence and uniqueness of its solution for this type of scatterer. Finally, we discuss an alternative way of deriving the VIE for an arbitrary object with discontinuities by means of a continuous transformation of the everywhere smooth refractive-index function into a discontinuous one.

Preferred mode of presentation: Oral

Optically resolving size and composition distributions of particles from the volume scattering functions

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Particles in the ocean vary significantly in their size and compositions, ranging from molecules to aggregates of several millimeters, from organic to minerals and from animate to non-living. Many physical and biogeochemical processes in the ocean vary with the size and composition of particles. However, most of field measurements can only resolve particles of sizes typically $> 1 \mu\text{m}$, little is known about the size distribution of submicron particles. In addition, little is known about the in situ composition of particles. Significant technological and theoretical advances have taken place over the last decade or so in the field of light scattering, which allow us to (1) measure the detailed angular scattering in situ; (2) drop the idealized and unrealistic, yet frequently used, assumption of spherical particles; and (3) interpret this angular scattering measurement in terms of, and retrieve, the size distribution and composition of particles of sizes $0.02\text{--}200 \mu\text{m}$ [1,2]. The results have been validated in several studies with independent measurements of acoustically determined size distribution of bubbles, LISST-based estimates of particle size distribution, and laboratory gravimetric determinations of the mass for particulate organic and inorganic matter [3,4]. In this presentation, we will summarize these results, particularly towards improving the estimate of carbon flux using the particle size and density distributions retrieved from the in situ measurements of volume scattering functions.

References

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