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DOE/SC-ARM-15-063

Airborne Open Polar/Imaging Nephelometer for Ice Particles in Cirrus Clouds and Aerosols Field Campaign Report

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April 2016

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Principal Investigator

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Work supported by the U.S. Department of Energy,
Office of Science, Office of Biological and Environmental Research

Executive Summary

The Open Imaging Nephelometer (O-I-Neph) instrument is an adaptation of a proven laboratory instrument built and tested at the University of Maryland, Baltimore County (UMBC), the Polarized Imaging Nephelometer (PI-Neph). The instrument design of both imaging nephelometers uses a narrow-beam laser source and a wide-field-of-view imaging camera to capture the entire scattering-phase function in one image, quasi-instantaneously.

The laboratory instrument's sensitivity allows fully resolved phase functions of gas molecules (Rayleigh scattering) and low-concentration background aerosol particles.

We have opened up this laboratory instrument and designed a mount so that it can ride on the underside of an aircraft wing. The aircraft we designed the mount for is the National Aeronautics and Space Administration (NASA) P-3, housed at the Wallops Flight Facility, Virginia, but the design is adaptable to other aircraft. The laser source and imaging camera will be housed in the same module and separated from a reflecting mirror by several meters of free air.

The camera will capture the full phase function of the ice crystals and particles in the clear air stream beneath the wing, approaching ambient conditions as closely as possible, and avoiding shattering of ice crystals. The O-I-Neph signal-to-noise ratio will be high enough to overcome solar background light because of the choice of a high-power, stabilized-pulsed laser, and proper narrow-band filters on the camera. If needed, the laser wavelength can match a gas absorption band (like the O2 A-Band), which would further minimize the solar background, although our tests have shown that this should not be necessary. Several eye safety measures are implemented into the laser module design, preventing hazardous conditions. A beam steering system mitigates potential wing gyrations and movement.

The main objectives of this work were to:

a. Raise the technology readiness level (TRL) of our laboratory imaging nephelometer for airborne measurements of phase functions and the full-phase matrices of ice crystals from cirrus clouds and from aerosol particles in an open cell system environment (no inlets).
b. Provide the instrumental capability that will allow us to invert the O-I-Neph phase matrix measurements to retrieve particle size distribution, refractive indices, and the general scattering properties of ice crystals and aerosol particles (e.g., Dubovik et al. 2000 and Dubovik et al. 2002).
c. Provide the instrumental capability to study the relationship between the phase function of ice particles and aerosols and the non-sphericity and/or shape of the scattering particles.

As part of this effort we have designed and successfully built the O-I-Neph as an aircraft instrument for the measurement of the polarized phase function of aerosol and cloud particles. This current version of the O-I-Neph was built for the NASA P-3 aircraft and is awaiting its first opportunity for an engineering flight test and science flights.

<u>Added January 2015</u>: The O-I-Neph successfully flew on the NASA P-3 during NASA's Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) field campaign in Denver, July 2014. First-light data were collected and compared with data from a ground-based PI-Neph.

Acronyms and Abbreviations

3D	three-dimensional
ARM	Atmospheric Radiation Measurement Climate Research Facility
CDR	Critical Design Review
DISCOVER-AQ	Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality, a NASA satellite mission
DOE	U.S. Department of Energy
LACO	Laboratory for Aerosol and Cloud Optics
NASA	National Aeronautics and Space Administration
O-I-Neph	Open Imaging Nephelometer
PDR	Preliminary Design Review
PI-Neph	Polarized Imaging Nephelometer
SEAC4RS	Studies of Emissions and Atmospheric Composition, Clouds, and Climate Coupling by Regional Surveys
TRL	technology readiness level
TSI	Total Sky Imager
UMBC	University of Maryland, Baltimore County

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1.0 Description of the Open-Imaging-Nephelometer Instrument

The current configuration of the Open-Imaging-Nephelometer (O-I-Neph) instrument consists of two pylons (one active and one passive) to be mounted under the wing of the National Aeronautics and Space Administration (NASA) Wallops P-3 aircraft. The active pylon contains a pulsed laser system, a beam steering device, a fast camera, a polarization modulator and custom-made imaging optics tailored to the particular geometry of the O-I-Neph system. The passive pylon contains a retro-reflector system that reflects the laser beam back to the active pylon. Figure 1 shows a three-dimensional (3D) model with the current configuration of the O-I-Neph system mounted under the wing of the P-3 aircraft.

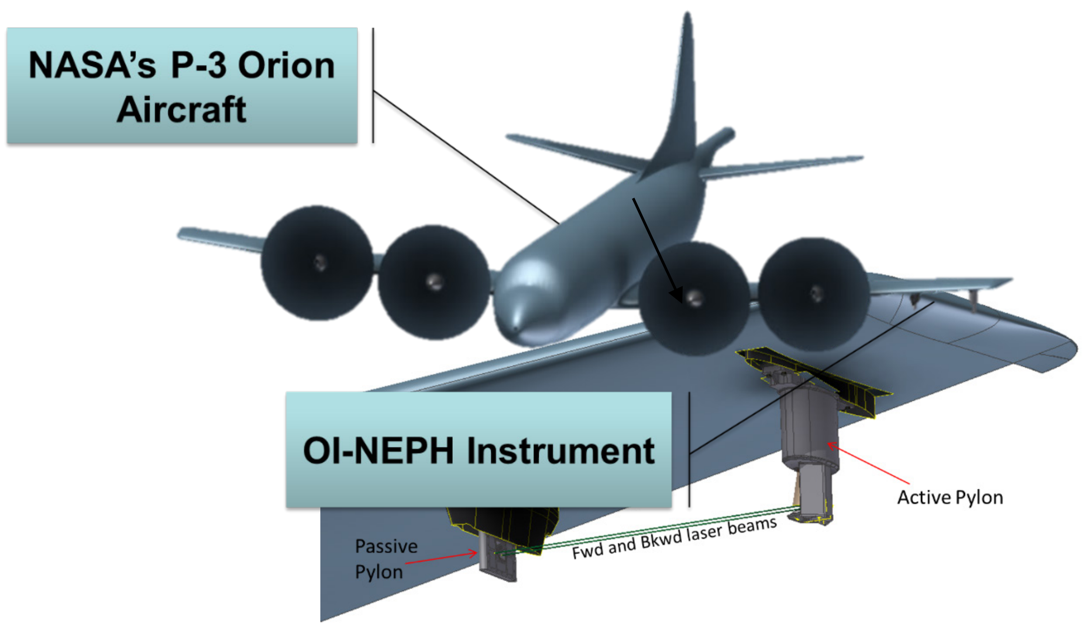

Figure 1. 3D model of the O-I-Neph system mounted under the wing of the NASA Wallops P-3 aircraft.

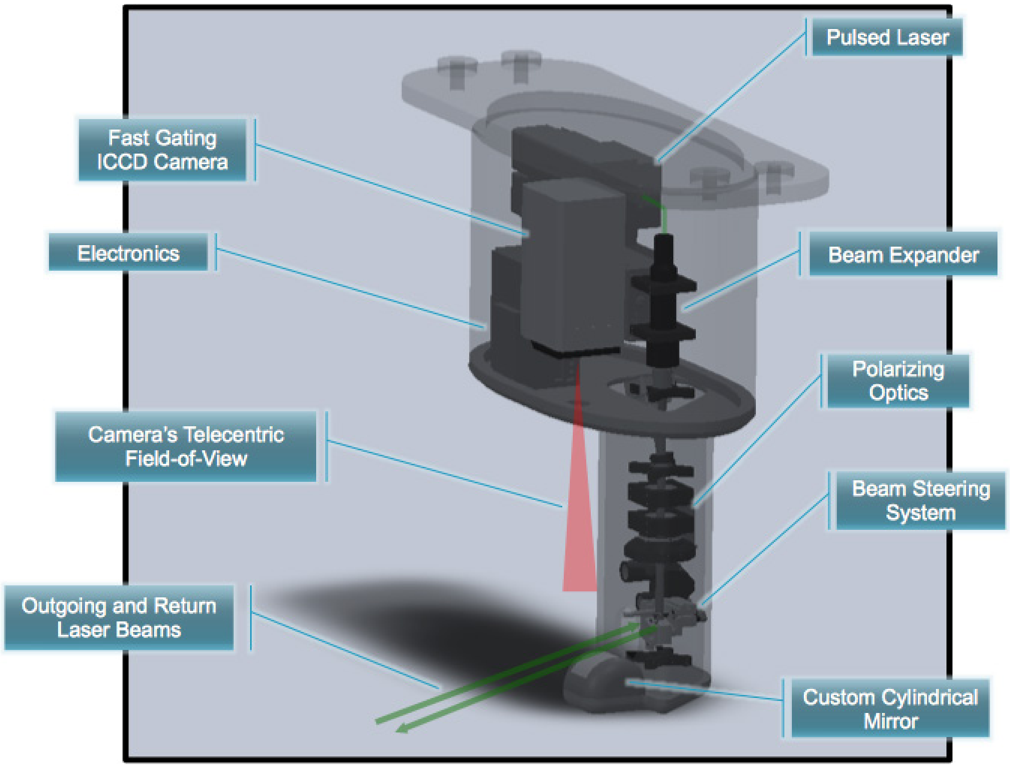

Figure 2. Schematic of the systems in the active pylon.

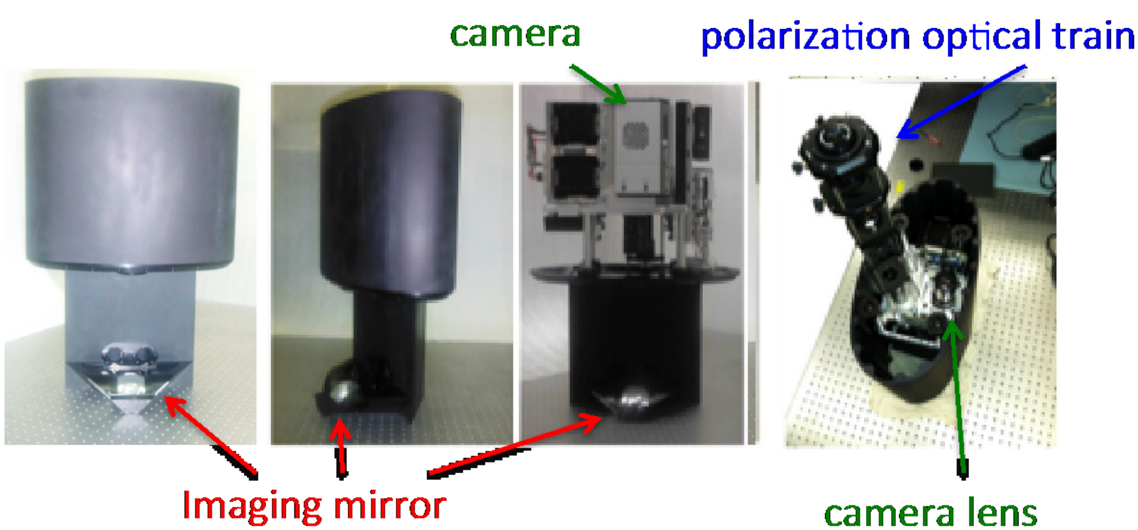

Figure 3. Details of the final assembly of the O-I-Neph active pylon.

Figure 2 shows the 3D model and Figure 3 illustrates the final assembly of the O-I-Neph active pylon detailing the external shell, the laser/camera system with the external shell removed (panel 3), the imaging mirror in two views (panels 1 and 2), and the polarization optical train (panel 4). The laser resides behind the camera in the panel 3 view. This pylon is the main component of the O-I-Neph system where all the active elements are mounted. The external shell represents a pressure barrier assuring that all active elements are pressurized inside the pylon.

The concept of the O-I-Neph is similar to its predecessor, the closed Polarized Imaging Nephelometer (PI-Neph), but the open version has been modified to accommodate the new challenges of open air measurements on an aircraft. The laser on the active pylon shoots a beam to the passive pylon where the beam hits the reflecting mirror (different than the imaging mirror) and is reflected back to the active pylon. As the beam travels in the open air between the two pylons, the molecules and particles encountered along each path scatter the light out of the path. Some of that light is scattered towards the active pylon. Light scattered from the forward beam towards the active pylon is *backscattered* (scattering angles 90 to 178.5º). Light scattered from the returning beam is *forward scattered* (scattering angles 1.5 to 90º). The imaging mirror on the active pylon, because of its cylindrical shape, captures the scattered light from both beams as an image on the mirror. The camera, pointed at this mirror, takes a picture of this image (Figure 4). In essence, the O-I-Neph camera is taking a picture of the phase function of the combined molecules and particles in the ambient air between the two pylons, over the scattering angle range 1.5 to 178.5º.

2.0 First Tests with the O-I-Neph System

The O-I-Neph system has been tested in the laboratory and outdoors. The results have been excellent, demonstrating the expected signal-to-noise ratio, image quality, stability, etc. One of the major advantages of the open system is that there are no walls and therefore the system has far fewer stray-light issues than the enclosed PI-Neph system, with which similar measurements are made inside a pressurized chamber.

Figure 4 shows an image captured by the O-I-Neph operating in the laboratory and sampling laboratory air. All lights were on during this operation, yet the background in the image is dark, allowing clear identification of the imaged beam and a very strong signal-to-noise ratio. Three design features make this possible: 1) The fast camera and pulse laser, 2) a narrow-band filter in front of the camera, and 3) in flight, the imaging mirror is pointed up at the wing, which provides a dark and constant background for the signal.

The phase function and other components of the scattering-phase function are obtained by measuring the intensity across the beam at different locations of the image, with each point on the image representing a different scattering angle. The results of the processing of an O-I-Neph image are shown in Figure 5. Two components of the scattering-phase function are shown: P11 (the phase function) and –P12/P11 (degree of linear polarization). These plots represent the properties of the laboratory air. For pure gaseous scattering (Rayleigh scattering), we would expect P11 to be symmetrical in the forward and backward scattering directions, and –P12/P11 to peak at 90º and be symmetrical on either side. The examples in Figure 5 almost match those symmetries, but deviate just enough to indicate that the air in the lab contained some suspended aerosol particles and was not composed of pure gas molecules. If the target of scientific interest were to be the suspended aerosols, or in other situations cloud hydrometeors, the well-characterized gas-scattering components of P11 and –P12/P11 could be modeled and the remaining signal inverted to retrieve particle size distribution and other physical and optical characteristics of the particles, droplets, or ice crystals.

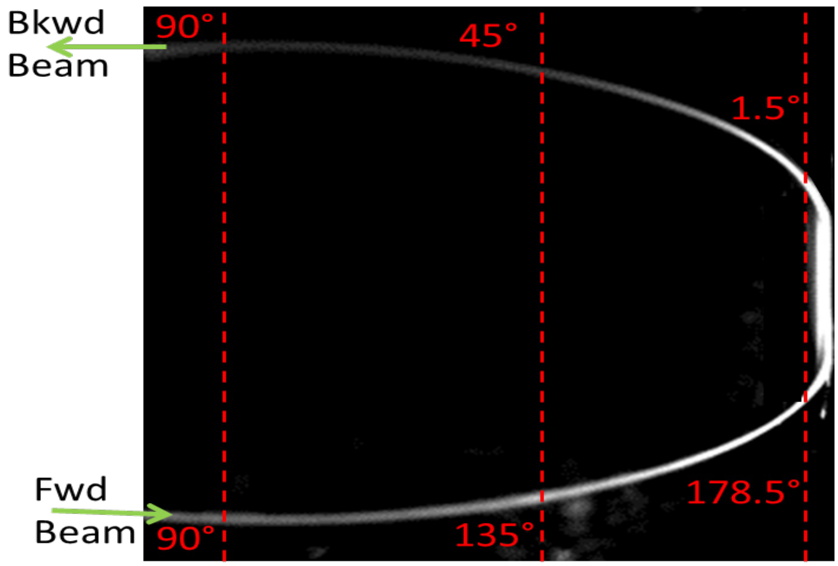

Figure 4. Image from the O-I-Neph camera taken during a laboratory test.

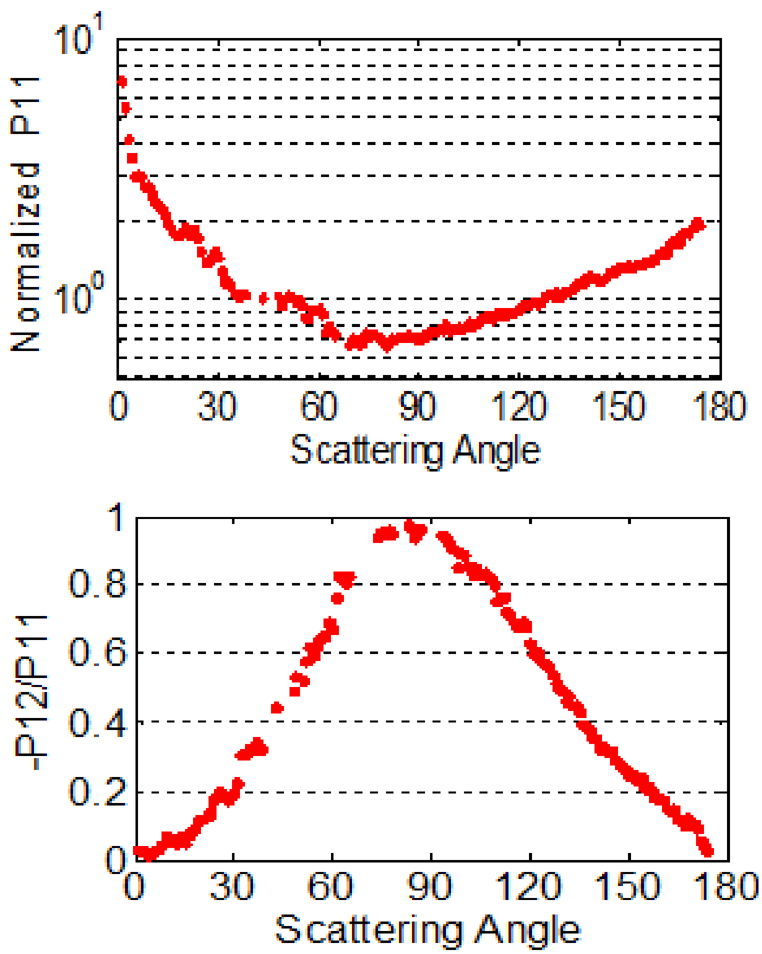

Figure 5. Examples of P11 (phase function) and --P12/P11 (degree of linear polarization) derived from an O-I-Neph image obtained during a test run.

In addition to the laboratory test shown here, we also successfully ran the O-I-Neph outside, in the sunlight, obtaining similar high-quality, stable results with a high signal-to-noise ratio.

Besides the challenge of overcoming the strong background signal of sunlight in an open system, the second challenge in developing the O-I-Neph for aircraft applications is to overcome the problems with wing motion. We solved this problem by implementing a beam steering system that can track the motion of the target at sub-millisecond speeds. The beam steering system was tested in the laboratory using a wing simulator, producing very impressive results.

3.0 Integrating onto Aircraft

Once the NASA P-3 aircraft was identified as the O-I-Neph's first airborne opportunity, we took steps to design the instrument for integration into that aircraft, while maintaining sufficient flexibility to adapt the instrument to other aircraft at a later time. The University of Maryland, Baltimore County (UMBC) LACO (Laboratory for Aerosol and Cloud Optics) team made several site visits to Wallops, where they established a strong working relationship with Wallops personnel. The interaction provided measurements and a model of the P-3 wing, which enabled the development of a design for electrical and mechanical integration. The O-I-Neph design underwent a Preliminary Design Review (PDR) at Wallops in July 2013, achieving a strong positive response and clearance to continue the integration process.

4.0 Main Achievements of this Project

The main achievement of this project was the production of a working O-I-Neph contained in an external shell and ready for integration onto the P-3. To achieve this, we had to:

- overcome the challenge of a bright background signal when working in sunlight
- overcome the second challenge of wing motion
- prove the success of these technical achievements with tests both in the laboratory and outdoors that show high signal-to-noise and stability and produce physically consistent measures of the scattering properties of gases and aerosols
- establish a working relationship with Wallops personnel and pass PDR.

Meeting these technical challenges, demonstrating success, and pushing through to actual flights has advanced the O-I-Neph to technology readiness level (TRL) = 9, the main objective of this project.

5.0 Next Steps

The next steps for the O-I-Neph development include additional indoor and outdoor tests. Because the O-I-Neph measures ambient air, it is more difficult to control the measured sample than it is for the closed PI-Neph system; this may create calibration issues that will need to be addressed. One way to meet this challenge is to transfer or constrain calibration by running the O-I-Neph side by side with similar, but well calibrated, instruments. We will run the O-I-Neph alongside the PI-Neph and a Total Sky Imager (TSI) nephelometer. The PI-Neph offers an opportunity to compare with very similar measurements, including comparisons of P11 and –P12/P11. However, the PI-Neph does not measure at ambient conditions and will dry the air sample to some degree. If the sample contains hydrated aerosol, results will differ between the two instruments. The PI-Neph cannot measure cloud hydrometeors. The TSI does not have the angular resolution of either the O-I-Neph or the closed PI-Neph, but it can be used to compare total scattering after integrating the O-I-Neph results over specified angular ranges. The same caveat concerning differences between ambient and dried air samples applies to the TSI, as well.

The next steps with this instrument must also include development of software and data analysis tools, plus adapting the Dubovik inversion to O-I-Neph data. The group has already made considerable progress in inverting 3-wavelength P11 data from the closed PI-Neph to obtain aerosol particle size distributions. See Figure 6, which shows P11 at two of the PI-Nephs 3 wavelengths, -P12/P11 at one of the 3 wavelengths, and the size distribution retrieved from the P11 data. These data illustrate the future potential of the Open-I-Neph, and the need to develop software to achieve the functionality seen here. These data also include retrievals for cloud droplets and ice crystals. Similar inversions need to be adapted to the O-I-Neph and new analysis and inversion tools developed for retrieval of cloud hydrometeors, including ice crystals.

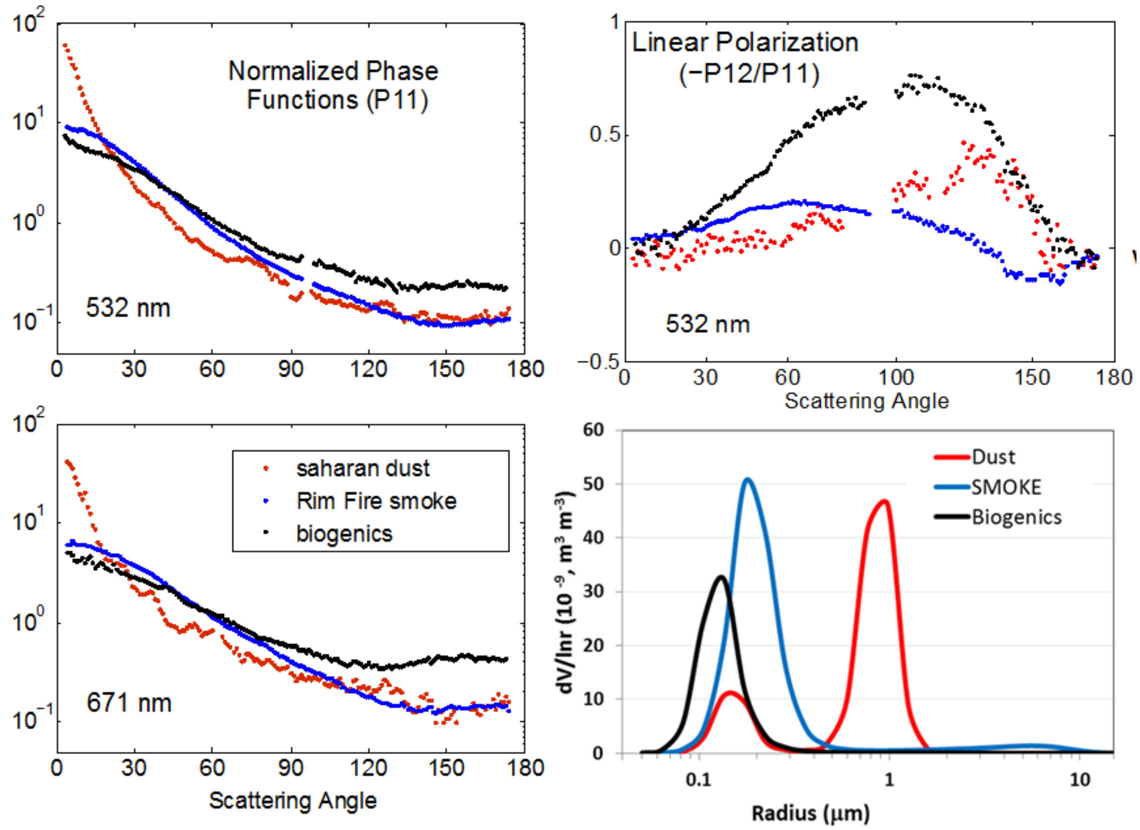

Figure 6. Example of size distributions inverted using Dubovik software from closed PI-Neph data for three types of aerosol encountered during the U.S. Department of Energy (DOE)'s Atmospheric Radiation Measurement (ARM) Climate Research Facility 2013 Studies of Emissions and Atmospheric Composition, Clouds, and Climate Coupling by Regional Surveys (SEAC4RS) deployment.

Finally, future steps for the O-I-Neph include a Critical Design Review (CDR) at Wallops, complete integration onto the P-3, test flights, and deployment under actual field campaign conditions. The P-3 is scheduled to participate in the DISCOVER-AQ campaign in Colorado in summer 2014. The O-I-Neph could be ready for that deployment, which would provide an excellent opportunity to push the technology and data analysis forward, and to begin to address the associated scientific objectives.

Added January 2015: Maiden Flight and First-Light Data

The O-I-Neph successfully completed CDR, integration, and a check-out flight, and achieved deployment for data collection during the DISCOVER-AQ campaign during the summer of 2014. Figure 7 shows a photograph of the two O-I-Neph pylons beneath the wing of the P-3 at the Wallops hangar in June 2014, just as they were depicted in the schematic of Figure 1.

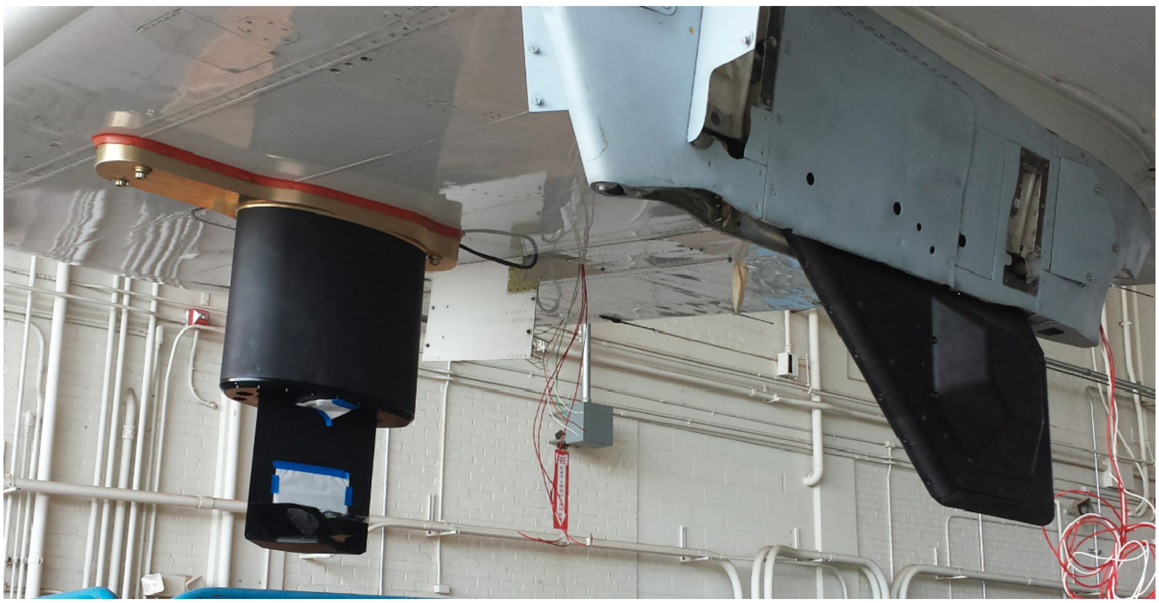

Figure 7. TO-I-Neph fully integrated beneath the wing of the NASA P-3.

The O-I-Neph was able to collect data and produce the P11 element of the scattering-phase matrix (phase functions) of particle and liquid water cloud droplets during the DISCOVER-AQ deployment in July 2014 in Colorado. Figure 8 shows first-light examples of O-I-Neph measured phase functions of aerosol at the bottom and top of an aircraft spiral and also the measured phase function of a water cloud encountered during one of the DISCOVER-AQ flights. Also shown is a comparison between the phase function at the bottom of the spiral and the corresponding phase function measured by a ground-based PI-Neph operating beneath the aircraft at the location of the spiral.

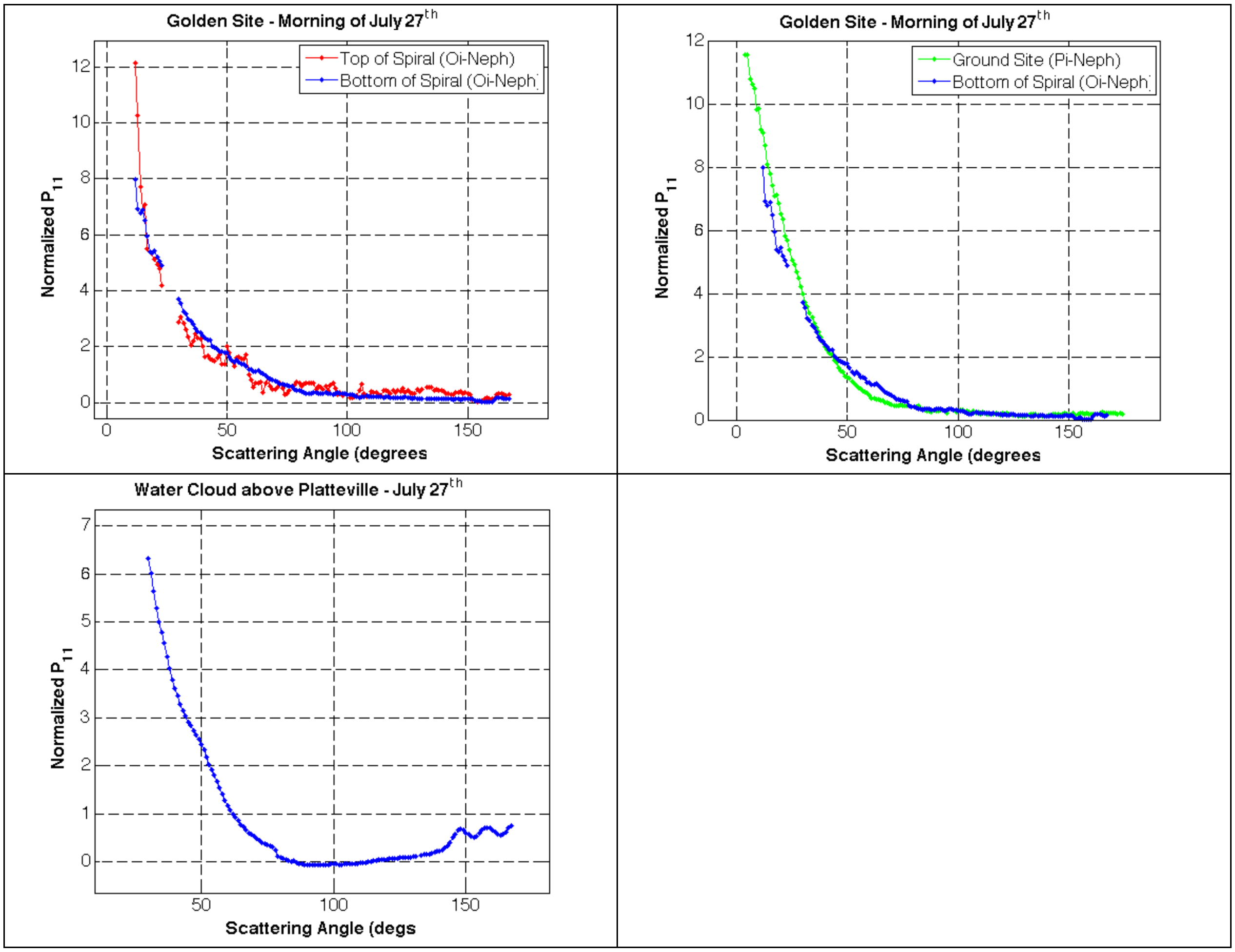

Figure 8. First-light data from O-I-Neph. The normalized P11 element of the scattering-phase matrix (phase function) measured by the O-I-Neph from beneath the P-3 wing on 27 July 2014 during the DISCOVER-AQ campaign in Colorado.

In the upper left of Figure 8 are two phase functions of cloud free air, likely aerosol, corresponding to the top and bottom of an aircraft spiral. Above, the phase function from the bottom of the spiral is compared with measurements from a PI-Neph located on the ground beneath the aircraft spiral. To the left is shown the phase function from a water droplet cloud encountered on the same flight.

In particular, it is important to emphasize the phase function presented on the bottom left of Figure 8. This phase function was obtained inside a water cloud and shows features on the left side indicating the tendency of the extremely high forward scattering saturating the scale of this particular setting, and the oscillations on the right side indicating the cloudbow or the rainbow produced by the cloud droplets. One of the main advantages of the O-I-Neph system is its ability to measure undisturbed cloud and aerosol particles due to the nature and geometry of the open system.

6.0 Conclusion

The O-I-Neph performed as expected with no significant glitches. Further work remains to fine-tune the calibration and rigorously evaluate, quality-assure, and process the collected data, including applying inversion software to make retrievals of particle properties. The instrument is ready to fly again, and ready to be tested in an aircraft that will encounter ice crystal clouds to evaluate its effectiveness in measuring cirrus optical properties without shattering the crystals. In the future, flying the O-I-Neph on the outside in tandem with a PI-Neph inside the aircraft will allow for unique scientific comparisons between ambient and controlled measurements of aerosol particles aloft. However, for now, the project has come to satisfactory conclusion with the completion and test of this unique new instrument. The O-I-Neph team is currently writing proposals for next field campaigns and for the development of level 2 data processing algorithms that should convert the O-I-Neph data to geophysical parameters highly desired by the scientific community.

7.0 References/Bibliography

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