

# Ocean, Land and Meteorology Studies Using Space-Based Lidar Measurements

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*Abstract:* - CALIPSO's main mission objective is studying the climate impact of clouds and aerosols in the atmosphere. CALIPSO also collects information about other components of the Earth's ecosystem, such as oceans and land. This paper introduces the physics concepts and presents preliminary results for the value-added CALIPSO Earth system science products. These include ocean surface wind speeds, column atmospheric optical depths, ocean sub-surface backscatter, land surface elevations, atmospheric temperature profiles, and A-train data fusion products.

*Key-Words:* - lidar ocean wind aerosol temperature altimetry

## 1 PHYSICS CONCEPTS

This study focuses on the following five different Earth system science experimental products, which will be developed and maintained by graduate students at Stevens Institute of Technology:

- ocean surface wind speed using clear sky CALIPSO 1064nm ocean surface backscatter;
- 532nm column atmospheric optical depth using ocean surface backscatter and collocated wind speeds from AMSR measurements;
- ocean sub-surface backscatter using 532nm perpendicular polarization measurements;
- CALIPSO land surface and canopy top height using the elevation-in-tail (EIT) technique [4]; and
- CALIPSO atmospheric temperature profiles.

### 1.1 Ocean surface wind speed retrieval from space based lidar

The parallel polarization component of the CALIPSO lidar backscatter from ocean surfaces is primarily a result of specular reflection. When a laser beam hits a water surface at near normal incidence, about 2% of the laser energy is reflected and the rest of the energy goes into the water. For weak winds, the water surface is smooth and specular reflection is a narrow beam with little divergence. As wind speed increases, the surface roughens and the divergence angle of the same 2% of specularly reflected energy increases. Thus, lidar backscatter intensity from the ocean surface decreases as wind speeds increase. Simple relations [1-3, 6] between wind speed and ocean surface roughness (wave slope variance) can be applied to estimate ocean surface wind speed from 1064nm lidar clear sky ocean measurements.

### 1.2 Atmospheric column optical depth from combined AMSR and CALIPSO data

Using ocean surface wind speed measurements made

by the AMSR instrument aboard the AQUA satellite (75 seconds ahead of CALIPSO), we can estimate the lidar ocean surface attenuated backscatter for cloud-free

and aerosol-free atmospheric conditions,  $\gamma_{\text{clear}}$ . The actual ocean surface attenuated backscatter from CALIPSO measurements,  $\gamma_{\text{CALIPSO}}$ , will be less than  $\gamma_{\text{clear}}$  because of the extra attenuation from clouds and aerosols. The column optical depth of clouds and aerosols,  $\tau_{\text{cloud,aerosol}}$ , can therefore be accurately computed from the derived two-way transmittance,  $\exp(-2\tau_{\text{cloud,aerosol}}) = \gamma_{\text{CALIPSO}} / \gamma_{\text{clear}}$ .

### 1.3 Ocean sub-surface backscatter at 532 nm

Water absorbs most electromagnetic waves very quickly, except at visible and some UV wavelengths. At CALIPSO's 532 nm wavelength, the absorption coefficient of pure water is about 0.02 m<sup>-1</sup>. At 1064nm, the absorption coefficient is greater than 10 m<sup>-1</sup>. One of the most important scattering sources from the ocean subsurface is phytoplankton (microscopic plants). Phytoplankton grows by converting nutrients, sunlight, and carbon dioxide into plant material through photosynthesis, and is an important part of carbon cycle. While phytoplankton scatters sunlight, the chlorophyll in the plants also absorbs some fraction of the incident sunlight. Together, this absorption and scattering determines the color of the water. Understanding climate-ecosystem interaction requires accurate remote sensing of ocean biogeochemistry processes, motivating efforts to accurately separate the scattering and attenuation due to phytoplankton from the aerosol scattering and attenuation that occurs in the atmosphere.

For the first time in space, CALIPSO's sub-surface 532nm perpendicular channel provides direct

measurements of phytoplankton backscatter in water. Scattering by ocean surface glint, density fluctuations of water, and dissolved matter hardly depolarizes. The atmospheric attenuation, which is required in estimating ocean sub-surface backscatter, can be accurately accounted for using the ocean surface 532nm parallel backscatter plus the collocated AMSR wind speed data.

#### 1.4 Land surface elevation using the elevation-in-tail technique

A technique we refer to as Elevation Information in Tail (EIT) has been developed to provide improved lidar altimetry from CALIPSO lidar data [4]. The EIT technique is demonstrated using CALIPSO data and is applicable to other similar lidar systems with low-pass filters in the receiver. The technique relies on an observed relation between the shape of the surface return signals (peak shape) and the detector photomultiplier tube transient response (transient response tail). Application of the EIT to CALIPSO data results in an order of magnitude or better improvement in the CALIPSO land surface elevation measurements. The results of the EIT compare very well with the USGS' National Elevation Database (NED) high resolution elevation maps, and with the elevation measurements from the Shuttle Radar Topography Mission (SRTM).

#### 1.5 CALIPSO atmospheric temperature profile

After accounting for molecular attenuation (Rayleigh and O<sub>3</sub>), and using GEOS-5 reanalysis results and background aerosol backscatter from climatology values, atmospheric density profiles,  $\rho(z) = c \gamma \text{mol}(z)$ , can be estimated from CALIPSO's 532nm lidar measurements. Here  $c$  is the molecular backscatter cross section and  $\gamma \text{mol}$  is the estimated CALIPSO molecular backscatter profile measurements. When static equilibrium is assumed, temperature profiles can be derived from the CALIPSO density profiles. Compared to the density profile, the CALIPSO temperature profile retrieval is less uncertain because it is insensitive to errors in calibration.

## 2 PRELIMINARY RESULTS

### 2.1 Ocean surface wind speed

The first step in deriving ocean surface wind speed from CALIPSO is to verify the CALIPSO 532 nm and 1064 nm calibrations, and to make minor corrections if necessary. The relation between wind speed and wave slope variance (thus lidar backscatter) are well established [1,2] for wind speeds around 7 m/s. Both 1064 nm and 532 nm calibrations can be checked by

comparing theoretical lidar backscatter estimated from collocated AMSR wind speed to the measured CALIPSO ocean surface lidar backscatter for lidar shots with very little clouds/aerosols. Then, the relations between wind speed and wave slope variance at low wind speeds (0-5 m/s) and high wind speeds (>12 m/s) are re-examined. This is done by comparing collocated AMSR wind speeds and CALIPSO 532nm surface backscatter intensity. A revised relation between wind speed and wave slope is established based on global observations by CALIPSO and AMSR. Applying the inverse of the wind speed – wave slope relation, ocean surface wind speed is derived from CALIPSO's single shot 1064nm ocean surface backscatter. The monthly mean wind speed, shown in the upper panel of Figure 1, compares well with AMSR wind speed. More details can be seen in [3].

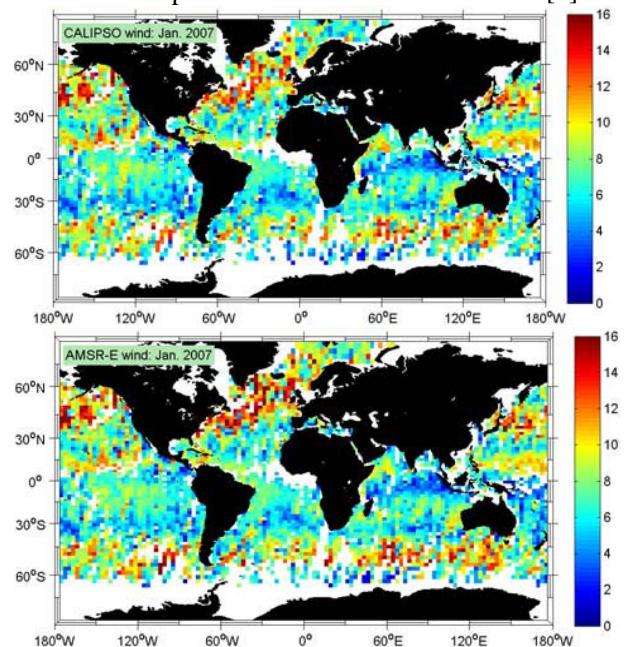


Figure 1. Comparison of CALIPSO and AMSR wind speeds. While there are many global ocean surface wind speed products available from microwave instruments, the CALIPSO ocean wind product is the only one with a high spatial resolution (70 meter footprint for a single lidar shot). With the small footprint size, it provides improved coastal wind speed information and enables global statistics of small scale wind gusts, which are important for studying air-sea interactions.

### 2.2 Column atmospheric optical depth

Column atmospheric optical depth can be estimated from the measured two-way transmittance at the ocean surface using CALIPSO ocean surface backscatter and collocated wind speed from AMSR. Once the collocated AMSR wind speed is determined, theoretical ocean surface lidar backscatter,  $\gamma$  theory, can be derived from the wave slope variance – wind speed

relation [3]. The column optical depth is then derived from the ratio of the CALIPSO attenuated backscatter measurement  $\gamma$  surface and theoretical backscatter  $\gamma$  theory, The cloud and aerosol optical depth derived from this approach is a direct measurement, without assuming aerosol and cloud physical properties, such as single scattering albedo and phase functions. The cirrus cloud optical depth derived from this method agrees well with the ones derived from molecular transmittance method using CALIPSO 532nm molecular backscatter. The aerosol optical depth derived from this method agrees with collocated HSRL measurements ([5]). Figure 2 shows the monthly mean column aerosol optical depth. This product is the first one with direct measurements of global aerosol optical depth from space.

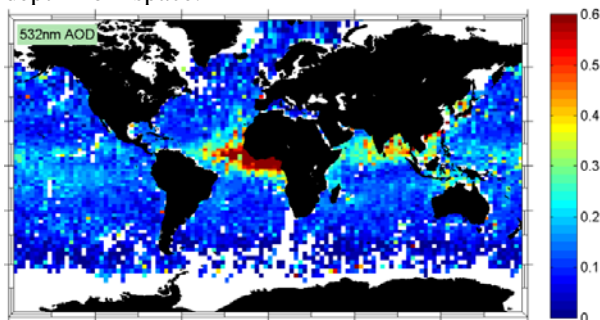


Figure 2. Monthly mean aerosol optical depths of January 2007, using sea surface two-way transmittance derived from CALIPSO 532nm ocean surface backscatter and AMSR wind speed.

### 2.3 Ocean sub-surface backscatter

The CALIPSO ocean sub-surface backscatter data are the sub-surface 532nm perpendicular integrated returns.

Surface wind speed derived from the single shot 1064 nm CALIPSO measurements and the collocated AMSR wind speeds (with coarser spatial resolution) are used to avoid the contamination from foam and bubbles under high wind conditions. Atmospheric attenuation can be corrected accurately using the column atmospheric optical depth estimated from the CALIPSO 532nm parallel polarization measurements at the ocean surface and the collocated AMSR wind speed. Figure 3 shows the January 2007 monthly mean ocean sub-surface backscatter result.

One of the advantages of ocean ecosystem active remote sensing is the clear separation of light scattered by aerosols from the ones scattered in water. Combined with ocean color measurements, this subset of unambiguous ocean and atmospheric properties may help improve ocean color algorithms and reduce the uncertainties. We are also trying to use CALIPSO data for developing other ocean science data products, such

as the ocean mixed-layer depth.

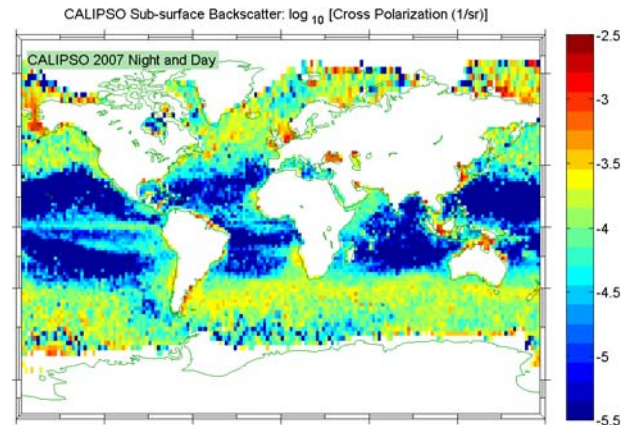


Figure 3. Ocean sub-surface backscatter from perpendicular polarization channel of CALIPSO.

### 2.4 Accurate surface elevation from CALIPSO

Using the EIT technique, CALIPSO surface elevation is derived by using CALIPSO's 532nm perpendicular polarization measurements.

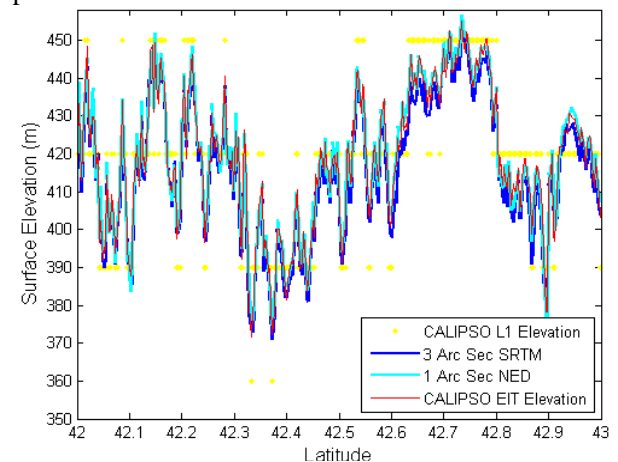


Figure 4. Comparison of land surface elevation from SRTM, NED and the ones derived from CALIPSO EIT method. The perpendicular polarization signal rarely, if ever, saturates over land. The parallel polarization channel may saturate for desert and other bare soil surfaces.

Figure 4 shows the comparisons between the CALIPSO surface elevations (red) with those from the synthetic aperture radar (SRTM) and the USGS's high-resolution elevation maps over US. The rms differences are around 2 meters, which is likely a result of CALIPSO's 40 MHz onboard clock uncertainty. For surfaces covered by dense vegetation canopy, the EIT surface elevation using CALIPSO data can provide a global survey of the canopy top height statistics. The seasonal/inter-annual variations of the canopy heights, derived from canopy top height variation over CALIPSO's 16-day orbit repeat cycles, may provide important information on the global carbon cycle.



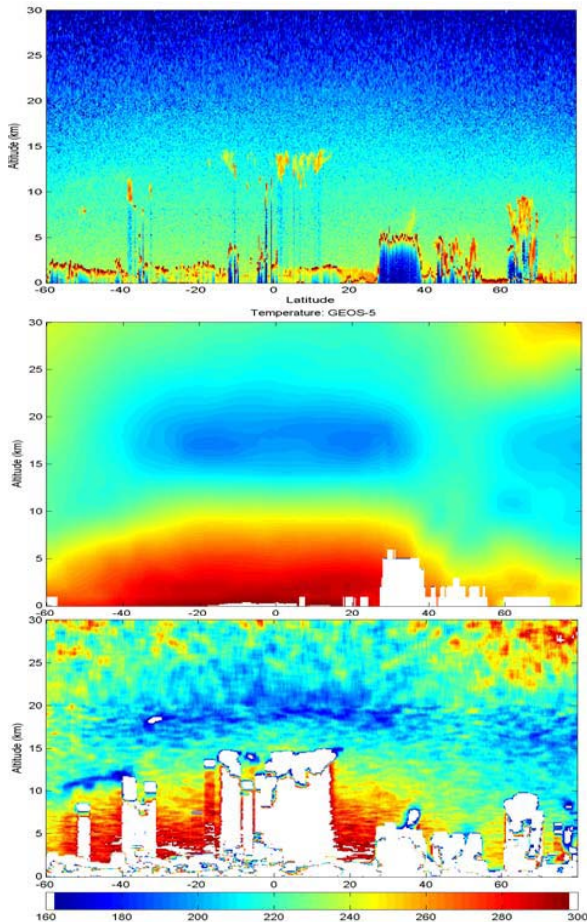


Figure 5. Upper panel: one of the CALIPSO nighttime orbit; Middle Panel: Temperature from GEOS-5; Lower panel: Temperature profile derived from CALIPSO.

### 2.5 Temperature profile

The upper panel of Figure 5 shows one nighttime orbit of CALIPSO 532nm attenuated backscatter. The lower panel of Figure 5 shows the preliminary result of temperature profiles derived from the CALIPSO data, using equation (1). As CALIPSO's backscatter profile starts at around 40 km, the atmospheric pressure at 40 km altitude from GEOS-5 is used to substitute for lidar measurements above 40 km. Comparing with the GEOS-5, the retrieved temperature provides important meteorological information such as tropopause height. The temperature profiles can be improved significantly later on when background aerosols and clouds are removed. The temperature retrievals can be used for detecting subvisual cloud and estimating backscatter aerosol scattering ratio, and for 532nm calibration/validation.

## 3. SUMMARY

Thanks to the engineering and scientific contributions by the entire lidar remote sensing community, lidar remote sensing from space is the new frontier of Earth

observations. The high quality lidar data collected by space-based lidar, thanks to the ingenuity of the CALIPSO engineers, needs to find its way to a broader scientific community. This study intends to demonstrate the potential payoffs of a space-based lidar such as CALIPSO in broader scientific research areas beyond the field of aerosols/clouds. Preliminary results are shown in this paper. We plan to train students at Stevens Institute of Technology to produce the data products introduced in this paper, which include ocean surface winds, atmospheric column optical depths, ocean sub-surface backscatter, surface elevations and canopy top heights, as well as atmospheric temperature profiles. We welcome collaborations from lidar researchers.

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