Instrument Improvements and Recent Deployments of NASA's Airborne High Spectral Resolution Lidar (HSRL-2)

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Abstract: NASA Langley Research Center's airborne High Spectral Resolution Lidar (HSRL-2) has been successfully deployed for more than a decade, measuring atmospheric aerosol and ozone profiles for science campaigns and satellite validation. Recent improvements to the optical receiver, interferometer, detector subsystems, gating and amplification electronics, and processing techniques have enabled 1) zero nadir-offset angle ocean subsurface retrievals of particulate backscatter and extinction at two wavelengths; 2) cloud top optical properties; 3) surface wind speeds over open water; and 4) near-surface aerosol/ozone products.

1. Introduction

The NASA Langley Research Center (LaRC) second generation airborne High Spectral Resolution Lidar (HSRL-2) is NASA's state-of-the-art lidar for investigating atmospheric ozone and aerosol particulates from airborne platforms. The HSRL-2 instrument has flown over 2,000 hours since 2012 on NASA's B-200 King Air, UC-12 King Air, Gulfstream III, Gulfstream V, and ER-2 aircrafts, participating in over a dozen airborne research campaigns.

In 2018, the instrument was upgraded to enable ocean profiling of scattering and extinction and measurements of fluorescence from chlorophyll and colored dissolved organic matter (CDOM), in conjunction with the standard atmospheric products already measured. These upgrades also enabled the retrievals of ocean surface wind speed, in-cloud extinction profiles, and improved HSRL filtering at 355 nm.

The upgraded configuration of the instrument has flown in conjunction with passive remote sensors during recent airborne campaigns to study aerosol-cloud-interactions and analyze air quality in both major urban areas and remote marine environments.

2. Instrument Description

The standard HSRL-2 atmospheric products are retrieved using an HSRL filtering technique to enable independent retrievals of both aerosol backscatter and extinction by separating the Brillouin scattering of molecules from the direct backscatter of larger particulates. In the 532 nm channel, this technique is performed using an iodine vapor cell as a filter. In the 355 nm channel, a field-widened Michelson interferometer is utilized, enabling direct extinction measurements at both wavelengths. Parallel-polarized and cross-polarized backscatter are measured at 355, 532, and 1064 nm, enabling aerosol depolarization retrievals at 355 and 532 nm.

Ozone concentrations are profiled via differential absorption, using 290 and 300 nm for the online and offline wavelengths, respectively. These wavelengths are generated in a non-linear optics (NLO) module where a portion of the 1064 nm light from the Nd:YAG laser in the HSRL system is used to pump two separate optical parametric oscillators (OPOs). The output signals at 1609 nm and 1945 nm from these OPOs are then mixed with a 355 nm beam (tripled from the original 1064 channel) to generate the 290 nm and 300 nm wavelengths, respectively.

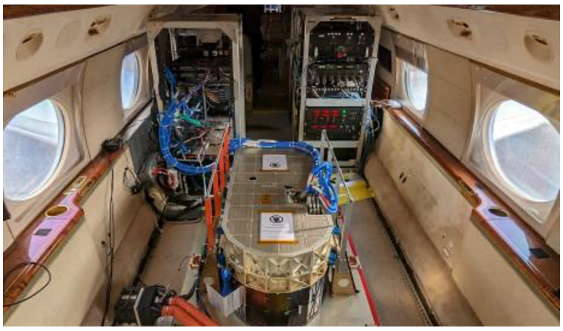

Figure 1. HSRL-2 instrument deployed on NASA's G-V aircraft during the STAQS field campaign.

To improve the performance of the field-widened Michelson interferometer used on the 355 nm channel, it was modified from a piezo-tuned "air arm" to a pressure-tuned version [1]. The piezo tuned version utilized three transducer arms to change the path length in one arm of the interferometer to tune the interference between both optical paths. The piezo-tuned version suffered from temperature sensitivity, translational instabilities from the piezo arms, and air density changes resulting from the translation. The pressure-tuned version allows for a rigid structure in the interferometer body, but uses a bellows to pump air in or out of the air arm cavity to effect a change in air density, altering the refractive index, and ultimately the optical path length.

The improvements to the interferometer performance during flight operations included approximately a two-fold increase in signal discrimination between the molecular and particulate backscattered light. A prototype version of the pressure-tuned interferometer was flown during the ORACLES field campaign in 2016 [2] and further refinements to the heating stability were implemented in 2018.

Previous ocean profiling efforts from airborne lidars have been enabled by tilting the instrument off-nadir by 10 degrees or more to avoid receiving the specular reflection of the laser from the ocean surface that otherwise creates a large signal spike which creates artifacts in the subsequent ocean subsurface signal. A goal for the HSRL-2 upgrade was to enable on-nadir ocean subsurface measurements, a likely requirement for future spaceborne ocean profiling efforts.

The sampling rate on the 355 nm, 532 nm, and fluorescence channels, was increased from 10 MHz to 120 MHz, enabling vertical resolutions of 1.25 m in the atmosphere and 0.93 m in the ocean. Microchannel plate photomultiplier tube (MCP-PMT) detectors were used with custom gating circuits to enable detectors capable of gating open, with a stable response, within the first few meters after the surface reflection impulse.

A previous version of the instrument, HSRL-1, has been used (with a 15° off-nadir tilt) for ocean profiling during the North Atlantic Aerosol and Marine Ecosystem Study (NAAMES) and Shipboard-Aircraft Bio-Optical Research (SABOR) campaigns [3]. Work from those campaigns showed agreement between the airborne HSRL with shipborne in situ measurements of backscatter, as well as the capabilities of the HSRL technique in evaluating satellite retrievals of ocean color from MODIS (Aqua and Terra), and VIIRS [4].

Each of the 355 and 532 nm detection channels are split with a polarizing beam splitter ahead of two separate detectors, the MCP-PMT for the ocean signal and a PMT for the atmospheric signal. To support airborne campaigns where both atmospheric and ocean targets are of importance, a half-waveplate is inserted ahead of each of the polarizing beam splitters to enable variable amounts of light to each detector. This split enables the maximum amount of light on each detector, set specifically to match the scientific goals for each campaign.

Three additional detectors were added to with the intent to enable fluorescence measurements from chlorophyll (680 nm) and CDOM (455 nm), with the third detector for a water Raman line at 650 nm, intended to be used as a reference for the chlorophyll channel. These channels are currently undergoing testing before use as an archived product.

With the improvements to the sampling rate, and the ability to correct for the atmospheric attenuation above a target using the HSRL technique, the HSRL-2 instrument has been used to retrieve opaque cloud-top extinction profiles. Current investigations are underway to look at phase partitioning in mixed-phase opaque clouds†. These improvements have also enabled the derivation of the near surface wind speeds over open water by relating the ocean surface return to wave-slope variance and ultimately 10 m wind speed [5,6].

3. Measurement Campaigns

The Aerosol Cloud meTeorology Interactions oVer the western ATlantic Experiment (ACTIVATE) field campaign was a three-year flight campaign targeting a statistical approach to measuring aerosol-cloud interactions over the western North Atlantic Ocean. Two aircraft were used in tandem to retrieve multiple vantage points of marine clouds and aerosols. One aircraft provided in situ measurements from both in cloud and cloud-free atmosphere, profiling from as low as 150 m above the sea surface to an altitude above cloud tops. The second aircraft would fly above the low-flying aircraft, spatially coordinated, releasing dropsondes and providing remote sensing retrievals of the same air masses and cloud scenes sampled by the lower aircraft.

The remote sensing aircraft was outfitted with both HSRL-2 and NASA's Research Scanning Polarimeter (RSP). The combined retrievals of in-cloud extinction from HSRL-2 and scattering cross sections from RSP have enabled retrievals of cloud-top droplet number concentrations and liquid water content†.

During this campaign, retrievals of prevalent, elevated depolarization from HSRL-2 were investigated utilizing the in situ measurements to determine that the targeted air mass samples contained dehydrated, crystalline sea salt [7].

Other recent NASA airborne campaigns have focused on mapping of atmospheric species relevant for air quality over large, populated cities in North America and Asia using remote sensing techniques. These campaigns have partially been conducted to help validate retrievals of nitrogen dioxide (NO_2) and ozone from satellites. A combined measurement effort between static in situ surface measurement sites, regional airborne sampling flights, and the satellite, are used to combine measurement accuracy near the surface (ground sampling), spatial resolution (airborne), and spatial coverage (satellite).

During these campaigns, the HSRL-2 instrument retrieved vertical profiles of aerosol particulates and ozone concentrations and was flown in combination with the GeoCAPE Airborne Simulator (GCAS), which provided a ~7 km cross-track swath of column NO_2 concentrations. A predetermined raster pattern, covering roughly 7,000 km^2, was flown as many as three times per day, measuring spatial and diurnal changes of ozone, NO_2, and particulates. The combination of 2-D horizontal imaging from the passive satellite simulator and the vertical profiling capabilities from the HSRL-2 lidar provides a distinct advantage for validating satellite remote sensing retrievals, providing important information on aerosol mixed layer heights and portioning of ozone and aerosol loading in the mixed layer and free troposphere.

This combination of instruments was flown in 2023 as part of an early validation attempt for NASA's Tropospheric Emissions: Monitoring of Pollution (TEMPO) satellite, known as the Synergistic TEMPO Air Quality Study (STAQS) field campaign. Flights were conducted over large metropolitan cities in North America including Los Angeles, Chicago, New York City, and Toronto.

The same measurement approach was used in winter 2024 as part of the Airborne and Satellite Investigation of Asian Air Quality (ASIA-AQ) over the major metropolitan regions of Manila (Philippines), Seoul (South Korea), Bangkok (Thailand), and Taiwan. These regions are all within the field of regard for the South Korean National Institute of Environmental Research's (NIER) Geostationary Environment Monitoring Satellite (GEMS) satellite, which also measures column NO_2 and ozone.

To better compare the airborne lidar retrievals with ground point source measurements, additional atmospheric products were produced at higher temporal (horizontal, along-track) averaging while increasing the vertical averaging. Typical atmospheric ozone and extinction retrievals would be made at 60 s (approximately 12 km) along-track and 225 m vertical averaging, but have been modified to 10 s (approximately 2 km) along-track and approximately 1 km in the vertical. Using these products have also been valuable for investigating correlations between near surface extinction and surface $PM_{2.5}$†.

The HSRL-2 instrument is also funded to participate in the Plankton, Aerosol, Cloud, and ocean Ecosystem – Post-launch Airborne eXperiment (PACE-PAX) satellite calibration/validation campaign in late Fall, 2024. Retrievals of 1) atmospheric aerosol backscattering and extinction will be used to better constrain the atmospheric losses impacting the satellite retrievals and validate the satellite retrievals of aerosol optical properties, and 2) subsurface ocean extinction and scattering profiles will be archived and used to support validation of PACE ocean retrievals.

4. Summary

Recent improvements to the HSRL-2 instrument have enabled ocean profiling, cloud retrievals, ocean near-surface wind speeds, and near-surface atmospheric products, along with the standard atmospheric products already produced. These new capabilities have been exhibited in recent airborne research campaigns targeting aerosol-cloud interactions, ocean-atmospheric interactions, and air quality in different regions around the world.

HSRL-2 data from completed campaigns are freely available for public use, six months after completion of the projects [8].

5. References

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† *More details on these topics may be available at this ILRC conference from our collaborators.*