Challenges in the use of spaceborne lidar observations of aerosols and clouds for near real-time and operational applications

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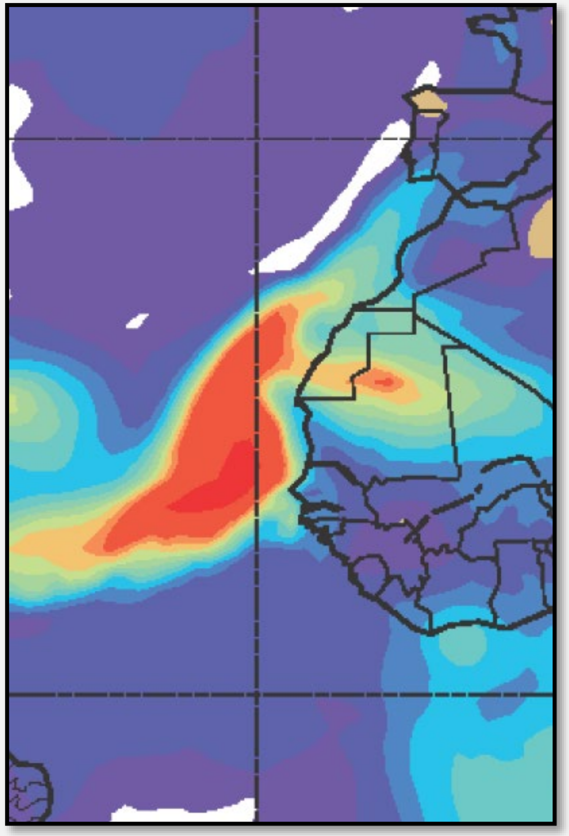
Goal: Clearly identify the challenges for operational users and recognize that these are not insurmountable obstacles.

Applications and operational agencies that can benefit

Aerosol trajectory modeling



NRL, NOAA, ECMWF, JMA

Hazardous plume monitoring

Volcanic Ash Advisory Centers (VAAC)

Air quality forecasting

NOAA, EPA

Numerical weather prediction

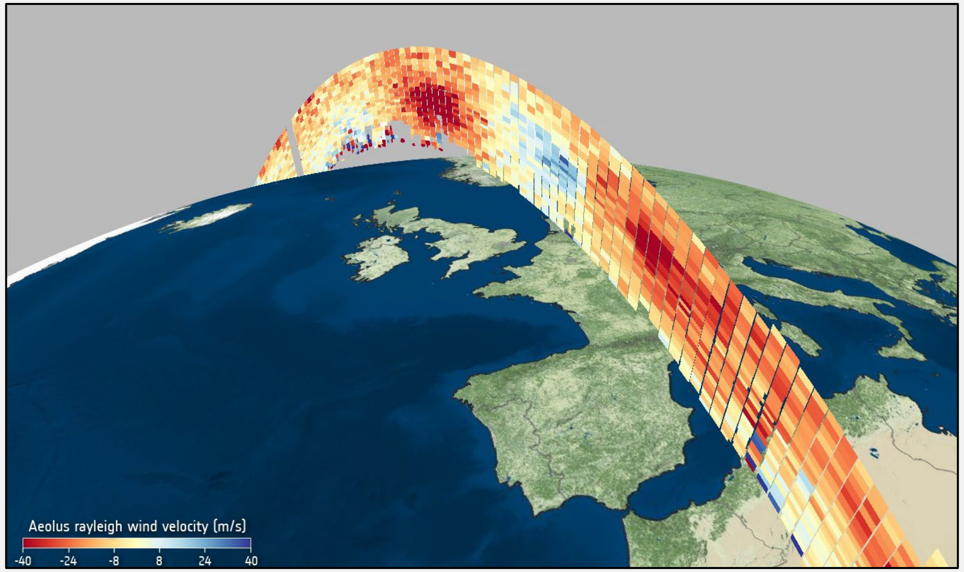
ECMWF, Météo-France, UK Met Office, NOAA, NWS

Successful uses of spaceborne lidar observations for applications

AEOLUS

Wind lidar designed for operational use.

HLOS wind observations operationally assimilated at ECMWF, Météo-France, DWS, UK Met Office, starting in 2020



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CALIOP

Primarily used for validation and development of retrievals and models employed by operational communities.

Hazardous plume monitoring validation

- Ash mass forecasts
- Passive ash height retrievals
- Modeled smoke plume heights and 3D transport

AQ model evaluation

- CMAQ smoke plume injection heights
- Aerosol dispersion accuracy

Aerosol trajectory modeling

Aerosol assimilation experiments demonstrate benefits of CALIOP observations

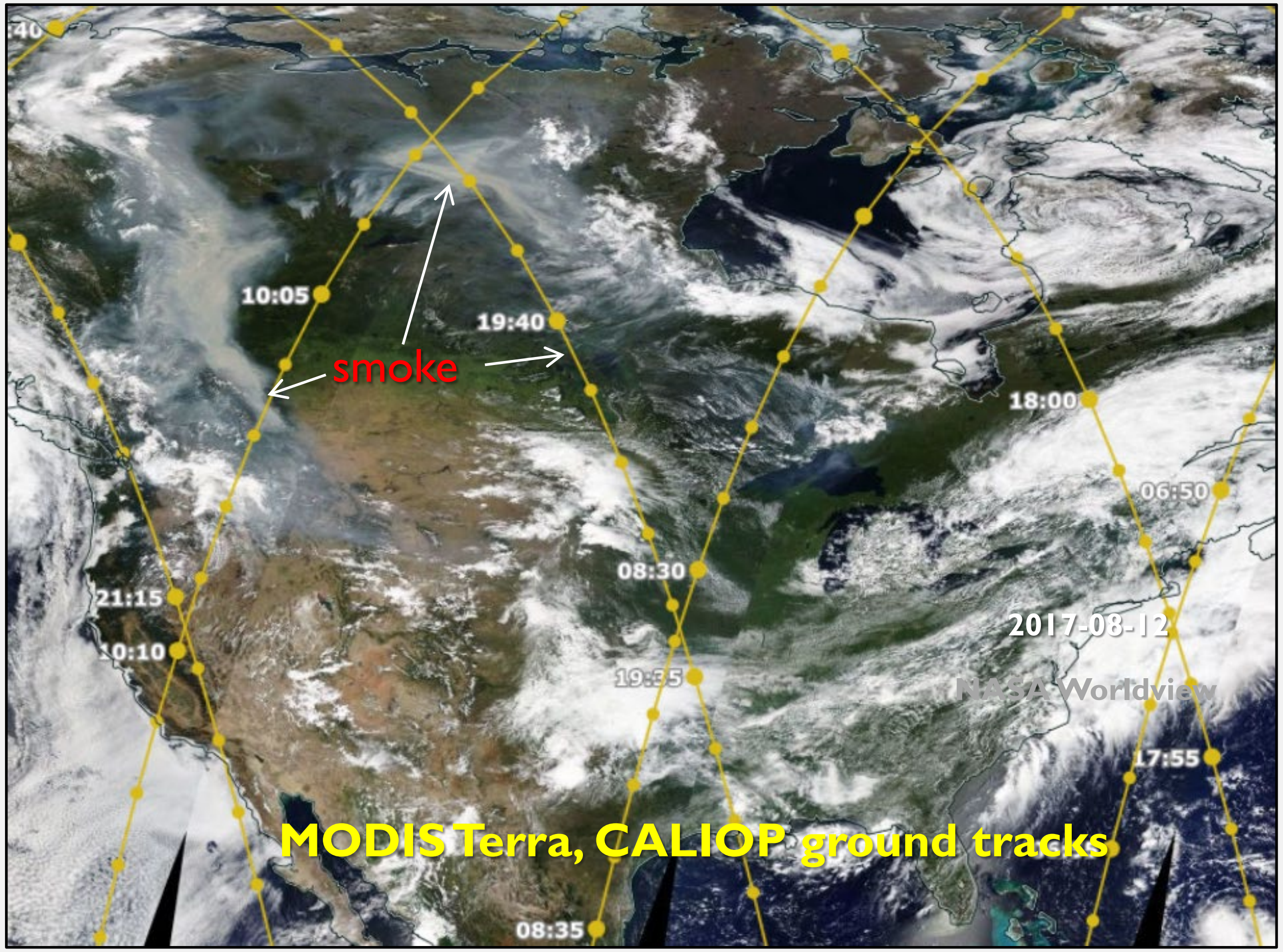
Numerical weather prediction

Cloud height & phase used for development and validation of operational passive instruments used for NWP

Challenges: Spatial coverage

Large distances between adjacent ground tracks

- Small scale events likely not observed: plumes from small fires, minor volcanic eruptions.
- Large scale events more likely to be captured. Difficult to associate a smoke observation to fire source in multiple wildfire events.
- Uncertainty in ability to observe an event discourages operational use by Volcanic Ash Advisory Centers.



NASA Worldview

Challenges: Spatial coverage

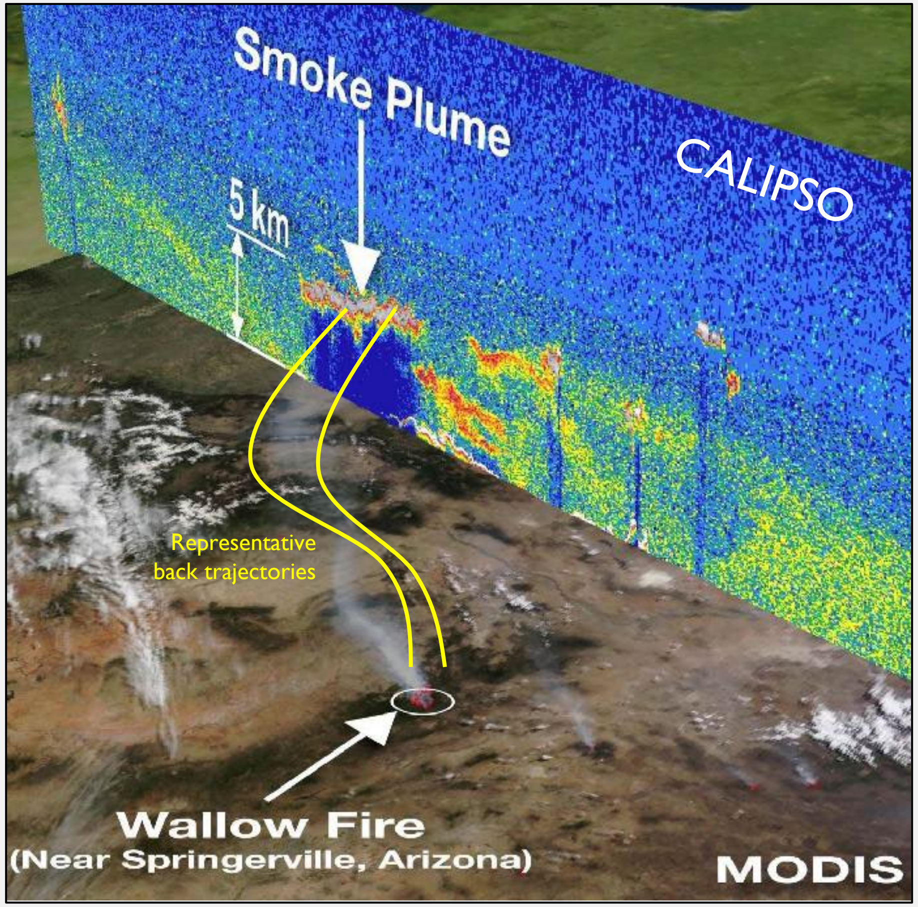
Applications most impacted:
Volcanic ash and wildfire smoke monitoring for air quality and aviation safety.

Applications that can accommodate sparse coverage:
Global aerosol assimilation and NWP models.

Recommendations

- Develop tools to more easily couple lidar observations to trajectory models for rapid forecasting. Incorporate overpass predictions to indicate next plume encounter.

- More advanced lidar systems
  - Multi-beam push broom lidar
  - On demand steerable lidar
  - Constellation of lidar-enabled satellites (small sats?)



NASA /Kurt Severance, Jason Tackett and CALIPSO Team.

Example of work-around:
Trajectory models can link lidar plume observations to fire sources to establish smoke plume injection height

Challenges: Revisit time

Time between successive overpasses

Revisit time is a pronounced challenge for spaceborne lidar, depending on application:

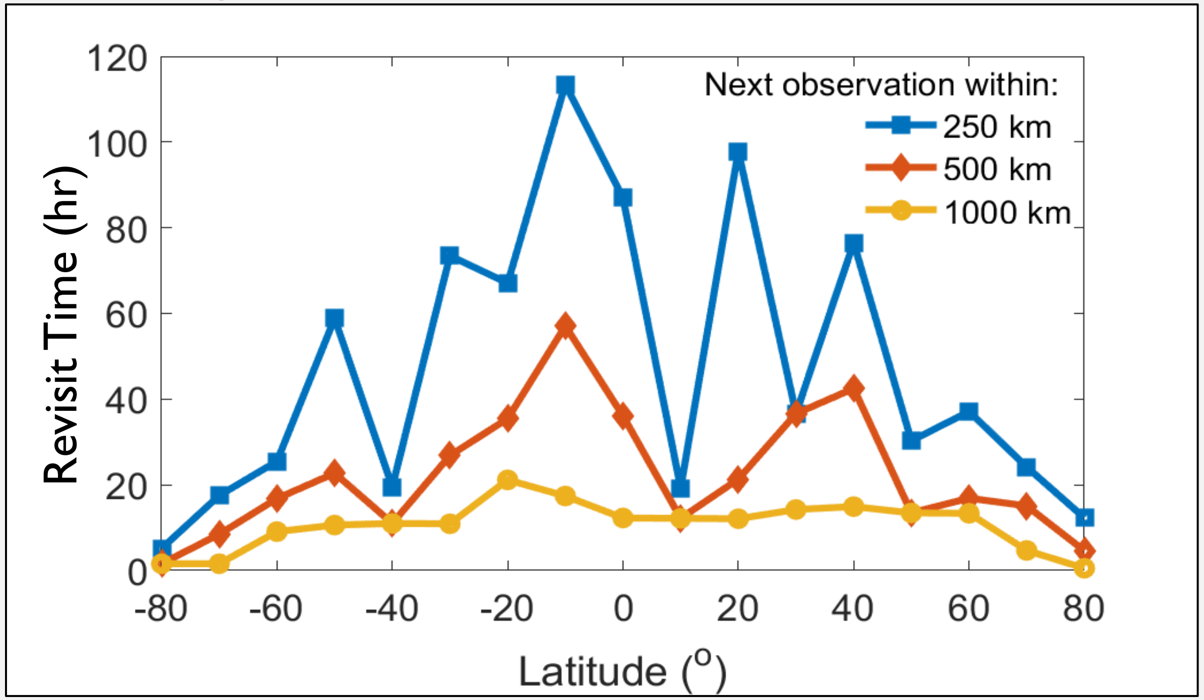
- Substantial issue for tracking hazardous plumes from small scale events.
- Not a challenge for global assimilation models.

Recommendations

Same as latency

- Tools to couple lidar observations to models; overpass prediction applications; multi-beam lidar systems.

Average Time Between CALIOP Observations

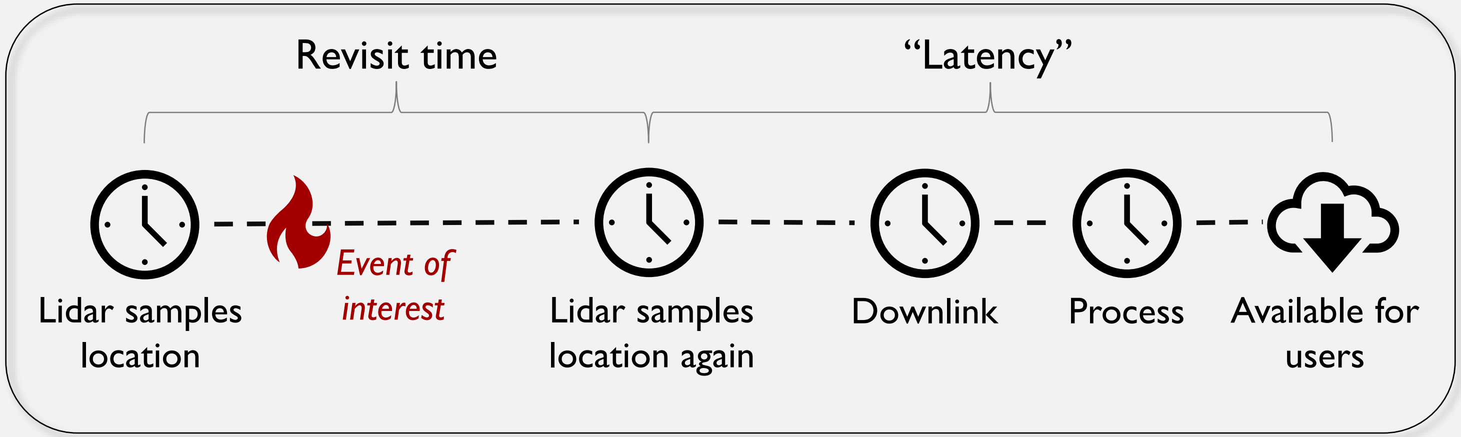


Challenges: Latency

Latency exacerbates delay due to revisit time and spatial coverage limitations

CALIPSO expedited latency: 12-24 hr
too long for near-real time applications.

AEOLUS winds latency: 3 hr
perfect for operational assimilation *by design*.



Recommendations

- Invest in more ground stations.
- Identify latency needs of applications being served during mission concept and prioritize if appropriate.
- More frequent downlinks (two high-latitude sites can downlink every 90 min).

Latency Needs
Based on AOS Applications Impact Team Survey

	Ideal	Helpful
Aviation hazards (volcanic ash)	< 15 min	1 hour
AQ forecasting	1-3 hours	6 hours
Aerosol trajectory modeling	3 hours	6 hours
NWP	3 hours	3-6 hours

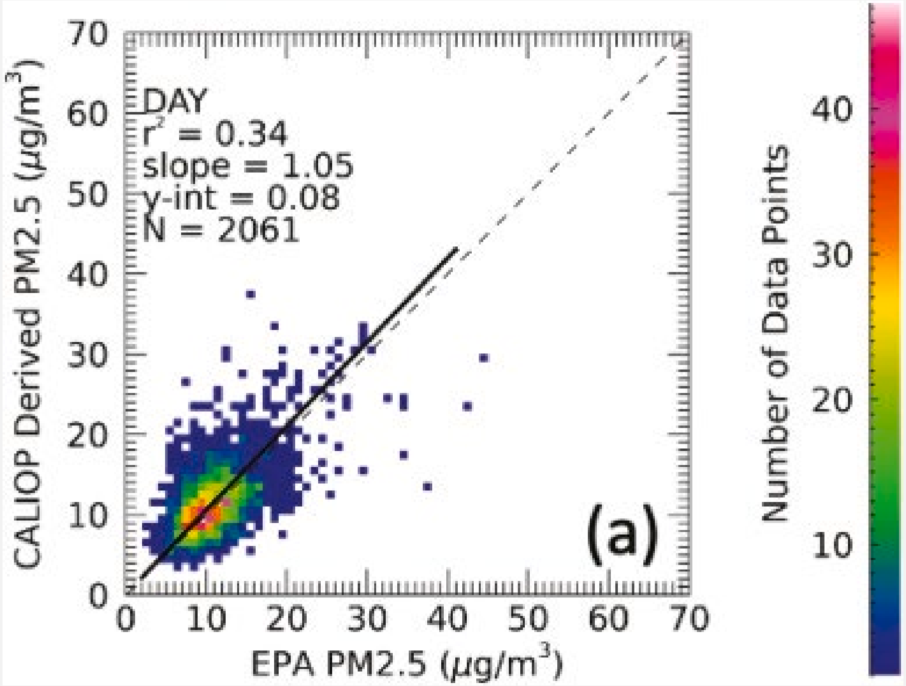
Challenges: Uncertainties in retrieval products

Lidar can provide surface $PM_{2.5}$ estimates based on aerosol extinction profile

- $PM_{2.5}$ estimates depend largely on extinction retrieval accuracy – strongly impacted by lidar ratio in elastic backscatter lidars.
- Retrieval uncertainties are largest at the bottom of the profile for backscatter lidars.
- Accurate speciation is required for aerosol mass extinction efficiency.

Recommendations for next generation

- HSRL systems provide more accurate extinction than elastic backscatter lidars.
- Multi-wavelength polarization HSRL systems could improve aerosol speciation and cloud-aerosol discrimination accuracy.
- Aerosol speciation on a per-range bin basis rather than per-layer basis can improve accuracy near surface.



Example of $PM_{2.5}$ retrievals from CALIOP: Adapted from Toth et al., 2022 Atmos. Environ.

Challenges: Error characterization for data assimilation

Accurate error estimates required for data assimilation

- Uncertainty for a given range bin required, but errors from higher layers are propagated in top-down lidar retrievals. Difficult for models to simulate.

Biases need to quantified and corrected

- Misclassifications in aerosol type can lead to biased lidar ratio selection, but how to know a misclassification has occurred?
- Cloud contamination is a concern.

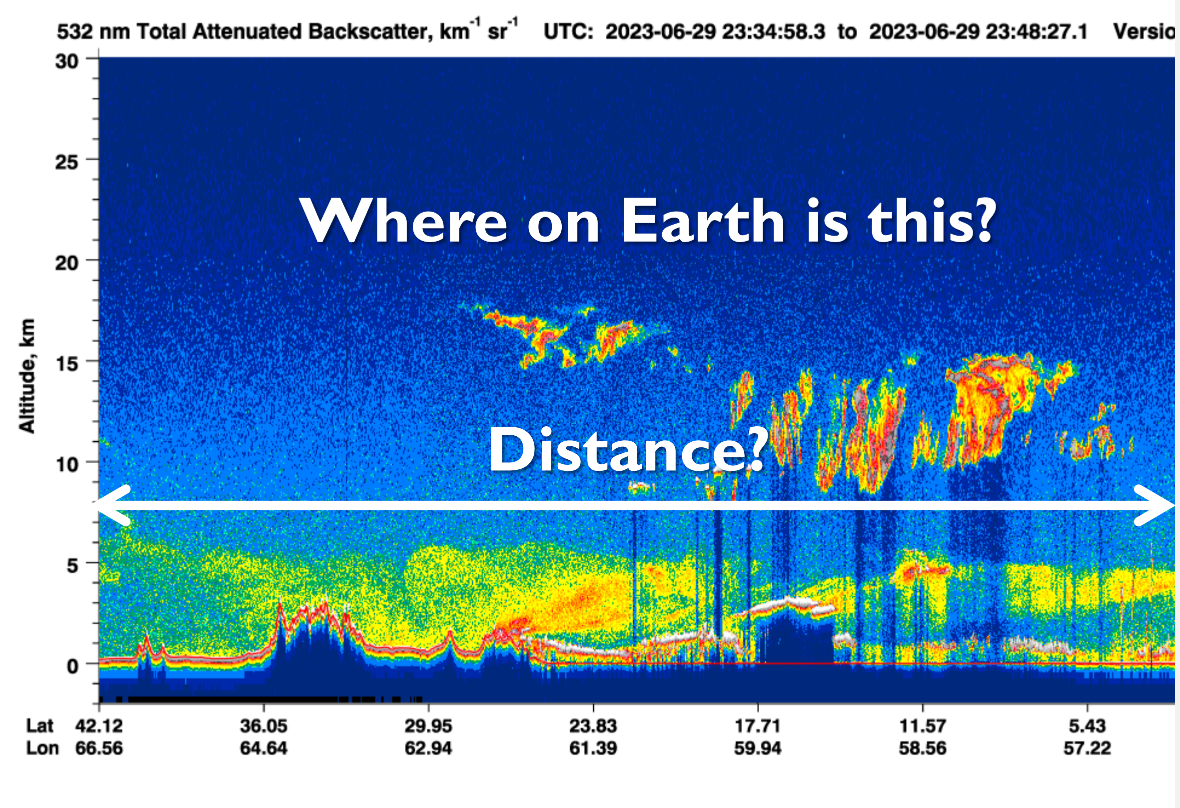
Need to provide measurables that models can assimilate

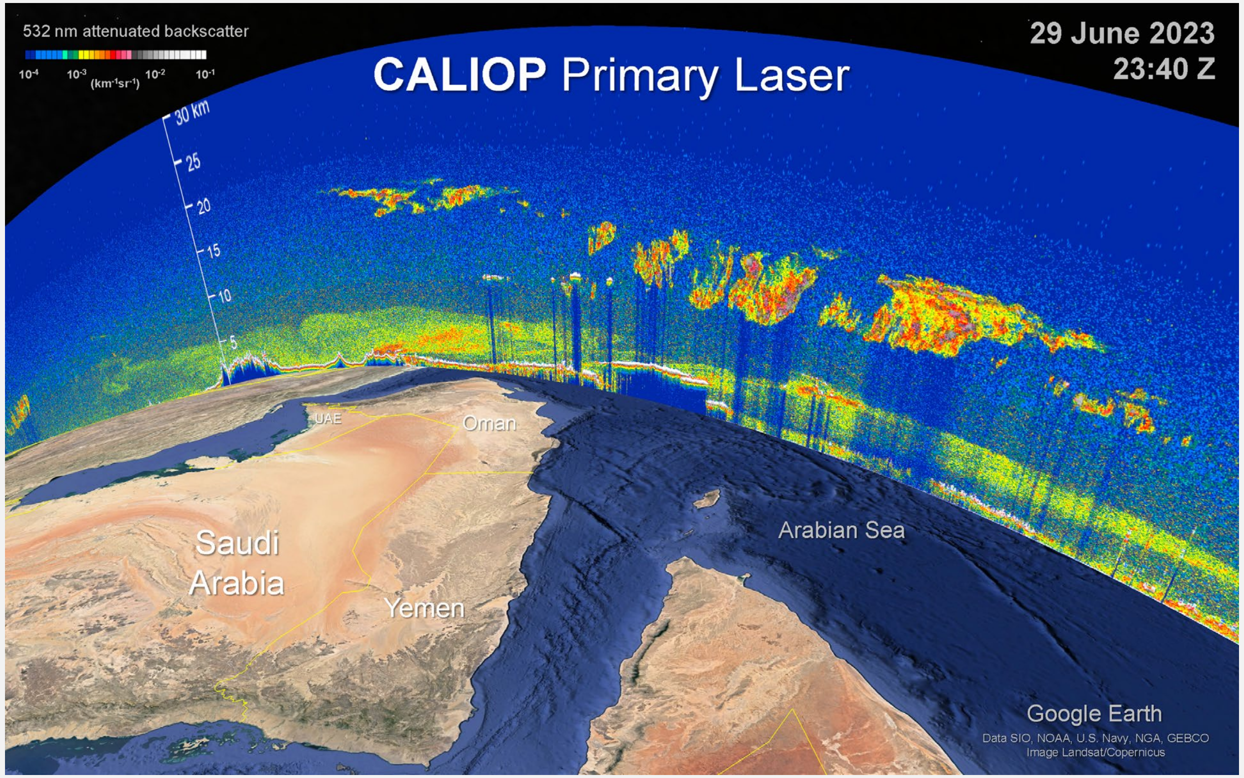
- Prognostic variables for models are mass and number concentration; converting to optical properties is a source of error (Benedetti et al., 2018).
- Aerosol types inferred by lidar data do not match modeled types.

Recommendations

- HSRL systems provide robust measurements of aerosol backscatter and extinction with accurate uncertainty estimates on a range bin level.

Challenges: Visualization tools





No geophysical context in 2D lidar browse images.

Recommendation for lidar:

Develop 3D interactive visualizations on a globe

- More intuitive and facilitates more broad usage.
- Requirements should be developed by missions, possibly for pre-existing tools (e.g., NASA Worldview).

Challenges: Programmatic challenges

Long-term strategy to maintain measurement continuity required

- Operational agencies less inclined to invest time and labor for limited duration missions.
- ESA Copernicus Programme is an excellent example of planning continuous operational missions.

Interagency mandates for operational missions

- NASA focuses on technology development and research missions, while NOAA has an operational mandate. How to optimize?
- If operational applications are a priority, funding must be supplied for development and sustained support.

Copernicus Operational and Planned Missions

[Image source](#) [Credit:ESA](#)

Path forward

Key strategies for AOS and IceSAT-2 applications engagement

Understanding community needs

- Essential in all phases of mission design through mission execution.
- Engage potential users in workshops, surveys, focus groups.
  - Even better – visit users where they work, learn how they work.
- Learn measurables, data formats, and resolutions needed.

Educate new data users prior to mission execution

- Early adopters programs – provide simulated data for development.
- Training (e.g., NASA's Applied Remote Sensing Training Program).

Provide tailored data products for operational needs

- Small file size products with only essential, quality-controlled information.
- Interactive visualization tools.

References

Rubin, J. I., Reid, J. S., Hansen, J. A., Anderson, J. L., Collins, N., Hoar, T. J., Hogan, T., Lynch, P., McLay, J., Reynolds, C. A., Sessions, W. R., Westphal, D. L., and Zhang, J.: Development of the Ensemble Navy Aerosol Analysis Prediction System (ENAAPS) and its application of the Data Assimilation Research Testbed (DART) in support of aerosol forecasting, Atmos. Chem. Phys., 16, 3927–3951, https://doi.org/10.5194/acp-16-3927-2016, 2016. https://creativecommons.org/licenses/by/3.0/

Toth, T. D., J. Zhang, M. A. Vaughan, J. S. Reid, and J. R. Campbell, 2022: "Retrieving Particulate Matter Concentrations over the Contiguous United States through the Use of CALIOP Observations", Atmos. Environ., 274, 118979, https://doi.org/10.1016/j.atmosenv.2022.118979. https://creativecommons.org/licenses/by-nc-nd/4.0/