ARM TR-019

Micropulse Lidar Handbook

March 2006

Atmospheric Radiation Measurement
Climate Research Facility
U.S. Department of Energy

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

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1. General Overview

The micropulse lidar (MPL) is a ground-based optical remote sensing system designed primarily to determine the altitude of clouds overhead. The physical principle is the same as for radar. Pulses of energy are transmitted into the atmosphere; the energy scattered back to the transceiver is collected and measured as a time-resolved signal. From the time delay between each outgoing transmitted pulse and the backscattered signal, the distance to the scatterer is infered. Besides real-time detection of clouds, post-processing of the lidar return can also characterize the extent and properties of aerosol or other particle-laden regions.

Figure 1. The micropulse lidar.

2. Contacts

2.1 Mentor

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2.2 Instrument Developer

Vendor/Manufacturer

Current Version:
Science and Engineering Services Inc. (SESI)
Contact: I.H. Hwang
Phone: 301-989-1896

New Version:
Sigma Space Corp
Contact: Savyasachee Mathur
4801 Forbes Boulevard
Lanham, MD 20706
Phone: 301-552-6300 x209
Fax: 301-577-9466
http://www.sigmaspace.com
Four are on order with an estimated time of arrival of July 2006, two repaired and one upgrade with an estimated time of arrival of August 2006
Seven total by FY 2007

3. Deployment Locations and History

SGP-C1, Lamont: The MPL at the Southern Great Plains (SGP) site is currently operating within specifications.

NSA-C1, Barrow: A prototype MPL having polarization sensitivity has been operating at Barrow since November 2003. As this capability is still under development, only the standard MPL product is being operationally produced from this prototype system.

TWP-C1, Manus: The MPL at Manus is currently operating within specifications.

TWP-C2, Nauru: The MPL at Nauru is currently operating below specifications. While still capable of detecting high cirrus, the daytime sensitivity is much reduced. This system is anticipated to be replaced in first quarter 2007.

TWP-C3, Darwin: The MPL at Darwin is currently operating within specifications.

AMF-M1, Niamey, Niger: The MPL at Niamey is currently operating within specifications.

In response to unacceptable downtime and lengthy repairs, the Atmospheric Radiation Measurement (ARM) Program is purchasing additional MPL systems. An additional six units are on order with an upgrade of the first Sigma unit with the new Nd:YAG laser. All ARM sites will receive the new units with the current MPL relegated as spares.

4. Near-Real-Time Data Plots

Near-real-time MPL data plots are available from the Data Quality Office for each site. Thumbnail images of the most recent data are available from the ARM DQHandS Plot Browser website. Select the site of interest and select the associated MPL datastream. For the SGP site, choose sgpmpl. Then choose either a list or thumbnail view option. The most recent week of data is the default range.

5. Data Description and Examples

See MPL Quick looks from National Aeronautics and Space Administration (NASA)-Goddard Space Flight center.

5.1 Data File Contents

Datastreams produced by the MPL are available from the ARM Archive:

5.1.1 Primary Variables and Expected Uncertainty

The MPL has one measurement channel that records backscatter signals up to 20+ km. The primary quantity from this signal is the lowest detected cloud base in meters.

Additional quantities possible through post-processing of the raw signal return include a relative backscatter profile at 523 nm. From the relative backscatter profile, other data products are possible including multiple cloud decks, cloud and layer boundaries, as well as aerosol extinction and backscatter profiles. After the new units are deployed, cloud phase information will also be available.

5.1.1.1 Definition of Uncertainty

The uncertainties in reported cloud base height have several sources. There is an inherent calibration uncertainty of the timing electronics of about 2%. This translates directly into an uncertainty of +/- 2% for all reported distances.

Also, the measured lidar profiles are collected in discrete “range bins” with finite width. Reported cloud heights are centered within the range bin, so cloud base heights will have an uncertainty of +/- 1/2 the range resolution. Early MPL systems deployed at SGP and Tropical Western Pacific (TWP) C1 (Manus) had a range resolution of 300 m. ARM MPL systems are currently operated with 30-m resolution including all MPL data ever collected from the North Slope of Alaska (NSA), TWP C2 (Nauru), TWP C3 (Darwin) and ARM Mobile Facility (AMF) M1.

Several uncertainties are more difficult to quantify. The MPL is an eyesafe lidar, and as such transmits a very low power laser beam, typically less than ~40 mW at 523 nm. Thus, it is subject to signal–to-noise limitations in conjunction with solar background noise. Moreover, the laser beam is attenuated or extinguished as it passes through the atmosphere. These two effects combine to make detection of high thin clouds more difficult during the day. Furthermore, over time laser systems degrade and produce less powerful pulses, so the sensitivity of the MPL will depend on the health of the laser system in the MPL. In addition to these measurement limitations, other uncertainties are difficult to quantify. Exactly “what is a cloud” is difficult to define. Algorithm differences can yield biases in reported cloud base height. More significantly, one algorithm may identify a particular atmospheric structure as being “cloud” while another algorithm may not, so algorithm sensitivity is also a difficult uncertainty to quantify.

5.1.2 Secondary/Underlying Variables

This section is not applicable to this instrument.

5.1.3 Diagnostic Variables

This section is not applicable to this instrument.

5.1.4 Data Quality Flags

Besides actual cloud-base heights, there are two sentinel values present in the data.

A cloud-base height = 60 km is reported for a “blocked beam” condition. Literally, this condition means that insufficient backscatter has been detected at even near-range bins. This situation can arise from heavy fog or can be caused by water, ice, or debris accumulating on the view port window.

A cloud-base height = 0 is reported when the sky overhead is determined to be cloud-free.

5.1.5 Dimension Variables

This section is not applicable to this instrument.

5.2 Annotated Examples

These two examples demonstrate typical MPL data. The Figure 2 represents a near perfect clear atmosphere. The structure between 03:00 - 11:00 hours and 2-6 km shows an elevated signal level caused by an aerosol layer. Other aerosol structure can be found else where, as well. Figure 3 demonstrates typical MPL data with clouds. Multiple cloud decks can be detected if the first deck is sufficiently optically thin, see 02:00-07:00 hours.

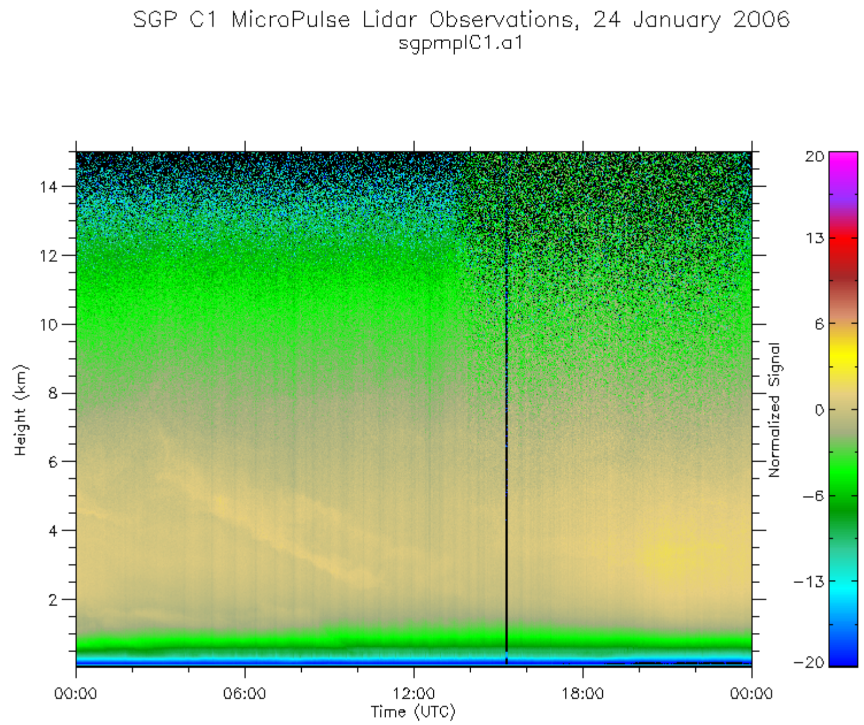

Figure 2. MPL data observations showing a near perfect clear atmosphere.

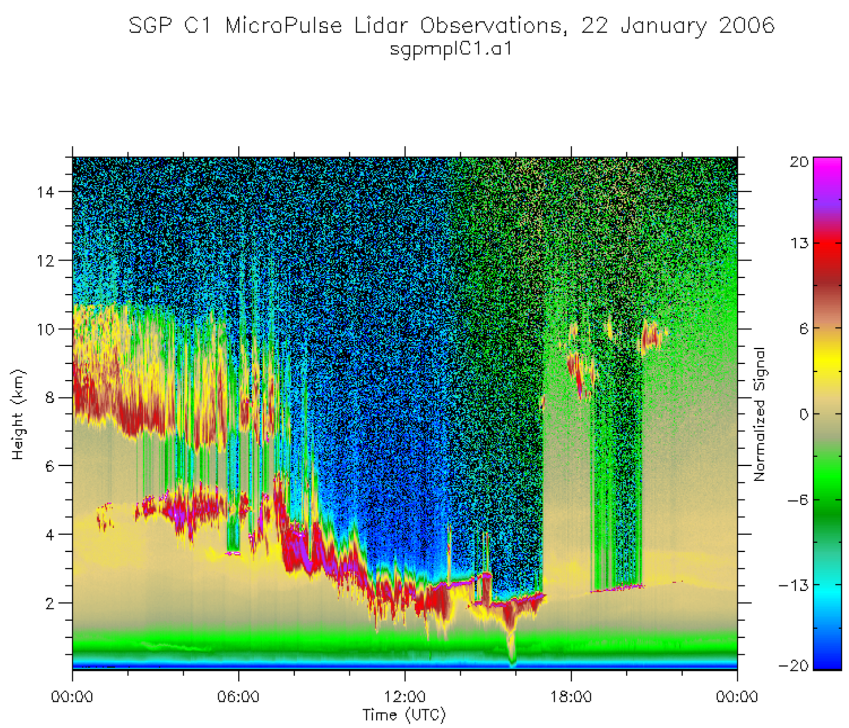

Figure 3. MPL observations showing typical MPL data with clouds.

5.3 User Notes and Known Problems

The MPL systems located at the tropics have additional safety hardware. A large shutter covers the telescope to prevent direct sunlight from striking the primary mirror in the telescope. The shutter closes every day at solor noon. The backscatter data will not be present during solar noon even though the system continues to produce records. No such precautions are needed when the latitude is great enough that the sun never appears directly overhead.

The current tropical locations are TWP-C1 Manus, TWP-C2 Nauru, TWP-C3 Darwin, NIM-M1 AMF Niger.

5.4 Frequently Asked Questions

What MPL datastream should I use for clouds?

Use the Active Remotely-Sensed Cloud Locations (ARSCL) if it is available. If not, then use MPLnor (MPL normalized). If neither is available, use the a1-level file.

What MPL datastream should I use for aerosol products?

ARM MPL aerosol retrievals are currently in development but are not operationally available. For limited periods, aerosol products from the ARM MPL at the SGP site are available from NASA's MPLnet. For qualitative indications of aerosol, the normalized backscatter profiles from MPLnor are excellent indicators of aerosol layers and relative abundance. Use of a1-level MPL datastreams for aerosol detection is not advised.

What is the lowest cloud the MPL can detect?

Early MPL systems had relatively coarse range resolution of 300 m. Also, these systems had high levels of detector "afterpulse," a long-lived residual of the transmitted laser pulse evident in the range-resolved profile, but not actually emanating from the atmosphere. Additionally, all MPL systems require correction of near-range signal with the magnitude of the correction increasing inversely with distance. These three elements combined to limit initial MPL cloud detection to about 300 m. Improvements in all three areas now offer the potential of reducing this to perhaps 60-90 bins, but current algorithms still use the old lower limits.

6. Data Quality

6.1 Data Quality Health and Status

The following links go to current data quality health and status results.

- DQ HandS (Data Quality Health and Status)
- NCVweb for interactive data plotting using.

The tables and graphs shown contain the techniques used by ARM's data quality analysts, instrument mentors, and site scientists to monitor and diagnose data quality.

6.2 Data Reviews by Instrument Mentor

QC frequency: Monthly basis

QC delay: Next week

QC type: Graphical plots

Inputs: Raw data

Outputs: Raw cloud base height (cbh) estimates compared with VCEIL and MPL cbh estimates; processed backscatter profiles

Reference: Routine data quality monitoring of the MPL at the SGP site consists mainly of cross comparisons of raw MPL cbh estimates with those from the VCEIL.

6.3 Data Assessments by Site Scientist/Data Quality Office

All DQ Office and most Site Scientist techniques for checking have been incorporated within DQ HandS and can be viewed there.

6.4 Value-Added Procedures and Quality Measurement Experiments

Many of the scientific needs of the ARM Program are met through the analysis and processing of existing data products into "value-added" products (VAPs). Despite extensive instrumentation deployed at the ARM sites, there will always be quantities of interest that are either impractical or impossible to measure directly or routinely. Physical models using ARM instrument data as inputs are implemented as VAPs and can help fill some of the unmet measurement needs of the program. Conversely, ARM produces some VAPs not in order to fill unmet measurement needs, but instead to improve the quality of existing measurements. In addition, when more than one measurement is available, ARM also produces "best estimate" VAPs. A special class of VAP called a Quality Measurement Experiment (QME) does not output geophysical parameters of scientific interest. Rather, a QME adds value to the input datastreams by providing for continuous assessment of the quality of the input data based on internal consistency checks, comparisons between independent similar measurements, or comparisons between measurement with modeled results, and so forth.

For more information, see VAPs and QMEs. Select MPL

Two VAPs currently use the raw MPL datastream. Whenever possible, the following VAPs should be used instead of the raw or a1-level MPL datastream.

- **MPLnor**: "MPLnor" stands for *MPL normalized*. It produces "normalized" backscatter profiles (in arbitrary units) with all known instrument artifacts removed. To improve signal to noise, MPLnor applies further temporal and spatial averaging. It also reports up to three layers of clouds along with cloud base and cloud top when possible. Both a “sensitive” and “robust” cloud mask are provided where the “robust” cloud mask is simply the “sensitive” mask with some filters applied to remove false positives.

- **ARSCL**: “ARSCL” stands for *Active Remotely-Sensed Cloud Locations*. It represents a composite product combining measurements from ceilometers, lidar, and radar. Lidar and radar measurements are complementary in that lidar are more sensitive to smaller particles often found in cirrus or low water vapor clouds. However, radar is able to penetrate multiple cloud decks that are impossible for lidar to penetrate. Thus, this composite product provides the best of both instruments and is currently the ARM Program’s last word on cloud detection.

In addition, several other VAPs involving MPL measurements are under development including thin-cloud optical depth retrieval and aerosol properties retrievals.

7. Instrument Details

7.1 Detailed Description

7.1.1 List of Components

The MPL consists of the following four main components: (1) a computer; (2) a dedicated data acquisition and lidar control system; (3) a Nd:YLF laser in the current systems, a diode-pumped Nd:YAG laser in the new systems; and (4) a co-axial transceiver for transmitting the laser pulses and detecting the collected photons. A description of each component is as follows

1. **The Computer**: Currently, IBM laptops are used with most of the ARM MPL systems. A migration to Dell desktops will deploy with the new MPL systems from Sigma.

2. **Lidar Control System**: The lidar control system provides conditioned power to the photon detector and laser energy monitor. It contains an integrated A/D converter for reporting vital system parameters to the instrument PC. It also contains the range-selectable multi-channel scalar which accumulates the range-resolved backscatter profiles. The current controller is a custom control system produced by Science and Engineering Services Inc. (SESI). The new systems use a custom controller produced by Sigma Space.

3. **Laser-Diode Pumped Nd:YLF or Nd:YAG Laser System**: A rack-mount laser system provides CW laser diode infrared pump radiation via fiber optic to the Nd:YLF laser head within the transceiver. The rack-mount laser system also controls the pulse repetition rate of the Nd:YLF laser head incorporated into the MPL transceiver (described below). Originally, all MPL systems used Spectra Physics diode lasers (model 7300 or “R-Series”), but as these lasers were discontinued all MPL systems now use laser systems with similar specifications from other third party vendors. The new MPL system will use a Photonics Nd:YAG diode pumped laser.

The wavelength is 532 nm instead of 523 nm from the Nd:YLF. Also the diode is integrated into the laser head instead of being fiber coupled. All other aspects of the lasers are similar.

4. **Co-Axial Transceiver**: The “transceiver” serves as both transmitter of the outgoing laser pulses and receiver of backscattered light. Approximately 1.0 watt of infrared CW pump radiation is converted to about 30 mW pulses of green laser light (523 nm or 532 nm) at 2500 Hz by the laser head with a non-linear optical frequency doubler. The pulses of green light pass through a linear polarizing beam splitter and a depolarizing wedge, and expand to fill an 8-inch Celestron telescope.

   The detection optics begins with the same 8-inch Celestron telescope. Returning photons incident on the telescope are collected and pass through the depolarizing wedge. About half of the collected photons pass through the polarizing beamsplitter cube and half are reflected. Light passing through the beamsplitter is collimated and passed through two narrow-band interference filters (0.15 nm fwhm) in order to reject most of the ambient light, and is ultimately focused onto a photon counting APD module from Perkin Elmer model SPCM-AQR-121-FC.

7.1.2 System Configuration and Measurement Methods

The MPL is configured to operate autonomously in an unattended manner 24 hours a day. Standard ARM deployments have the MPL oriented vertically (or slightly off vertical).

Figure 4 shows the main optical components internal to the MPL.

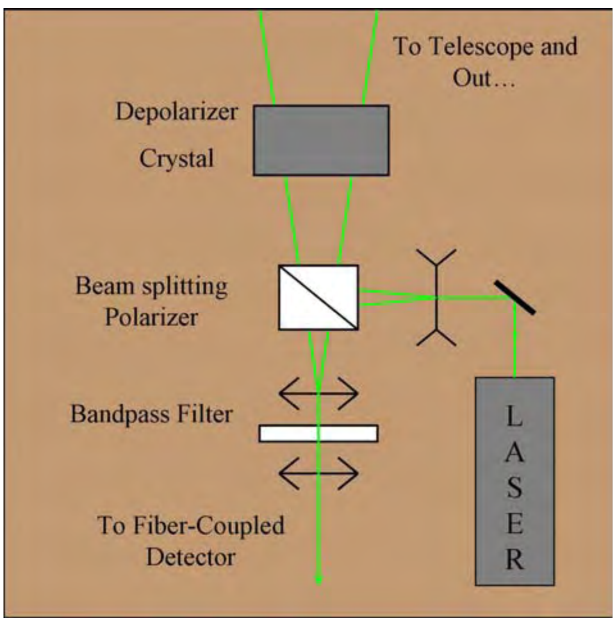

Figure 4. MPL Optical Block Diagram.

7.1.3 Specifications

Wavelength of laser pulse: 523.5 nm or 532 nm

Length of laser pulse: ~10 ns = 3 m

Range resolution (height interval): 30 m

Maximum range for cloud base height: 18 km

Typical averaging: 30 seconds

7.2 Theory of Operation

The principle is straightforward. A short pulse of laser light is transmitted from the telescope. As the pulse travels along, part of it is scattered by molecules, water droplets, or other objects in the atmosphere. The greater the number of scatterers, the greater the part scattered. A small portion of the scattered light is scattered back, collected by the telescope, and detected.

The detected signal is stored in bins according to how long it has been since the pulse was transmitted, which is directly related to how far away the backscatter occurred.

The collection of bins for each pulse is called a profile. A cloud would be evident as an increase or spike in the back-scattered signal profile, since the water droplets that make up the cloud will produce a lot of backscatter.

7.3 Calibration

7.3.1 Theory

Little calibration is necessary for cloud-base height determination. To fix the distance scale, it is necessary to use a calibrated-pulse generator capable of producing a trigger pulse and a second delayed pulse with an accurately known time lag. The two pulses are used to mimic a transmitted laser pulse and detected backscatter pulse with time delay relating to a simulated distance.

Absolute calibration of the magnitude of the lidar signal is much more difficult. The following instrument-level corrections are required:

1. "Dead-time" correction to account for detector non-linear response
2. Detector "afterpulse" subtraction
3. Background subtraction
4. Range-squared correction
5. Near-field detector overlap correction
6. Energy-monitor normalization.

7.3.2 Procedures

Detector "dead-time" correction

The silicon avalanche photodiode detectors do not respond perfectly linearly to varying incident light levels. Because the detected lidar signal varies by several orders of magnitude, corrections for detector non-linearity are required for absolute calibration. A vendor-supplied correction table relating detected count rate to actual incident count rate is provided by the vendor for this purpose.

Detector "afterpulse" subtraction

The detector exhibits transient counts due to initial saturation from the outgoing laser pulse. These transient counts appear in the collected profile and are significant at very near ranges (< 1 km) where the transient count rate is high and also at far range (> 10 km) where atmospheric signal is weak. By collecting profiles with the lidar cover in place, the afterpulse behavior of the detector is measured. This beam-blocked "afterpulse" profile is then subtracted from actual atmospheric profiles in post-processing. This subtraction is not perfect as it assumes that the afterpulse profile does not change over time and that the afterpulse present with a beam block in place is identical to that present during normal operating conditions.

Background subtraction

After application of the above two corrections, the ambient background is determined as the average count-rate present between 40-55 km. This averaged background is subtracted from the measured atmospheric profile.

Range-squared correction

The outgoing laser pulse presents a target of finite size. This target is imaged onto a detector with a finite field of view. When the spot size of the outgoing pulse becomes smaller than the detector field of view, the received signal exhibits a decrease in intensity proportional to the range squared. This is intrinsic to the optical detection method and is not representative of the atmospheric profile itself. To remove this measurement artifact, the measured signal at each range bin is multiplied by the square of the range to that range bin.

Near-field detector overlap correction

At near-range, closer than about 3-5 km, the spot size of the outgoing pulse yields an image larger than the detector field of view. This results in an under-representation of near-range signal. In order to characterize this near-field artifact, the lidar is operated with the beam oriented horizontally. Under appropriate well-mixed conditions, the horizontal profile should display an exponential dependence on range showing a nice linear shape at far range on a semilog plot. However, the measured horizontal profile at near range will show a distinct roll-off tending towards zero signal at zero range. At each range bin from 0 to 5 km a multiplicative factor is determined as the ratio of the expected exponential behavior and the measured signal. These multiplicative factors are characteristic of the optical overlap between the outgoing spot size as a function of range and the detector field of view. Correction of the measured profiles with this overlap correction yields properly characterized atmospheric profiles at near-range.

Energy-monitor normalization
Fluctuations in the laser output power or pulse energy appear linearly in the measured signal but are of course unrelated to the actual atmospheric profile. To remove this measurement artifact, the measured lidar signal is divided by laser energy are reported by an energy monitor internal to the lidar.

Absolute calibration
While application of the above corrections should yield an atmospheric profile of attenuated backscatter with all instrument artifacts removed, absolute calibration of the measured profile is problematic. In particular, the overall system transmittance is only coarsely known and no attempt is made to measure the transmittance of the MPL viewport window. Typically, determination of the overall system calibration is obtained by comparison of the relative profile against other external measurements, modeled results, or both. For example, the lidar system calibration my be determined by scaling clear-sky profiles to match a modeled Rayleigh attenuated backscatter profile at high altitude after compensating for optical depth typically provided by an external source.

7.3.3 History

As MPL systems are returned to Pacific Northwest National Laboratory for repair, timing calibration checks of the multichannel scalar are performed using Stanford Research Systems precision pulse generators with sub-nanosecond accuracy. We have never yet found a multichannel scalar out of specification. The MPLnor VAP applies each of the calibrations described in the above section. The detector deadtime corrections are from vendor-supplied data sheets unique to each detector. Each of the other corrections is determined either through measurements conducted during installation, or from the real-time data.

7.4 Operation and Maintenance

7.4.1 User Manual

This section is not applicable to this instrument.

7.4.2 Routine and Corrective Maintenance Documentation

Little maintenance is required other than routine cleaning of the viewport window and gentle cleaning of dust from the telescope. Daily visual checks are required to confirm the software or computer has not locked up. The inspection includes the computer clock and the 30-second backscatter profiles are updating.

7.4.3 Software Documentation

This section is not applicable to this instrument.

7.4.4 Additional Documentation

SGP Preventative Maintenance Procedure at SGP Site.

7.5 Glossary

See the ARM Glossary.

7.6 Acronyms

AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement Program
ARSCL	Active Remotely-Sensed Cloud Location
Cbh	cloud base height
MPL	micropulse lidar
NSA	North Slope of Alaska
QME	Quality Measurement Experiment
SESI	Science and Engineering Services, Inc.
SGP	Southern Great Plains
TWP	Tropical Western Pacific
VAP	Value-added Product

Also see the ARM Acronyms and Abbreviations.

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