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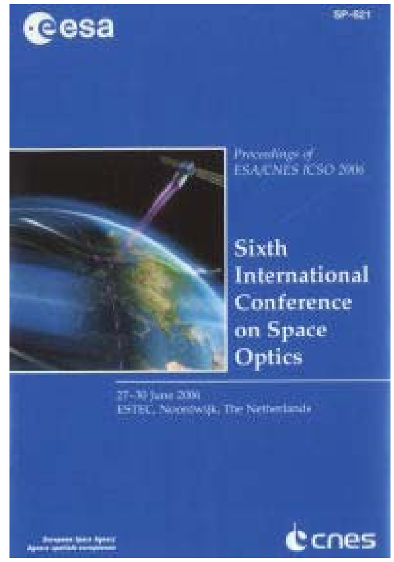

A novel spaceborne lidar calibration technique: the multi-calibration lidar experiment

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A NOVEL SPACEBORNE LIDAR CALIBRATION TECHNIQUE: THE MULTI-CALIBRATION LIDAR EXPERIMENT

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ABSTRACT

Although the noticeable progress achieved by ground-based lidars, using lidars as an operational spaceborne instruments still poses issues to be solved. A key issue is the long-term stability of the instrument over the mission lifetime, as a whole as well as at the level of each subsystem; another important issue is related to the processes of calibration in pre-launch and operational phases. Ground truth validation is also a critical process. This paper covers some of these aspects and focus on the instrument calibration and validation with a view of ensuring accurate instrument data during the whole instrument lifetime. The proposed concept is based on a combined space-ground lidar multi-calibration experiment using five lidars. The lidar instrument will be engineered for use in two versions: for ground and, qualified, for space. The lidar will need to operate at two wavelengths (first and second Nd-YAG harmonics), with polarization capability. Five similar instruments need to be employed. A spaceborne lidar will operate together with three ground-based lidar located in the tropics, sub-tropics and midlatitudes. A fifth lidar will operate for four months each year at each ground site. Such sites will coincide with the satellite overpasses. The measurement schedule will consists of series of simultaneous ground and satellite measurements at each site satellite overpass. Additional measurements from other instruments and local sites capabilities could be added.

1. INTRODUCTION

Using lidars in space for the study of the atmosphere is one of the relevant scientific and technological progresses achieved in the last years. Among the most relevant are the Lidar In-Space Technology Experiment (LITE) and Geoscience Laser Altimeter System (GLAS) missions [1]. LITE was flown on the Shuttle Discovery, operating during 10 days on September 1994. Important information was provided by that mission both for scientists and engineers [2]. GLAS, aboard the Ice, Cloud and Land Elevation Satellite (ICESat), was launched on January 2003 and is still operating [3]. ICESat's primary goal is to quantify ice sheet mass balance and understand how changes in the Earth's atmosphere and climate affect polar ice masses and global sea level [4]. Very recently a new space lidar have bee launched. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission is just beginning [5].

Notable efforts have been dedicated to the calibration and validation of the space lidar missions. Among them are relevant the ones conducted for LITE [6, 7, 8] as well as for GLAS [8, 9] and for CALIPSO [9, 10].

Several lidar networks are available for validating spaceborne lidar measurements, but the instruments have different features both with the space lidar as well as among the network instruments. Also under appropriated conditions the space lidar could be used for building transfer functions between the network lidars. But there are still unresolved problems. Among then the appropriated calibration is one of the most complex.

The study of cloud and aerosols radiative impact is an imperative of the current research on climate evolution. That is the main uncertainty in the current knowledge of the climate system [11]. Lidar measurements both ground and space based provide the detailed information about cloud and aerosols optical properties and vertical structure, necessary for evaluating its radiative impacts.

The mission proposed will have both scientific and technological goals. In one side, scientific, the intensive measurements of clouds and aerosol optical properties and vertical distribution will provide a unique ground and space lidar merged dataset. It will be useful for many different research subjects on clouds and aerosols, including their radiative impacts. In the other, technological, the improvement of the calibration procedures and the generation of transfer functions between ground and space based lidars. It will have an important impact on the quality of the merged ground and space based measurements. Also the long-term stability of the same instruments design under ground and space conditions will be tested. The

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information derived from such studies will provide the basement for future lidar designs.

2. LIDAR DESIGN:

As in the CALIPSO design the whole system will consists on a laser transmitter subsystem, a receiver subsystem, and the payload controller subsystem. The flying system will have three similar lasers. They will operate singly for a period of two years. They will serve also as backup laser in case of the failure of the preceding operating laser before his two years operations ended. The other four lidar systems with the same general design will have only one laser.

Table 1: Space lidar Transmitter Required Parameters

Laser	Diode-pumped Nd:YAG
Pulse Energy	> 100 mJ: 532 nm
	> 100 mJ: 1064 nm
Rep Rate	> 30 Hz
Pulse Length	20 nsec
Line width	30 pm
Polarization Purity	99.9% (532 nm)
Beam Divergence	100 μrad (after beam expander)
Boresight Range	±1 degree, 1.6 μrad steps

The transmitter will consist on diode pumped Nd:YAG lasers operating at the fundamental and doubled wavelength. The second wavelength (532nm) will be polarized. On Table 1 the minimum required parameters for the space lidar transmitter are shown. Laser power higher than 100mJ will be required. Also repetition pulse higher than 30Hz will be used. Parameters were selected considering the CALIPSO improvements and the most recent advances in laser technology. Appropriated beam expander and beam steering systems will guarantee alignment between transmitter and receiver. One important particularity in the transmitter design for the four ground based lidars is that the beam divergence after the beam expander should be 2.3 mrad. That feature will allow similar footprints diameters at 15km of altitude above ground both for the space and ground based lidars. It will play a main role in the multi-calibration procedure described below.

Receiver will operate at three channels. The first will operate in analogical regime at 1064nm with an arrangement of avalanche photodiodes (APD). The second at third channel will operate at 532nm in photo counting regime, using high efficiency photo multiplier tube (PMT) detectors. The original 532nm returned signal will be separated in two orthogonal polarized components. For reducing the solar background illumination in the 532-nm channels, a narrowband etalon in combination with a dielectric interference filter is used.

Because in the atmosphere the molecular, aerosol, and cloud backscattering cover a big range of values, the linear dynamic range of the lidar should spans many orders of magnitude. Consequently the lidar linear dynamic range should be no less than $4 \times 10^6 : 1$.

Table 2: Lidar Receiver Required Parameters

Telescope diameter	≥ 1 meter
Field of View	~ 100 μrad
Digitization Rate	> 10 MHz
Linear Dynamic Range	$> 4 \times 10^6 : 1$
1064 nm Channel	
Detector	APD
532 nm Channel	
Detectors (2)	PMT
Polarization Beam Splitter	

The inclusion of the capability of measuring volume depolarization at 532nm follows important improvements of CALIPSO [5] over LITE [2]. Laser output at 532nm will be polarized. The receiver system will be designed to detect changes in the return signal at this wavelength. The signal will be separated in two orthogonal polarization components. Then the parallel and perpendicular polarized signals will be registered separately by independent PMTs. The figure 1 shows schematically the receiver design.

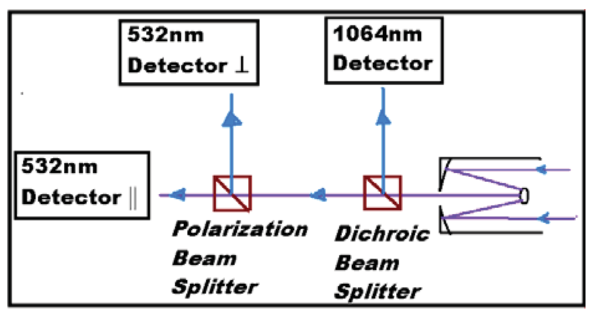

Figure 1: Block diagram for the lidar receiver.

All the five lidars will consist in the same design. The lidar instrument will be engineered for use in two versions: for ground and, qualified, for space. The test of the same design operating simultaneously both in space and at the ground is an important component of the experiment. The mobile (fifth) lidar will have design particularities for guaranteeing its roughness because its destination to be transported to different lidar sites, as well as its airborne and ship borne temporal deployments.

Each of the lidar systems will be complemented with an imaging infrared radiometer following the successful results achieved by CALIPSO with similar instrument arrangement [5]. Its goal is to retrieve cirrus clouds particle sizes. That information will be used for one of the calibration procedures, explained below.

3. PROPOSED MEASUREMENTS STRATEGY

The proposed concept is based on a combined space-ground lidar multi-calibration experiment using five similar lidars. A spaceborne lidar will operate together with three ground-based (stationary) lidar located in the tropics, sub-tropics and midlatitudes. A fifth lidar will operate, in one version of the experiment design, for four months each year at each ground site. Additionally airborne mission's carrying the fifth lidar will be conducted once a year.

In other version of the experiment design the fifth lidar will operate in situ with another lidar different for the three ground based mentioned earlier. It will take place in the frame on international experimental campaigns engaging at least one of the ground sites. Such sites geographical location will be selected guarantying the best coincide possible with the satellite overpasses. Also an appropriated latitudinal distribution will be guaranteed for conducting measurements in the tropics, sub-tropics and midlatitudes. Fig. 2 depicts schematically the latitudinal distribution of the lidars. An option to consider is to install the fifth lidar on a ship for increasing the number of space and shipboard coincident measurements. This subject is discussed below.

The measurement schedule at the ground sites will consists of regular measurements the year around. Intensified series of measurements at the ground sites will be conducted at each satellite overpass. These measurements will be planned for producing the best spatio-temporal coincident measurements between ground and satellite lidars. Additional measurements from other instruments and local sites capabilities (as sun photometer, millimeter radar etc.) will be added.

Standardized processing and quality control algorithms will be applied for all ground-based measurements. Space lidar measurements will be subject to the appropriated quality control and processing. Then the sets of spatio-temporal coincident measurements will be inter-compared. Adjustments in the processing algorithms for both ground and spatial measurements will be applied for obtaining the best possible agreements for the aerosol and cloud parameters measured. The resulting sets of measurements will then be merged, producing a unique dataset.

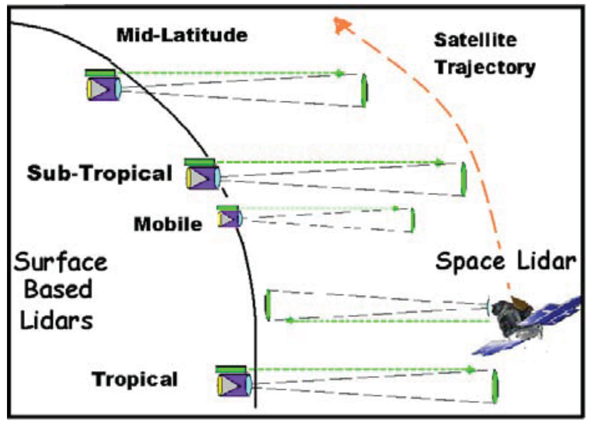

Figure 2: Schematic diagram of the lidar arrangement.

Making use of fifth, mobile lidar, together with the space lidar, the resulting set of measurements will be used then to obtain transfer functions among the three ground based lidars. Using only the coincident measurements of the space lidar with other lidars, transfer functions will be developed. The stress of the transfer function using both different methods will be tested.

Another alternative to consider is to install the fifth lidar onboard a ship. The ship could be located precisely at overpasses positions. To the author's knowledge that option has been not used until the present for calibrating and validating space based lidars. In the long-term using a shipboard lidar could be less expensive than using a lidar onboard an aircraft. Other benefit is that the shipboard lidar will measure the whole atmosphere column from the sea surface to the stratosphere. That is not possible using airborne lidars, because they are not able to measure the lower levels of the atmospheric boundary layer. Also operative decisions could be taken for moving the ship carrying the lidar to a better position to sample high aerosols concentration cores. It could be the case of an explosive volcanic eruption carrying considerable amount of aerosols to the stratosphere. Another case could be a Saharan dust layer traveling across the Atlantic to the Caribbean. The advantages of installing the fifth lidar onboard a ship makes this option suitable for consideration.

Main technical parameters of the instruments will be registered and stored in files different from the files containing measurements information. In the case of the space lidar such information will be transmitted together with the telemetry and measurement information.

4. SIMULATION AND TEST REQUIRED

The expected performance both of the space and ground based lidar design versions should be modeled. The end-to-end model should simulate the synthetic lidar signals based on system parameters and the different mechanisms of the interaction of the laser radiation with the atmosphere constituents. The system parameters will include lidar transmitter and receiver and satellite orbital parameters.

The simulations should take into account the more recent achievements in this subject. In that sense it will include the improvements introduced in the recent simulations conducted for GLAS, CALIPSO and WALES [4, 12, 13, and 14].

The laser should be tested for degradation and stability to qualify for a space mission. The whole receiver and transmitter subsystems, in his space version, should be tested to qualify for a space mission too. A similar version design of the laser and both subsystems, but with fewer requirements than for a space mission, will be used for the ground based lidars. The mobile lidar will be tested for its roughness considering its mobile condition as well as its alternative deployment on board an aircraft and/or a ship.

Pre-launch tests of the space lidar will be conducted for guaranteeing the instrument qualifies for space operation. Particular pre-launch tests will be conducted for determining the lidar constant. Similar tests will be conducted with the rest four lidars for determining the lidar constant for each one.

5. CALIBRATION PROCEDURES

Several state of the art calibration procedures will be used for this mission. The first will be the determination of the lidar constant in pre-launch tests for the space lidar at both wavelengths. It will be followed by in flight molecular calibration for 532nm. It will use nighttime observations in the upper stratosphere, following the procedure conducted for LITE [7]. Then the 1064 nm return channel will be calibrated with reference to 532 nm calibrations. Another calibration technique to be used will be conducting comparisons of the 532- and 1064-nm backscatter signals from cirrus clouds [8].

Other of the procedures will consist in the measurement of the solar radiation scattered by ice clouds. Because the background scattered solar radiation by ice clouds is almost completely unpolarized, there are little differences between the two polarization channels [10].

Additionally, technical studies will be conducted about the performance of the same instrument design in different conditions. It will cover the performance of space, ground-based, airborne and ship borne lidars (in case that this last option is used). For that purpose the files containing technical information will be classified and stored appropriately.

6. MULTI-CALIBRATION

This is the core of the proposed mission design. The task will be conducted in three steps. The first one will be the individual inter-calibration of each one stationary lidar with the mobile one. The second step will the inter-calibration of the mobile lidar and the space lidar. The third and final step will be the inter-comparison of the coincident calibrated space lidar measurements with the three calibrated stationary lidars dataset. The final product of this step will be an assembled lidar database merging the five lidar inter-calibrated profiles, together with the estimates of the percent differences derived from the coincident measurements. Table 3 depicts each step together with the participating lidar and output datasets.

Table 3: Multi-calibration steps, participant lidars and output.

Step	Participating lidars	Output
1	Mobile + individual stationary	Level 1: calibrated profiles (3 sets)
2	Mobile + space	Level 2: calibrated profiles (1 set)
3	Mobile + all stationary + space	Level 3: assembled calibrated profiles (1 set) % differences estimates

6.1 Individual inter-calibration of the mobile lidar with each stationary lidar

The three sets of simultaneous measurements of the mobile lidar with each one of the stationary lidars will be used in this step. Using the mobile lidar as calibration tool, each one of the three individual profiles datasets will be calibrated having the mobile lidar as the reference. Using the simultaneous stationary lidar calibrated measurements and the mobile lidar measurements an individual transfer function will be derived for each stationary lidar. That function will be used for re-calibrating the rest of not-simultaneous measurements conducted at each individual stationary lidar. Three new calibrated datasets will be produced using those functions, one for each stationary lidar. This will be the Level 1 calibrated data, consisting in three sets of ground based measurements.

6.2 Inter-calibration of the mobile and space lidar

One set of coincident measurements will be used in this step. It will contain all the spatio-temporal coincident measurements of the mobile and the space lidars. Special software will be developed for processing those coincident measurements. It will include the initial separately processing of the space lidar and the mobile lidar with particular algorithms for the space and mobile lidars. Then the inter-calibration of both instruments will be implemented. Depending on the atmospheric conditions, under which the measurement was conducted, molecular density, cirrus clouds or aerosols will be used for inter-calibrating both instruments.

A new inter-calibration procedure will be tested. The backscattered signal at the level of "common footprint" will be used for that purpose. Because of the different beam divergence between the space lidar and the other four ground lidars, at certain level both instruments will have the same footprint. That feature is shown schematically in figure 3.

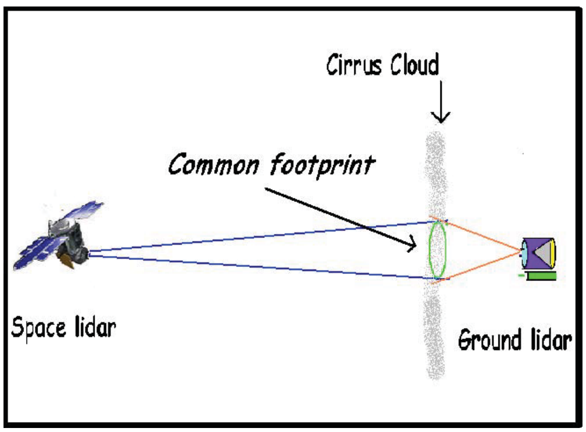

Figure 3: Schematic diagram of the different beam divergences between the space and ground based lidars. The so called common footprint is shown.

Table 4 shows the footprint diameters and areas calculated for the beam divergences of the space lidar (100µrad) and the ground based lidars (2.3mrad). The last row contains the space lidar to ground lidar footprint area ratio. The so called common footprint is reached at the altitude of 15km where the ratio is 1. That is the altitude level where the space and ground based lidar sample the same volume of the atmosphere. The beam divergences were selected for establishing the common footprint at this altitude, because that is in general free of aerosols and few clouds reach that level. Only in the tropical regions deep convection and cirrus clouds reach that level. In the case of the cirrus they could serve as calibration target [10].

The procedure consist in using the return signal of both space and mobile lidar for inter-calibrate both instruments. As in the former step, the mobile lidar will be used as reference.

Table 4: Footprints of the ground based and space lidars at three altitude levels.

	Altitudes	10km	15km	20km
Space Lidar	Diameter (m)	69.5	69.0	68.5
	Area (m^2)	3,793	3,739	3,685
Ground lidar	Diameter (m)	46.0	69.0	92.0
	Area (m^2)	1,662	3,739	6,648
Space/round based area ratio		2.3	1.0	0.6

Once the space lidar coincident profiles with the mobile lidar have been inter-calibrated a transfer function will be derived. It will be used to re-calibrate all the space measurements not coincident with the mobile lidar. The resulting space lidar measurements set will be the Level 2 calibrated dataset.

6.3 Inter-comparison and merging of the datasets

The four calibrated datasets (space plus three ground based lidars) together with the mobile lidar (reference dataset) will be used in this step. Spatio-temporal coincident measurements between the calibrated space lidar profiles and the three calibrated ground based profiles will be selected. They will be used for calculating the differences between each pair of instruments (the space and each one ground based) for clouds and aerosols separately. Such differences are determined by the instrumental errors and the natural variability, in space and time, of the atmospheric parameter measured.

Then the five lidar datasets, the four calibrated and the mobile reference one, will be merged producing a unified, calibrated dataset.

7. FINAL REMARKS

It has been proposed combining lidars with similar design and instrumentation located in space and at the ground for a complex multi-calibration experiment. Both scientific and technological questions will be answered, providing better capabilities for combining lidar measurements both in space and ground based. A unique lidar dataset will be provided, covering scientific and technological interests. The present design is based on an elastic backscatter lidar for measuring cloud and aerosols, but is not exclusive for other parameters. Similar designs could be applied for DIAL and wind lidars. A more ambitious design will include several space instruments like the current developing A-train with two or three ground based sites equipped with instruments replicating the ones in space. Additional mobile instruments versions will complement the whole design. Then an instrument by instrument multi-calibration will be conducted.

Existing capabilities at the sites selected for installing the stationary lidar could be used. It includes sunphotometer, millimeter radar, spectroradiometers and any other instruments conducting measurements directly related to aerosol and clouds features.

The carry out the proposed mission design will require the assembly of a multidisciplinary working team consisting of two main groups. One will be devoted to the scientific goals and the other to the technological. International cooperation will be necessary for the developing and conduction of such mission. There are several research teams all over the world with experience in space lidar instruments design and construction who could contribute with expertise and personnel for the implementation of the proposed mission design.

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