LIDAR ALGORITHMS FOR ATMOSPHERIC SLANT-RANGE VISIBILITY, PLANETARY BOUNDARY LAYER HEIGHT, METEOROLOGICAL PHENOMENA AND ATMOSPHERIC LAYERING MEASUREMENTS

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Abstract

A development of novel algorithms and techniques implemented within the Laser Remote Sensing Unit (LRSU) of the National Technical University of Athens (NTUA), in collaboration with Raymetrics S.A. is been made, in order to incorporate them into a 3-Dimensional (3D) scanning lidar system. The lidar is transmitting at 355 nm in the eye-safe spectral region and the measurements are then transposed to the visual range at 550 nm, according to the World Meteorological Organization (WMO) and the International Civil Aviation Organization (ICAO) rules of daytime visibility reference. These algorithms are able to provide 3D visibility for tower aircraft controllers, meteorologists, but also from pilot's point of view. Other algorithms are also provided for the detection of the 3D atmospheric layering and the Planetary Boundary Layer Height (PBLH).

Introduction

Flight and ground safety at airports has to do, in many ways, with visibility and meteorological conditions in the area. A major flight safety issue is to obtain visibility measurements, especially from the pilot's point of view and to be able to have accurate measurements of some meteorological parameters, not only above the airport, but also in Slant Range (SR) directions. According to [1] the atmospheric visibility is a complex phenomenon to be estimated because of the psychological and physical condition of the observer and has to do mainly with the atmospheric extinction coefficient compared with molecular and aerosol particles in solid or liquid form in the atmosphere. The atmospheric extinction comes mainly from scattering and less from absorption of light. The visibility estimation varies and is based upon individual perception, the light source characteristics and the transmission factor. During the last years many operative techniques have been developed to estimate the atmospheric visibility and provide real time meteorological conditions at airports like scatterometers, transmissometers, nephelometers, telephotometers, etc. Additionally, automated algorithms for atmospheric layering detection noise subtraction have been, already, proposed [2]. The detection was made typically using the slope and other techniques, which presume a homogeneous atmosphere [3]. Another algorithm called STRAT [4] is using SNR (Signal to Noise Ratio) and molecular power received thresholds to derive atmospheric layering , cloud and PBLH detection. Therefore, to our knowledge there are no studies comparing aerosol backscatter and extinction coefficients derived from vertical and slant range (multi-angle) measurements, in **non**-homogeneous atmospheres, except using synthetic lidar data in homogeneous atmospheres [5]. Also novel algorithms are demonstrated for the extraction of PBLH using a new technique.

Instrumentation

The lidar system used for this study is the EOLE 10-wavelength elastic-Raman-DIAL lidar system which is located in Athens, Greece (220 m, asl.) at LRSL-NTUA. It can perform independent measurements of $\alpha_{aer}(\lambda,R)$ and $\beta_{aer}(\lambda,R)$ (at 355, 532 and 1064 nm), as well as the water vapor and ozone mixing ratio in the troposphere [6]. The algorithms presented in this paper were qualified and tested (at 355 nm and verified by the data obtained at 1064 nm) based on EOLE data [6]. These algorithms will be then implemented in the software of the 3D scanning lidar system constructed by Raymetrics S. A., based on 355 nm with co-polar and cross-polar detection channels, and 387 nm N_2 Raman detection channel, designed for aviation, meteorology and environmental applications for vertical and slant range measurements.

Fig. 1: 3D scanning lidar by Raymetrics S. A. based on 355 nm with co-polar and cross-polar detection using a 387 nm N_2 Raman detection channel, designed for aviation, meteorology and environmental applications for vertical and slant range measurements.

Fig. 2: EOLE 10-wavelength elastic-Raman-DIAL lidar system which is located in Athens at LRSL-NTUA. It can perform independent measurements of $\alpha_{aer}(\lambda,R)$ and $\beta_{aer}(\lambda,R)$ (at 355, 532 and 1064 nm), as well as the water vapor and ozone mixing ratio in the troposphere [6].

NOSUB-S/R

Once we have calculated the signal RCS, we apply a denoising filter to effectively reduce the noise of the lidar return signal and to automatically estimate the reference calibration height (Rref). To this end, two novel filters are mainly used. These are the NOSUB-S Filter (NOise SUBtraction algorithm by Steps) and the NOSUB-R Filter (NOise SUBtraction algorithm by Ratio). A number of steps taken for each NOSUB and they can operate autonomously or in cooperation, for $\alpha_{aer}(\lambda,R)$, $\beta_{aer}(\lambda,R)$ or $P(\lambda,R)$ values. The algorithms can be applied, from the first vertical measurements, to the $P'(\lambda,R)$ values, using the BPS method and automatically selects Rref, which is recalculated each time according to LADDER technique.

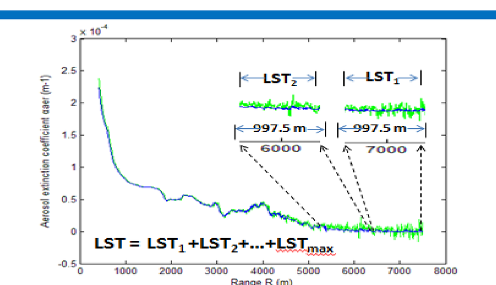
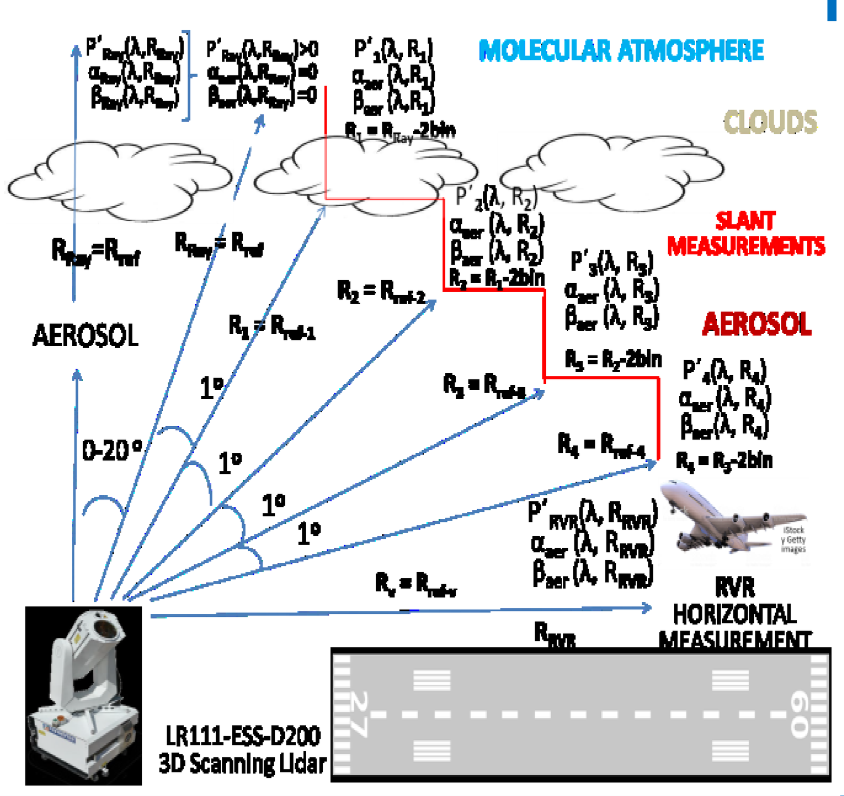


Fig. 3: Application of NOSUB-S/R on $\alpha_{aer}(\lambda,R)$ values retrieved at 355 nm. The green line denotes the retrieved $\alpha_{aer}(\lambda,R)$ and the blue line is the denoised one. "Distance packages" typically equal to 997.5 m for each LST.

LADDER Technique

There has been a lot of questioning on whether aerosol backscatter $\beta_{aer}(\lambda,R)$ and extinction $\alpha_{aer}(\lambda,R)$ coefficients can be derived from operational lidar slant range measurements without any large error estimations, resulting from assumptions like atmospheric homogeneity conditions presumed, in a large scale and on automatic retrieval of these values [7,8]. Methods like the slope technique or the ratio method are mainly using the assumption of homogeneous atmospheres over longer distances, to provide slant range atmospheric parameters; however in this way, the error on the derived parameters increases due to the instability of the prevailing atmospheric conditions, as a function of distance R. Other methods like the multiangle one, assume that a horizontal constant value of $\beta_{aer}(\lambda)$ is present at any distinct height, which is not the case for the LADDER technique and "real" atmospheres. Moreover, the Optical Depth Solution according assumes that the aerosol backscatter to extinction coefficient is constant and the optical depth must be estimated by other independent measurements, in the vertical direction, like from a solar radiometer, or by a Raman lidar. Even if this method seems to work well, the problem becomes noticeable when trying to make slant-horizontal range measurements, where this value cannot be retained as constant and cannot be found, especially in horizontal measurements and in longer ranges, where the lidar signal may become too noisy. According to lidar equation and the work of Klett [9,10], in vertical pointing measurements, there is an aerosol-free height, where we can set the $\alpha(\lambda,R)$ and/or $\beta(\lambda,R)$ equal to their molecular values. Scanning the atmospheric volume by a 3D scanning lidar, we can retrieve $\alpha_{aer}(\lambda,R)$ and/or $\beta_{aer}(\lambda,R)$ by making measurements like "stair steps" from vertical to horizontal direction, every 1°, like "walking down a ladder". In this way, we take as reference height (Rf), the distance at which we abstract 1-2 slant - height bins (1 bin is equal to the spatial resolution ΔR) for every new measurement and we retain the last value of $\alpha_{aer}(\lambda,R)$ and/or $\beta_{aer}(\lambda,R)$, at which RF was previously taken, as the new calibrating values for $\alpha_{aer}(\lambda,R)$ and/or $\beta_{aer}(\lambda,R)$. Furthermore, the LADDER technique maybe compared to the Boundary Point Solution (BPS) [11]. BPS assumes that the aerosol backscatter to extinction coefficient is constant and range-independent and sets the extinction coefficient as a known value at a specific range (boundary conditions). The same technique was used by Klett [9,10] and this setting of initial conditions is the only similarity with LADDER technique: in this technique, after the first vertical lidar measurements and the use of the NOSUB-S/R denoising algorithms, the reference height is calculated, such as the values of $\alpha_{aer}(\lambda,R)$ and/or $\beta_{aer}(\lambda,R)$ become zero. Then, it is easier to retrieve $\alpha_{aer}(\lambda,R)$ and/or $\beta_{aer}(\lambda,R)$ for lower heights from the lidar signal.



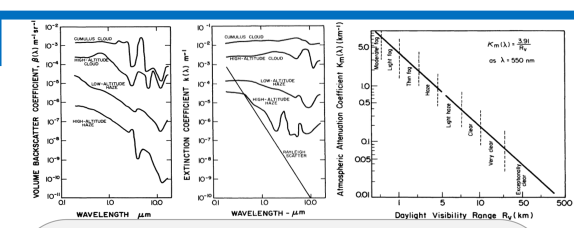


Fig. 4:(Left) Aerosol volume backscatter coefficient as a function of wavelength for different types of clouds and haze [12]. (Middle) $\alpha_{aer}(\lambda,R)$ as a function of wavelength λ [12]. (Right) Variation of atmospheric extinction coefficient with visibility range Rv, at the wavelength of 550 nm and contrast ε=0.02 [12].

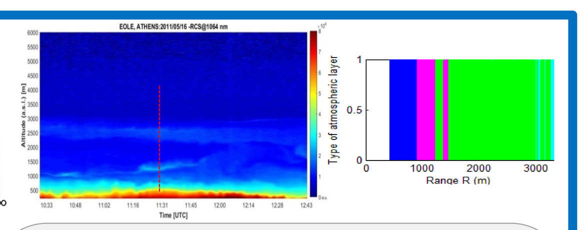


Fig. 5:(Left) RCS signal acquired at 1064 nm by the LRSU-NTUA. (Right) NAVIS and METCON algorithms applied in 3D lidar data pointing to the vertical (355 nm) at 11:30:10 UTC, starting at 417.5 m a.g.l. up to 3000 m. Blue color denotes "Light Fog", Purple "Thin Fog", Light Blue "Light Haze" and Green "Haze". Tower visibility is 523 m and pilot's visibility is 1928 m from the range of 3000 m.

METCON and NAVIS

METCON (METeorological CONditions) and NAVIS-T/P (Novel Algorithm for VIsibility measurement) – T (Tower of the Airport)/P (Pilot) algorithm (cf. Figs. 4 and 5) are able to provide meteorological conditions like clouds, haze, fog, etc., versus distance (R), for any vertical or slant range lidar measurements plus the visibility. The same 3D scanning lidar can be used to characterize the atmospheric conditions and visibility. It takes into account Fig. 4 as provided in [12]. In this Fig. well qualified Koschmieder law is been used for $\alpha_{aer}(\lambda,R)$ and $\beta_{aer}(\lambda,R)$ vs R for visibility and transpose from 355 nm (lidar) to 550 nm.

VASPAT-L/D Algorithms

A novel algorithm called VASPAT-VARiable SPAce Time is used to determine aerosol layering (L) and distribution (D), based on the existence of the $\beta_{aer}(\lambda,R)$ and $\alpha_{aer}(\lambda,R)$ coefficients, in 3D of the current atmosphere. VASPAT-L/D is pre-required for the next presented algorithm VASPAT-PBLH. In VASPAT-L/D we take the values of $\alpha_{aer}(\lambda,R)$ or $\beta_{aer}(\lambda,R)$ versus height or slant range distance (R); we then create "space filters" of different number of bins, in order to create different "tools", to further process the $\alpha_{aer}(\lambda,R)$ and/or $\beta_{aer}(\lambda,R)$ profiles. In this work we used 12 different space filters (G2 to G269) from 15 m (2 bins) to 2017.5 m (269 bins), a good space filter for the RVR .

Afterwards, we check if the measured value of the calculated $\beta_{aer}(\lambda,R)$ in any of these filters is greater than $1.2*10^{-6}$ m^{-1} sr^{-1} and lidar ratio $C(\lambda,R) = 1/3 * 10^{-2}$ sr^{-1} ($\alpha_{aer}(\lambda,R) > 4*10^{-5}$ m^{-1}) [12]. Then, we check if the ratio of two consecutive average values of $\alpha_{aer}(\lambda,R)$ in any of these "space filters" from a package of bins to the next package of equal number of bins are greater than 10-12%. As next step, the algorithm calculates the derivatives of all space filters (dG3/dR), at every distance (R), for vertical or slant measurements and we do the same to produce the 2nd order derivatives (d^2G3/dR^2). A series of calculations is thus been made to provide the atmosphere aerosol layering (VASPAT-L) so that we will be able to have a clear vision of the 3D spatial distribution of $\alpha_{aer}(\lambda,R)$ and/or $\beta_{aer}(\lambda,R)$ around airport sites (VASPAT-D). We check if these 1st order derivatives have the same sign for a number of continuing space filters like G2, G3 and G5.

So, if the first order derivatives with the same sign correspond to values greater than 30° angle change, we keep these values at distance (Rx) and we give them a type of 'beginning' (positive values of first order derivatives and negative values of second order derivatives "plus" 12% change of $\beta_{aer}(\lambda,R)$ from the next package of equal number of bins) or 'ending' (negative values of first order derivatives and positive values of second order derivatives corresponding to values greater than 30° angle change "plus" 12% change of $\beta_{aer}(\lambda,R)$ from the next package of equal number of bins).

Furthermore (Fig. 6) with blue color we show the 'beginnings' and with green color the 'endings' of a case presented for that purpose. In this way we are able to produce in total, atmospheric Layering (VASPAT – L) and we are able to have a clear understanding of the Distribution (VASPAT – D) of the attenuation coefficient ($\alpha_{aer}(\lambda,R)$) and/or backscattering coefficient ($\beta_{aer}(\lambda,R)$) in a 3D way surrounds a 3D scanning lidar or an area, for example, an airport.

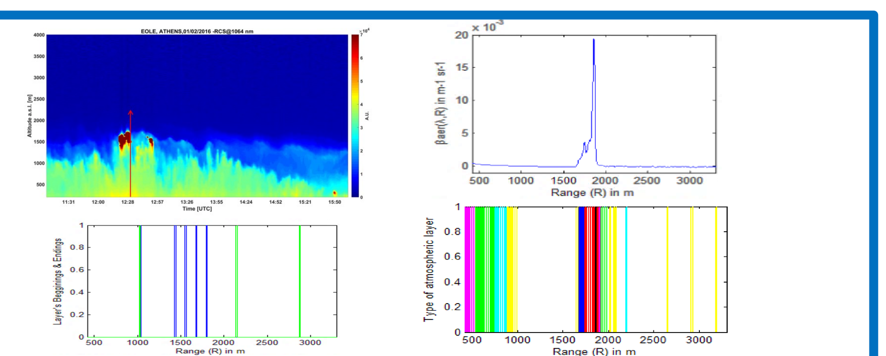


Fig. 6: (Upper Left) RCS signal acquired at 1064 nm from LRSU NTUA data (01/02/2016) (Upper Right) $\alpha_{aer}(\lambda,R)$ values acquired at 12:29:40 UTC (Bottom left) VASPAT – L / D algorithm in use at a 3D lidar in vertical position, at 355 nm, starting at 417.5 m above ground and ending around 3000 m. With blue color are the 'beginnings' and with green color are the 'endings' in total agreement with (Bottom right) colored visualization of meteorological conditions according to METCON algorithm, where blue color is light fog equivalence, red is moderate fog, purple is thin fog, green is haze, light blue is light haze and yellow denotes 'Sky clear' – 6 km to 10 km visibility.

VASPAT-PBLH Algorithm

Another novel algorithm called VASPAT-PBLH is presented here. At first, we place the 3D scanning lidar pointing to the vertical or up to ±20° around the vertical. Then, we start measuring for at least 15-20 min in order to acquire at least 15-20 or more lidar data files. Then, we proceed to time filters. Keeping the outcomes provided by VASPAT-L/D, we can make use of time filters after the use of the above mentioned space filters. In this case, our goal is to find the PBLH with a time slot corresponding to 15-20 lidar data files (e.g. each data file is acquired within 1.5 min.) Then, we keep track of the layering (L) and distribution (D) calculated values, and then, we make use of the layer "endings" ($\alpha_{aer}(\lambda,R)$ negative 1st derivative and positive 2nd derivative).

Then, we check which is the most common time depending "ending" layer in all times series within for e.g. 15-20 min period of measurements, which finally, determines the most probable PBLH. In this algorithm we tread PBLH as a layer 'ending' with no 'beginning' in every specific small time frame of 15 or more minutes. The ideal would be half an hour of recording time of $\alpha_{aer}(\lambda,R)$ and/or $\beta_{aer}(\lambda,R)$, but in any case less than an hour where PBLH could have a small or medium change especially in medium weather conditions.

The idea is to take advantage of that unique characteristic of PBL. To avoid tracking a common layer ending as PBL, we keep track of the matrices that the 'beginnings' produce in order to subtract them and their corresponding 'endings' from our final PPBL matrix of Possible PBL heights. In this way, we exempt of some common possible PBL heights and then we try to find common 'endings' that correspond to a produced PPBL matrix. The algorithm can be restricted by a maximum altitude of PBLH of 3000 m, 4000 m or even 5000 m depending on the latitude of the measurement and most common PBLH through past years. VASPAT-PBLH algorithm uses different settings depending on the atmospheric conditions and guided by VERDE (VERtical DECision) algorithm presented here.

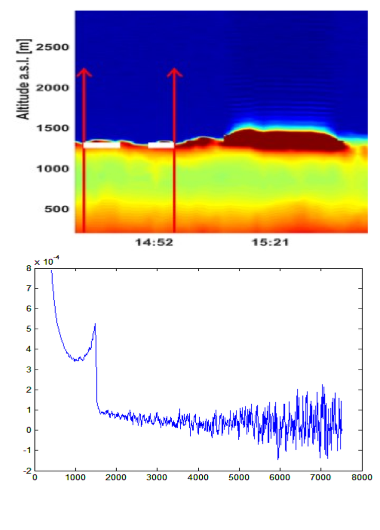


Fig. 7: (Up) RCS signal acquired at 1064 nm from LRSU NTUA data at 31/10/2011 from 14:33:10 to 14:56:30 UTC, where VASPAT – PBLH gave PBLH estimation, (Bottom) indicative record of $\alpha_{aer}(\lambda,R)$. The PBLH is derived at 1435 m±75m.

VERDE Algorithm

VERDE, in general, "cuts" the atmosphere in vertical, slant or horizontal slices of 200 m and measures the optical depth (τ) from the beginning of lidar measurements (lowest altitude about 210 m) and till 1200 m, for Greece latitude.

VERDE algorithm can be used at any height or distance (slant – horizontal) seems feet in order to provide the blurriness of the atmosphere and to assist VASPAT algorithms avoiding any miscalculations. Then, it calculates τ and if exceeds a barrier of $4*10^{-4}$ for high altitude cloud (no visibility through it) according to [12] (Fig. 4), at 355 nm and then it counts this atmospheric slice as a blurry one.

The algorithm tries to see how many slices are blurry and in which altitude lower than 1200 m (for PBLH finding for mid-latitudes) from the whole of the 10 to 15 min (15 or more data files) or more (user depending) of time recording. Then, it addresses VASPAT – PBLH to the use of VASPAT – PBLH LOWER ALT -1, etc. These last algorithms are all the same VASPAT – PBLH algorithm with different settings that are already inputted in VASPAT - PBLH and run accordingly.

VASPAT-PBLH Vs OTHER PBLH finding methods

VASPAT-PBLH took the challenge to be compared with other well-known techniques of PBLH finding, like the extended Kalman filter, radiosonde, threshold method, gradient method, logarithmic gradient method, inflection point method, variance method and wavelet covariance transform method.

The RCS plots produced by LRSU NTUA are shown in Fig. 8, while the red dots represent the application of extended Kalman filter method and other techniques for PBLH finding. This work has be done by D. Alexiou during his M.Sc. Thesis at NTUA [13].

By taking these lidar data we compared them with data produced by our VASPAT algorithms. There were no outcomes for the dust case, while for the **etesian** case the outcome was **1512.5 m** for the time period **07:56:50-08:22:00 UT**C, for the **sea breeze** case the outcome was **1767.5 m** for the time period of **09:04:30-09:28:00 UTC**, for the **clear sky** case it was **1732.5 m** for the time **06:17:30-06:40:00 UTC** and for the **clouds case** the outcome was **1872.5 m** for the time of **07:44:30-08:07:50 UTC**.

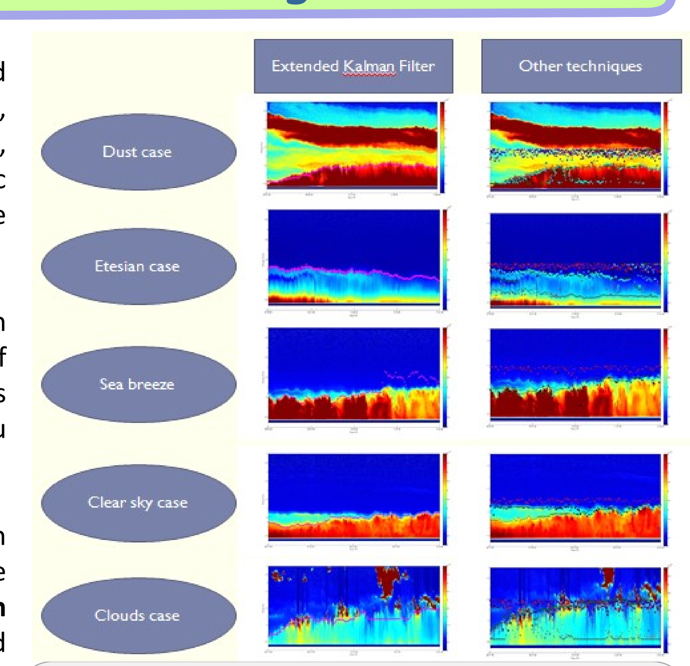


Fig. 8: Temporal evolution of the PBLH as derived using the extended Kalman filter (left-hand side images) and other techniques (right-hand side images) for different meteorological conditions: dust, Etesians flow, sea breeze, clear sky conditions and clouds case [13].

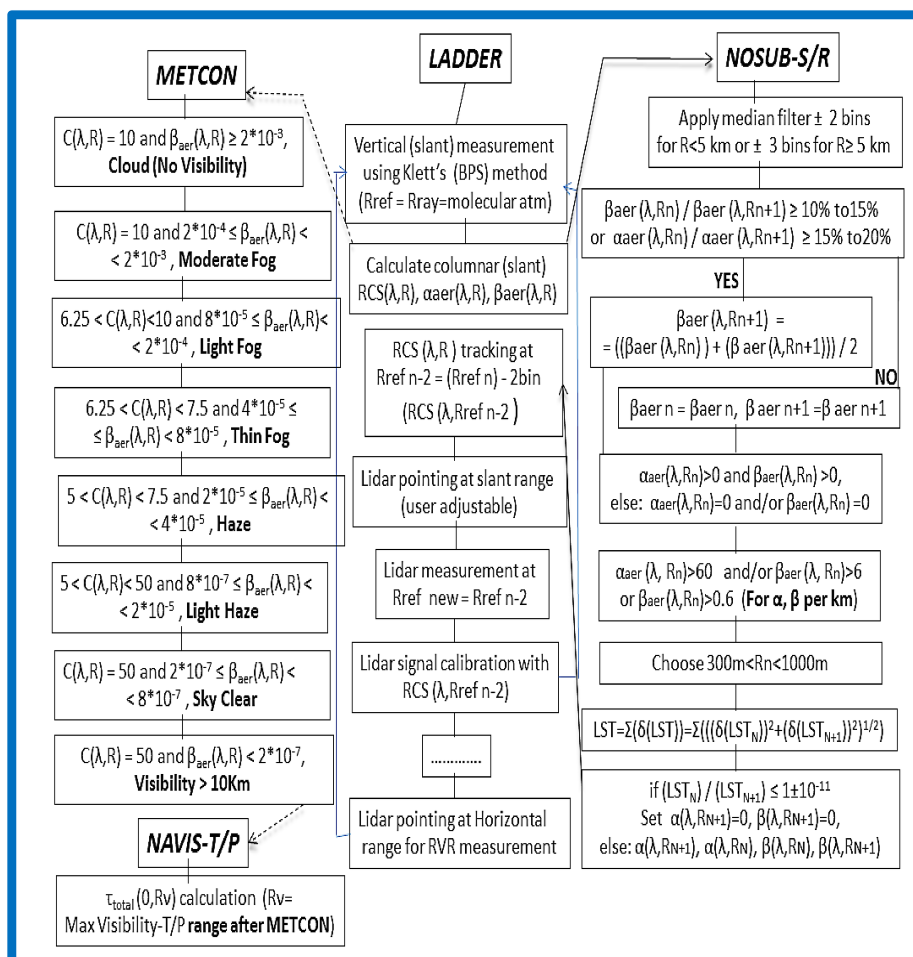


Fig. 9: Flow chart of the LADDER, NOSUB-S/R, METCON and NAVIS-T/P algorithms. The sign …. denotes the repetition of the above steps from vertical to the horizontal pointing of the lidar device, for the RVR measurement.

SUMMARY

In this paper we presented novel algorithms and techniques applied to 3D scanning lidar slant range measurements to evaluate horizontal, slant and vertical visibility for tower aircraft controllers, meteorologists, but also from pilot's point of view, as well as for the detection of atmospheric layering of the 'present' weather and the distribution of $\beta_{aer}(\lambda,R)$ and/or $\alpha_{aer}(\lambda,R)$ in three dimensions. In order to derive layering and PBLH of the atmosphere, we took the same processed signal and pass it through VERDE and VASPAT algorithms.

The initial comparison with other PBLH finding techniques showed that the latter algorithms found to produce results (in an automatic way) very close to the true PBLH data. Meteorological reports (METARs - Meteorological Aerodrome Reports) can find these algorithms extremely helpful and with the incorporation of a 3D scanning lidar, a very attractive combination can be made, especially to airport tower controllers, meteorologists and aircraft pilots.

References

[1] CIMO (Commission for Instruments and Methods of Observation) (WMO-No. 807), 2008.
[2] W. Gong, et.al., "Signal simplification and cloud detection with an improved Douglas-Peucker algorithm for single-channel lidar", Meteorol. Atmos Phys., 113, 89-97, 2011.
[3] V. A. Kovalev, W. E. Eichinger, "Elastic Lidar," Wiley Interscience, 2004.
[4] Y . Morille, et. Al. "STRAT: An automated algorithm to retrieve the vertical structure of the atmosphere from single-channel lidar data", J. Atmos. Oceanic Techn., 24, 761-775, 2007.
[5] M. Adam, "Vertical versus scanning lidar measurements in a horizontally homogeneous atmosphere", Appl. Opt., 51, 4491, 2012.
[6] P. Kokkalis, et al., 2012: "The EOLE lidar system of the National Technical University of Athens", Proc. 26th International Laser Radar Conference, pp. 629-632, 25-29 June 2012, Porto Heli, Greece.
[7] W. Vieeze, et. al., "Slant range visibility measurement for aircraft landing operations", Stanford Research Institute, 1972.
[8] R. H. Kohl, "Discussion of the interpretation problem encountered in single wavelength lidar transmissometers", J. Appl. Meteor., 17, 1034-1038, 1978.
[9] J. Klett, "Stable analytical inversion for processing lidar returns," Appl. Opt., 20, 211-220, 1981.
[10] J. Klett, "Lidar inversion with variable backscatter extinction ratios," Appl. Opt., 24, 1638-1643, 1985.
[11] G. Pappalardo et. al., "Aerosol lidar intercomparison in the framework of the EARLINET project. 3. Raman lidar algorithm for aerosol extinction, backscatter, and lidar ratio", Appl. Opt., 43, 5370-5385, 2004.
[12] R. M. Measures, "Laser remote sensing. Fundamentals and Applications," Krieger, Sys No 9247, MEA 621.3678, 1992.
[13] D. Alexiou, et al., "Planetary Boundary Layer height variability over Athens-Greece based on the synergy of Raman lidar and radiosonde data: Application of the Kalman filter and other techniques (2011-2016)", Proc. 28th International Laser Radar Conference, Bucharest, Romania, 2017 .

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Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης