Validation of TROPOMI Cloud Top/Bottom Height using BAQUNIN Lidar Systems: preliminary results

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Abstract: In the framework of the **BAQUNIN** (Boundary-layer Air Quality-analysis Using Network of Instruments, **https://www.baqunin.eu**) ESA project, three lidar system characterised by different design and measurement modes are operated in an urban (Rome downtown) and a rural (Montelibretti) sites of the Tiber Valley. This experimental setup is particularly useful for the evaluation of the impact of different environmental conditions (e.g. surface reflectivity, pollution load) on atmospheric composition satellite products., of the aerosol load retrieved from AERONET and EUROSKYRAD collocated systems (also part of BAQUNIN).
In this contribution we will discuss in detail the methods applied and the preliminary results of the validation of TROPOMI Level-2 Cloud products (offline), with particular focus on the estimated cloud boundaries (top/bottom). Two Lidar systems located in the Atmospheric Physics Laboratory (APL) of the Physics Department of Sapienza University (Rome downtown). At APL, a powerful multi-wavelength and multi-polarisation Lidar (MWL-LIDAR) has been designed and assembled using both custom made and commercial devices, while the controlling software has been developed in house. The system includes a large power pulsed laser, emitting pulses at 355, 532,1064 nm wavelengths, four receivers and twelve acquisition channels. MWL-LIDAR can be operative in no rain day and, for what concerns the Raman channels, in night conditions. In addition, a Raymetrics Aerosol Profiler (RAP) system, emitting at 1064 nm, is installed on the roof of APL a few meters apart from the MWL-LIDAR. Differently from the latter, RAP operates continuously (24/7). For the APL systems, the reference cloud boundary data are obtained from high time/space resolution Lidar range-corrected signal, providing very accurate estimates of the position of the cloud edges. The third system is a Vaisala CT25K ceilometer, located in the "Liberti" experimental campus of CNR-IIA, about 25 km distance from APL. This ceilometer is also operated in continuous mode and can provide reliable cloud bottom altitudes and, in case of optically thin clouds, the cloud top altitudes. The TROPOMI Level-2 offline products are gathered from the ONDA-DIAS system using a dedicated selection/extraction tool called TROPEX (TROPomi EXtraction) developed in the context of the BAQUNIN project. The validation approach consists in selecting the TROPOMI products for which the satellite observing view around the selected sites is almost nadir (viewing zenith angle < 10 degrees) and a variable horizontal search radius. The inter-comparison results are finally analysed in terms of satellite viewing geometry and cloud fraction, of relative distance from the site, and, in the case of APL, of the aerosol load retrieved from AERONET and EUROSKYRAD collocated systems (also part of BAQUNIN).

Instrumental setup
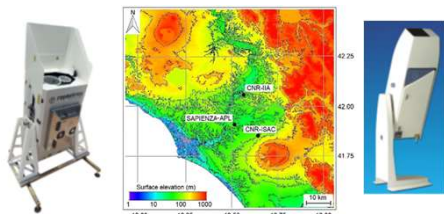
Parameter	RAP (APL – Mar 2021)	CT25K (IIA – Feb 2021)
Wavelength	1064 nm	905 nm
Energy per pulse	30 µJ	1.6±20% µJ
Pulse repetition rate	5 kHz	5.5 kHz
Time rosolution	10 s	15 s
Range	15 km	7.5 km
Range resolution	3.75 m	30 m
Beam divergence	0.3 mrad	0.6 mrad
Field-of-view divergence	2.3 mrad	0.66 mrad
Full overlap range	300 m	300 m

Data selection and collocation method

➢ Time lag (for ceilometers) Δt: 6, 15, 30, 45, 60, 90 minutes (from satellite overpass time)
➢ Search radius (for TROPOMI) Δs: 3, 5, 8, 12, 17 km (from validation site position)
➢ TROPOMI Line-of-Sight ΔL: ≤ 20° , ≤ 40°, ≤ 70°

For each (Δt, Δs, ΔL) triplet, valid ground based and satellite CBH and CTH data are selected and averaged.
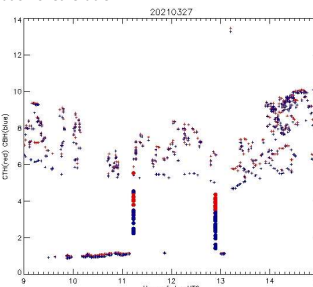For ceilometer data, multiple layers are averaged to single values.
TROPOMI average Cloud Fraction (CF) and Cloud Optical Thickness (COT) are associated to the matchup.
Multiple satellite overpasses are considered separately, i.e. for each overpass a single matchup is extracted.
For both satellite and ground-based selections, the standard deviation of selected data is calculated.
It should be noted that, in this work, the analysis consider only "detected cloud cases" from both satellite and ceilometers. This implies that if either satellite or ground instruments erroneously do not detect clouds then no matchup is created. Future developments will include the analysis of "missed clouds", thus providing a more rigorous estimate of the quality of the TROPOMI cloud products.
The time period considered in this work starts on **March 2021** and stops on **Feb 2022** (one full year).

APL and IIA Cloud Base/Top datasets

APL – RAP

A signal threshold approach is adopted, using RAP range corrected signal (RCS) and using its spatial and temporal variations.
The RAP CBH/CTH retrieval method is semi-automated, and is divided in four steps:
1) Range Corrected Signal (RCS) profiles daily time series obtaining a matrix of value
2) The aerosol layer of altitude is retrieved considering the variance of the signal along the profiles every 3 hours
3) Two threshold value (ThV) are used (inside and outside aerosol layer) to identify the cloud: for each element of the RCS matrix, if RCS value > ThV, the element is flagged as possible cloud
4) For each flagged element, the algorithm makes a check to exclude single spikes, and cloud layers with thickness less than the uncertainty of the algorithm, obtaining a new cloud matrix
5) Cloud top and bottom layer are retrieved from the last matrix, as respectively maximum and minimum height of the cloud layer identified
The method has been tested using RAP and Multi-wavelength LIDAR data acquired at APL, showing excellent performances, allowing for the detection of up to 10 cloud layers.
Future developments will include the estimate of the cloud optical thickness (COT) for each detected cloud layer.

IAA - CT25K

The CBH altitudes (up to three cloud layers) are retrieved using the method described in the CT25K User Manual (https://psl.noaa.gov/data/cruises/CT25K.pdf).
It should be noted that the instrument operated in this campaign was built on 2002, and recently refurbished. This old device has low S/N ratio and, consequently, low altitude clouds are more likely to be detected. In addition, no CTH information is retrievable

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TROPOMI L2 Extractor Tool (TROPEX)

TropEx (Tropomi Extractor) software is designed to download Sentinel 5P TROPOMI L2 data from ONDA and Copernicus portals and to extract selected information referred to the regions of interest (ROIs) in table below.
TropEx output files maintain the netcdf format and are composed by a selection of the main TROPOMI variables describing the atmospheric properties extracted on the ROIs and their variable attributes.
Information on TropEx data access can be requested to gabriele.mevi@serco.com

ROI name	ROI area (min longitude, min latitude, max longitude, max latitude) [deg]
Aosta	6.65617, 45.2503, 7.94383, 46.1497
Bologna	10.0391, 43.6007, 12.5609, 45.3993
Capogranitola	11.6, 36.6,13.6, 39.6
Lameziaterme	15.2, 37.8, 17.2, 39.8
Lampedusa	10.8430, 34.1510, 14.1570, 36.8490
Lazio	10.0835, 40.1014, 14.9165, 43.75
Milano	8.11692, 44.6007, 10.6831, 46.3993
Napoli	13.0120, 39.9007, 15.3880, 41.6993
Taranto	16.0173, 39.6007, 18.3827, 41.3993
Thule	-70, 76, -65, 77

References

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Mevi G., 2021, "TROPEX User Guide", BAQ-TEC-TEN-SER-046, https://www.baqunin.eu/documents/

CT25K User guide, M210345en-A, December 2002

http://cedadocs.ceda.ac.uk/1239/2/CT25K_Users_Guide_M210345ENA.pdf

Summary results

APL-TROPOMI CBH statistics (0.5<CF<0.9, LOS<20) bias+-std (numero)

Time lag / Rad	6min	15min	30min	45min	60min	90min
3	0.67±0.82(16)	0.60±1.02(16)	0.38±1.06(16)	0.33±1.11(15)	0.56±1.23(13)	0.66±1.53(13)
5	0.79±0.99(17)	0.42±0.94(17)	0.28±0.92(16)	0.32±0.93(16)	0.61±1.07(14)	0.72±1.31(14)
8	0.80±0.94(18)	0.51±0.88(17)	0.57±0.83(16)	0.41±0.86(15)	0.62±0.93(14)	0.79±1.22(14)
12	1.03±0.95(19)	0.74±1.73(19)	0.80±0.89(17)	0.63±0.95(16)	0.86±0.97(14)	0.90±1.26(14)
17	1.26±1.03(15)	0.90±2.16(17)	0.80±1.01(15)	0.77±1.01(14)	0.77±1.00(13)	1.09±0.94(12)

APL-TROPOMI CBH statistics (0.5<CF<0.9, LOS<70)

Time lag / Rad	6min	15min	30min	45min	60min	90min
3	0.67±1.04(33)	0.60±0.86(31)	0.55±1.12(36)	0.37±1.22(33)	0.49±1.30(28)	0.62±1.57(28)
5	0.90±1.95(46)	0.84±2.40(45)	0.72±2.73(47)	0.70±1.59(46)	0.73±1.62(42)	0.72±1.71(39)
8	0.78±1.76(56)	0.86±2.16(56)	0.79±2.18(59)	0.62±1.52(53)	0.86±1.57(50)	0.84±1.61(47)
12	0.85±1.72(60)	0.92±2.20(61)	0.80±2.05(62)	0.65±1.40(55)	0.84±1.43(51)	0.81±1.49(47)
17	0.77±1.78(58)	0.90±2.30(60)	0.79±2.06(62)	0.78±1.42(57)	0.79±1.43(54)	0.89±1.39(50)

IIA-TROPOMI CBH statistics (0.5<CF<0.9, LOS<20)

Time lag / Rad	6min	15min	30min	45min	60min	90min
3	NA	0.63±0.62(5)	0.63±0.56(6)	0.24±2.09(7)	0.48±2.01(8)	0.51±2.00(10)
5	NA	0.12±2.78(5)	0.30±2.49(6)	0.27±2.74(8)	0.26±2.63(10)	0.30±2.56(12)
8	NA	0.18±2.67(5)	0.21±2.39(6)	0.21±2.66(8)	0.22±2.57(10)	0.22±2.53(12)
12	NA	0.23±2.74(5)	0.25±2.43(6)	0.13±2.70(7)	0.09±2.63(8)	-0.18±2.43(9)
17	NA	0.24±1.97(9)	0.24±1.95(9)	0.26±2.32(10)	0.26±2.31(10)	0.12±2.17(11)

IIA-TROPOMI CBH statistics (0.5<CF<0.9, LOS<70)

Time lag / Rad	6min	15min	30min	45min	60min	90min
3	0.09±2.79(17)	0.63±2.23(24)	0.63±2.74(34)	0.16±2.65(35)	0.22±2.62(37)	0.51±2.57(42)
5	0.42±2.37(26)	0.40±2.17(34)	0.25±2.62(45)	0.12±2.50(47)	0.19±2.55(52)	0.15±2.50(57)
8	0.16±2.16(27)	0.18±1.99(36)	0.05±2.53(48)	-0.13±2.38(51)	0.12±2.46(56)	0.11±2.43(61)
12	0.23±2.06(28)	0.21±1.88(37)	-0.10±2.40(50)	-0.30±2.25(51)	-0.22±2.33(56)	-0.32±2.27(60)
17	0.22±1.75(28)	0.23±1.93(40)	0.04±2.39(50)	-0.21±2.23(51)	-0.20±2.31(55)	-0.28±2.22(60)

APL-TROPOMI CTH statistics (0.5<CF<0.9, LOS<20)

Time lag / Rad	6min	15min	30min	45min	60min	90min
3	0.02±0.90(16)	-0.13±1.06(16)	-0.34±1.08(16)	-0.45±1.13(15)	-0.10±1.22(13)	0.06±1.51(13)
5	0.04±1.00(17)	-0.24±0.95(17)	-0.41±0.92(16)	-0.42±0.93(16)	-0.18±1.07(14)	0.05±1.30(14)
8	-0.04±0.92(18)	-0.19±0.86(17)	-0.18±0.82(16)	-0.37±0.84(15)	-0.13±0.92(14)	0.11±1.14(14)
12	0.14±0.92(19)	0.06±1.76(19)	0.11±0.89(17)	-0.12±0.95(16)	0.16±0.97(14)	0.22±1.26(14)
17	0.53±0.97(15)	0.44±2.24(17)	0.11±0.81(15)	0.08±1.02(14)	0.10±1.00(13)	0.45±0.94(12)

APL-TROPOMI CTH statistics (0.5<CF<0.9, LOS<70)

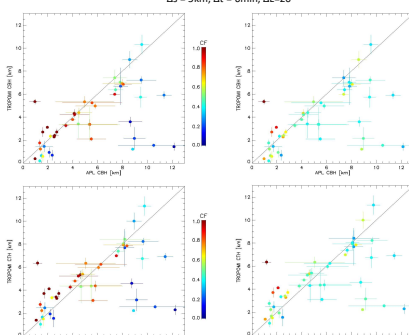| Time lag / Rad	6min	15min	30min	45min	60min	90min
3	-0.15±1.08(33)	-0.21±0.91(31)	-0.35±1.17(36)	-0.42±1.27(33)	-0.10±1.33(28)	0.06±1.58(28)
5	0.11±1.94(46)	-0.01±2.39(45)	-0.06±2.37(49)	-0.14±1.61(46)	-0.03±1.63(42)	0.03±1.71(39)
8	-0.06±1.77(56)	0.12±2.16(56)	-0.12±2.19(59)	-0.04±1.55(53)	0.16±1.59(50)	0.01±1.62(47)
12	0.08±1.71(60)	0.14±2.21(61)	0.11±2.05(62)	-0.04±1.43(55)	0.05±1.45(51)	0.03±1.50(47)
17	0.13±1.77(58)	0.13±2.32(60)	0.04±2.07(62)	0.04±1.44(57)	0.10±1.45(54)	0.13±1.40(50)

Conclusions

TROPOMI CBH and CTH products have been compared to counterparts estimated from data acquired by two ceilometers, part of the BAQUNIN supersite instrumental suite. The APL-RAP instrument is operated in an urban environment, while the IIA-CT25K device is located in a rural site.
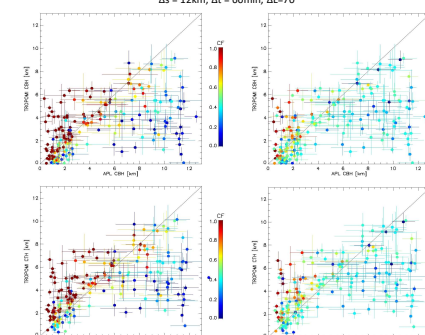The very preliminary comparison outcomes suggest that:
1) Ceilometers, even low S/N ones, can be used for TROPOMI cloud validation
2) The comparison cannot be performed without considering the cloud properties, such as Optical Depth and horizontal extension (Clod Fraction). In fact, the cloud related information content of satellite measurements is too low for small CF (CTH underestimated), and optically thick clouds impair the detection of CTH from ceilometer data.
3) Multiple-layers in ceilometer data should be used only if related COTs are also retrieved.
4) Matchup criteria should be tailored as function of instrumental (e.g., S/N) characteristics
5) Despite all **limitations and caveats**, and depending on selection criteria, the TROPOMI bias with respect to ceilometers can be very small: <100m for CBH (IIA) and for CTH (APL)

TROPOMI vs APL CBH (upper panels) and CTH (lower panel)
Δs = 5km, Δt = 6min, ΔL=20°

TROPOMI vs APL CBH (upper panels) and CTH (lower panel)
Δs = 12km, Δt = 60min, ΔL=70°