Lidar measurements of atmospheric extinction during the MAPTIP trial

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ABSTRACT

During the MAPTIP experiment, that was organized by NATO AC/243 (Panel 4)/RSG.8, the marine atmosphere was characterized, among others, with lidar (optical radar). The investigations were carried out both in horizontal planes (PPI scans), in vertical planes (RHI scans) and combinations of those two. In addition, the temporal variability of the atmosphere along one line of site was characterized by operating the lidar in a fixed direction at a sufficiently high repetition rate to follow the eddy structures. The marine aerosol layer was monitored within the surf zone and out to ranges of about 10 km. Slant path measurements provided information on the depth and structure of the mixed layer. Results obtained during this experiment are presented.

Keywords: Lidar, optical radar, transmission, extinction, turbulence, coastal area

1. INTRODUCTION

During MAPTIP[1], three backscatter lidars were active. Two aerosol lidars systems were operated from the Katwijk boulevard close to the MAPTIP beach station by the Fraunhofer-Institut für Atmosphärische Umweltforschung Germany (IFU). With these systems, the marine aerosol layer was monitored within the surf zone and out to ranges of about 10 km. Slant path measurements provided information on the depth and structure of the mixed layer. The third aerosol lidar was operated from MPN (MeetPost Noordwijk) 10.44 km from the beach station by TNO-Physics and Electronics Laboratory (TNO-FEL).[2] Horizontal measurements indicated the variability of the atmosphere at a fixed height but also the plumes that were generated by the ships over ranges of several kilometers. With this system it was shown that organized vertical convective structures were present during the major part of the experiment indicating the horizontal inhomogeneity of the atmosphere. Structures from several meters up to several kilometers have been observed, even in a very clear and quiet atmosphere. In addition, the lidar at the platform was operated at a slightly small negative elevation angle thus measuring the first 10 m above the sea surface. The large amount of structure in this area could clearly be monitored and indicated the influence of the waves on the overlaying atmosphere. Measurements at negative elevation angles also provided information on the height and frequency of the gravity waves.

2. LIDAR MEASUREMENTS FROM KATWIJK

2.1 Introduction

Two mobile lidar systems, operated by IFU, were placed on the parking area above the Katwijk beach station, i.e., approximately 15 m above the mean sea level. The trailers were oriented to allow the lidars to point approximately at MPN. The laser beams were located at least 2.2 m above the street level, i.e., above the heads of pedestrians or car drivers. Lidar 1 can be rotated 90 degrees in azimuth and tilted from horizontal to vertical. Lidar 2 can just be tilted, with an angular range up to approximately 40 degrees. For horizontal measurements, the laser of lidar 1 (fundamental wavelength: 1064 nm, harmonics: 532 nm and 355 nm) was not fired directly at MPN, but slightly to the right-hand side and at an elevation angle of 0.5 degree for safety reasons. Lidar 2 (wavelength 1560 nm) is eyesafe[3] and aimed directly at the upper decks of MPN, which resulted in a highly horizontal path. Finally, it has to be mentioned that due to the optical layout of the systems (bi-static), the lidars provide no information over the first 200 to 300 m (depending on the detector type used). This is caused by the limited field of view of the detection system which rejects light entering from larger angles.

The range-resolved measurements of the aerosol-induced light extinction performed during MAPTIP have yielded valuable insight into the typical spatial distribution of particles above the sea surface. Two lidar systems were operated above the Katwijk beach station (IFU). The lidars at the beach carried out mostly horizontal measurements, with constant direction towards MPN. Every half hour, slant-path measurements were scheduled to determine the vertical distribution of the aerosols. In addition to the lidar-based investigations, point measurements of extinction or visibility were carried out on both "platforms". The MPN results (DREV) were used to calibrate the far-field extinction coefficients obtained with the beach lidars. Part of the data recorded during the field experiment are presented.

2.2 Horizontal Lidar Measurements

Lidar 1 was available throughout the campaign and offered a choice of two wavelength pairs (1064 nm/532 nm and 1064 nm/355 nm). The standard schedule for horizontal measurements was x:10, x:20, x:40 and x:50, x denoting the full hour. x:00 and x:30 were usually reserved for slant-path measurements. In addition, long data series were recorded to determine the variability of the aerosol distribution in the surf zone.

The first two weeks of MAPTIP were characterized by a very clear atmosphere. Reduced visibility was observed just above the surf zone which extended to distances typically between 0.7 and 2.5 km from the lidar position, with some minor sea spray occasionally being observed even outside this range (maybe caused by breaking waves). Typical examples of range-corrected backscatter profiles are given in Figures 1 to 3. The enhanced backscatter signal in the surf region is clearly visible. It was mostly highly structured, although some of the structure disappeared in the presence of sufficiently strong winds blowing transversely to the coast line. With the wind blowing parallel to the coast occasionally wave-like structures could be observed even outside the surf zone. An example is shown in Figure 2. Averaging of the lidar signals over a 2 minute interval did not change the structure. This indicates a long lifetime of these features. The long distance between adjacent signal peaks (300 to 400 m) makes it difficult to invoke turbulence as the source of such a structure.

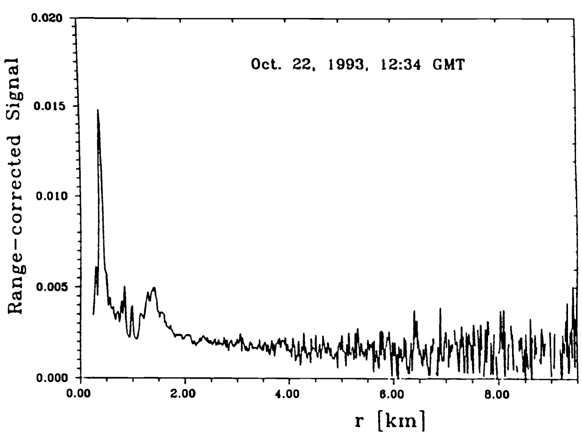

Figure 1: Range-corrected backscatter profile obtained on October 22, 1993, at 12:34 GMT (1064 nm); lidar elevation angle: 0.5°.

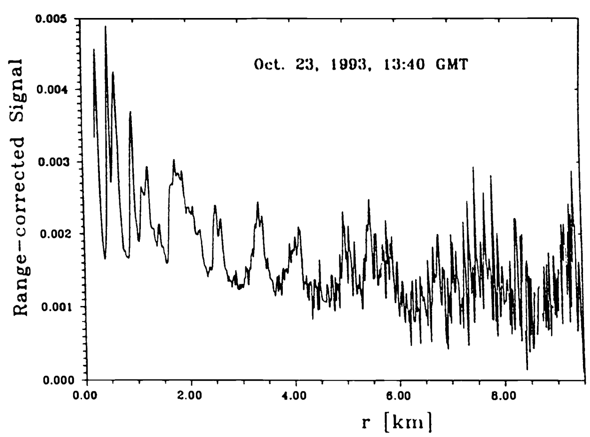

Figure 2: Range-corrected backscatter profile obtained on October 23, 1993, at 13:40 GMT (1064 nm); lidar elevation angle: 0.5°; the surf-zone extinction coefficient which one derives from this measurement is rather low (peak value: 0.0484 km^{-1}.

From the range-corrected backscatter profiles, the horizontal distributions of the extinction coefficients were calculated. The results are available in ASCII format for almost all days of the trial. Typical 1064-nm extinction coefficients for the surf zone range between 0.05 and 0.3 km^{-1}. Very interestingly, the values agree with those calculated from the MPN aerosol size distributions for lower heights above the sea (private communication Dr. Gathman, 1995 MAPTIP workshop at DREV, Canada). This demonstrates that enhanced aerosol is present also outside the surf region, but restricted to lower heights than that of the laser beam. It is important to note that test measurements with the horizontally pointing eyesafe lidar during the first two weeks of MAPTIP confirmed the same subdivision into surf zone and sea. Thus, the typical signal drop for lidar 1 beyond the surf zone cannot be ascribed to the finite elevation angle of that laser beam. This angle (+0.5 deg.) is rather small anyway and corresponds to just 8.7 m per km. The average optical depths of the surf zone for the clear period of MAPTIP is given in Table 1.

Table 1: Summary of the range-averaged 1064-nm extinction coefficients within and outside the surf zone for the clear period of MAPTIP (common-analysis days only); the index sz refers to "surf zone", r_{sz} the far boundary of the aerosol-rich part of the surf zone (not including minor structure or "aerosol waves"). The wind direction is given with respect to north. For comparison: the azimuth of the coast is approximately 36°.

date	time range [GMT]	r_{sz} [km]	$\langle\alpha_{sz}\rangle$ [km^{-1}]	$\alpha_{max,sz}$ [km^{-1}]	$\langle\alpha_{sea}\rangle$ [km^{-1}]	wind dir. [degr]	wind spd. [m/s]
10-23	12:45-13:15	1.1-1.2	0.042-0.049	0.07-0.10	0.017-0.028	38-40	5.5-5.7
	13:15-15:25	1.2-2.6	0.015-0.041	0.04-0.08	0.007-0.023	28-38	6.0-7.0
	15:25-17:15	1.3-2.8	0.019-0.055	0.04-0.08	0.011-0.027	30-44	4.4-6.3
	17:15-17:30	1.5-1.7	0.021-0.041	0.05-0.12	0.007-0.017	26-34	5.7-6.0
10-24	07:00-11:50	0.9-2.1	0.018-0.066	0.03-0.11	0.008-0.032	30-48	3.9-6.8
10-26	08:25-10:15	0.6-1.7	0.054-0.177	0.13-0.32	0.031-0.061	22-30	3.5-4.2
	10:30-14:20	0.7-3.6	0.026-0.074	0.04-0.08	0.026-0.065	02-12	5.6-7.1
	15:20-15:45	0.1-1.1	0.038-0.094	0.05-0.19	0.019-0.029	20-28	
10-28	08:00-15:00	0.7-2.7	0.038-0.101	0.09-0.26	0.040-0.088	32-120	0.9-3.2
	15:00-16:30	0.8-2.1	0.124-0.221	0.17-0.43	0.088-0.176*	34-66	1.3-2.1

* r < 3 km only; beyond 3 to 5 km onset of fog formation

Wind data: Measurements of FfO at the parking area above the beach station

The time intervals in Table 1 were selected according to changes in average wind direction, which in most cases resulted in changes in the surf-zone extinction coefficients. E.g., with the wind coming more from the sea side, the sea-spray peak positions were slightly shifted towards the beach, i.e., partly out of the observation range. This results in lower values for $\alpha_{max.sz}$. For October 23, this is not fully visible from the table since the full $\alpha_{max.sz}$ range is given instead of just the mean value. The changes of the wind direction are rather small anyway during this day.

During the final week of MAPTIP, foggy conditions prevailed (starting in the late afternoon of October 28). The visibility was rather short, typically 2 to 5 km. The Tydeman was frequently barely visible at its turning point next to the beach ($r \approx 2$ km). In contrast to this, the infrared cameras revealed clear sight to the horizon. This pronounced change in range with increasing wavelength could be verified by the eyesafe lidar. Despite the still rather short wavelength of 1560 nm, visual ranges between 30 and 60 km could be evaluated from the slope of the logarithmic backscatter signal. These values are confirmed by the frequent observation of MPN backscatter signal through the fog as can be seen from Figure 4. This is particularly remarkable since the light traverses the entire 10.44 km distance twice on its way from the laser to the detector.

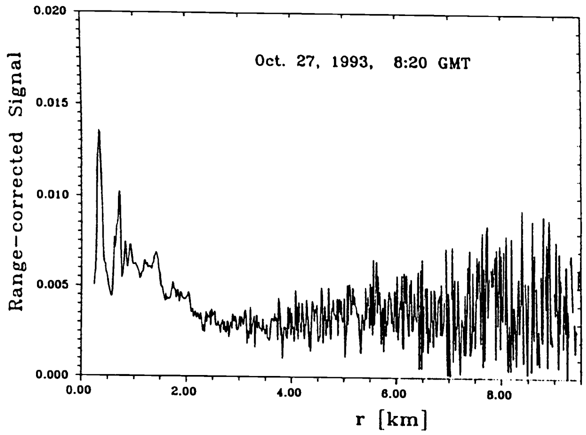

Figure 3: Range-corrected backscatter profile obtained on October 27, 1993, at 8:20 GMT (1064 nm); lidar elevation angle: 0.5°.

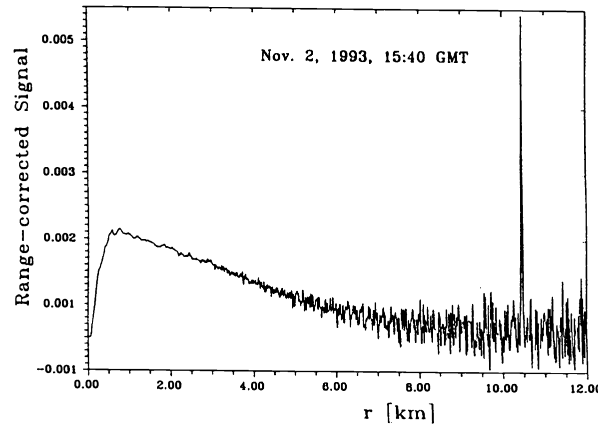

Figure 4: Range-corrected backscatter profile obtained during the fog period on November 2, 1993, at 15:40 GMT (1560 nm); lidar elevation angle: 0.0°; the spike starting at r = 10.44 km is caused by a reflection by MPN; the large signal gap up to r = 0.6 km is partly due to digitizer overflow. Some indication of surf-zone structure is visible around 1 km.

The wavelength dependence of the extinction coefficient, derived from all four lidar wavelengths is illustrated in Figure 5. The data were from Nov. 3, 1993, 15:05-15:20 GMT. The transition from an approximate λ^{-1} to λ^{-4} (Rayleigh scattering) behavior is obvious. One has to conclude particle sizes clearly below 1 μm from this result.

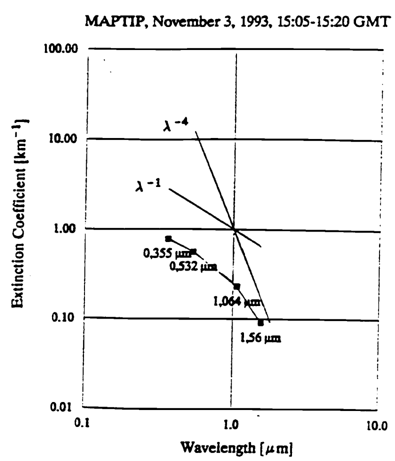

Figure 5: Extinction coefficients for lidar measurements in moderate fog on November 3, 1993, between 15:05 and 15:20 GMT; the displayed wavelength dependence suggests a transition from a typical behavior for light scattering by aerosols to Rayleigh-type scattering at around 1 μm which indicates a very small droplet size. Earlier measurements in denser fog have yielded even lower values for 1560 nm.

Since there is no complete coverage of the fog days by the eyesafe lidar, we recommend to apply a factor of 0.10±0.02 to the 532-nm extinction coefficients to obtain those for 1560 nm. For 1064 nm, a factor of 0.2 is reasonable. Further extrapolation, e.g., into to 3 to 5 μm and 8 to 10 μm wavelength ranges, is difficult since oscillations in the wavelength dependence may exist.

Again, surf aerosol spikes are seen in the near range of the backscatter profiles. This contribution is, however, substantially smaller than that from the fog.

2.3 Slant-path Lidar Measurements

The vertical distribution of aerosols and clouds was probed by slant-path measurements, typically every half an hour (x:00, x:30). The reason for not operating the lidar vertically was to reduce the loss of information caused by the near-range blindness of the receiver. The preferred, but not exclusive elevation angle was 20 degrees. In addition, occasionally quick angular scans were carried out in order to obtain the full two-dimensional information on the aerosol distribution.

Data of five angular scans have been evaluated. A crude analysis of two of them (October 22 and 23) is displayed in Figure 6 and Figure 7. For the most frequently set angle of 20 degrees, the boundary layer above the surf zone usually looks rather homogeneous. The backscatter profiles for lower angles indicate that surf-zone spiking in the backscatter signal may only be observed for angles clearly below 10 degrees. This elevation angle corresponds to a height of 177 m at 1 km distance from the lidar, which is a representative distance within the surf zone. It is, therefore, not unreasonable that mixing is rather complete around this altitude.

The evaluation of boundary-layer heights is frequently very difficult due to the presence of several pronounced cloud or aerosol peaks in the backscatter profiles. Even without clouds, the vertical aerosol distribution exhibits in many cases several steps which may occasionally reflect a superposition of nocturnal and diurnal structures. In the morning, a typical height deduced from the first step in the backscatter profile would be 0.1 to 0.2 km. Later on, a second step or cloud base around 0.7 to 1.1 km is observed.

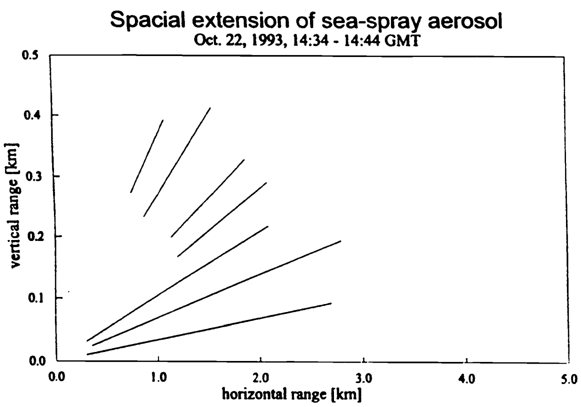

Figure 6: Crude analysis of an elevation-angle scan on October 22, 1993, between 14:34 and 14:44 GMT; the ranges with enhanced aerosol densities are indicated by lines for each angle of the laser beam.

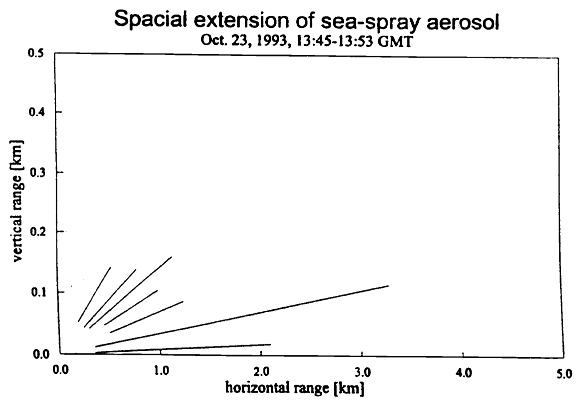

Figure 7: Same as Figure 6 for October 23, 1993, 13:34-13:53 GMT; the distribution in this figure looks entirely different from that in Figure 6.

3. LIDAR MEASUREMENTS FROM MPN

3.1 Introduction

During the MAPTIP experiment the vertical marine atmosphere was characterized, among others, with TNO's incoherent 1.06 μm SMAL backscatter lidar (Scanning Miniature Automatic Lidar[1]) from the MeetPost Noordwijk (MPN), some 10 km off the Dutch coast. This lidar combined a pulse energy of about 50 mJ with a net receiver diameter of about 20 cm resulting in a maximum system range of about 2 km. Atmospheric inhomogeneities, such as cloud layers, could be detected over much larger ranges. The repetition rate of this sensor could be varied from less than 1 Hz to about 10 Hz. A LeCroy digital oscilloscope temporarily stored the transient lidar signals which were subsequently transferred to the hard disk of a desk-top computer. After processing, the results were false-color coded for presentation purposes of the large amounts of data. In addition, typical or averaged profiles were presented in diagrams. The lidar was set up on the south-west corner point of the 12 m deck of MPN which provided an almost unobstructed field of view of about 225 degrees in azimuth direction and from about -15 degrees up to about 60 degrees in elevation angle. This provided the opportunity to sense the atmosphere from the water surface to altitudes up to about 1.5 km. The SMAL system was active from 18 October until 3 November 1993 over periods of less than a few minutes to more than 30 minutes.

3.2 Types of measurements

During the experiment, about 640 lidar sessions, varying in duration from a few seconds to more than 15 minutes, were carried out to characterize some of the static and dynamic properties of the atmosphere within a maximum range of about 2 km. Horizontal measurements provided the horizontal atmospheric extinction and backscatter coefficients and their temporal variability. In addition, this type of measurements have mapped ship plumes to distances of within a range of about 2.5 km. Extrapolation of these results indicate that ship plumes might be detectable over much larger ranges by using a tracking lidar. The vertical (dynamic) structure of the atmosphere, between about 25 m and about 1.5 km altitude, was determined by lidar observations at fixed and positive elevation angles (and fixed azimuth directions). These measurements provide about 500 kBy of information for each run and are usually presented in false-color or gray tone images. In addition, the mean and the standard deviation of the vertical profiles have been calculated. The false-color figures and the profiles have been analyzed and are described.

Well pronounced convective structures as well as wind-driven structures have been detected. Also, clear layers between convective layers and the cloud base, apparently rising from the sea surface were detected as well as well-mixed layers without capping cloud layers. Vertical lidar measurements have shown to provide excellent and unique information on the dynamic behavior of the vertical structure of the atmospheric mixed layer along the line of sight of the lidar. In a large number of occasions, well organized convective structures could clearly be detected to several hundreds of meters above the sea surface (some times to about 1 km altitude). In those cases, the atmosphere in the lowest layers was well-mixed. In occasions with moderate to strong winds, the atmosphere was well-mixed resulting in homogeneous light reflections from the mixed layer. Sometimes, wind driven, chaotic, structures with a relatively high signal-to-noise ratio were detected in the mixed layer (previous analysis have shown that the spectral behavior of the structures follow the well known -5/3 power law). In addition to recording the temporal behavior of the mixed layer, the cloud bases could be very well detected (within our selected recording range of about 2 km). The results from the vertical lidar measurements can be used to support the description of the stability condition of the atmosphere (stable, neutral or unstable) and can also reliably yield the depth of the mixed layer. This value may serve as an input quantity to support atmospheric models which in turn can predict propagation properties of EO systems. In addition, in occasions of convective structures, the depth of the entrainment layer can be determined.

The atmospheric returns in the lowest 15 m and the light reflections from the sea waves were monitored by aiming the lidar at a slightly negative elevation angle. Aerosol patches close to the sea surface have been monitored. These types of measurements can be used to study the processes within the first few meters above the sea surface in the marine environment and are rarely found in literature.

Lidar measurements in a fixed direction (along one line of sight) were alternated with measurements in the scanning mode to study the atmosphere over larger areas, both in the horizontal and in the vertical plane. In addition, some volume scans were carried out.

3.3 Typical Results

Four typical examples have been selected for presentation: two vertical measurements which show the different behavior of the mixed layer, one horizontal measurement with the plume from a ship and one measurement at a negative elevation exhibiting atmospheric structures in the lowest 10 m of the atmosphere including reflections from traveling sea waves. The results are shown in Figures 8 to 11.

In Figure 8, the vertical structure of the turbulent atmosphere is shown during a period of moderate wind speed (6.4 m/s) and overcast sky. The measurements were carried out at an elevation angle of 26 degrees over a range of 1600 m. The maximum height scale in the figure is about 700 m. The variation in the direction of the pattern can be an indication of a strong shear. The signal-to-noise ratio is very good, due to the high concentration of aerosols. However, due to the onset of detailed structures, the cloud layer at about 600 m altitude is not clearly visible.

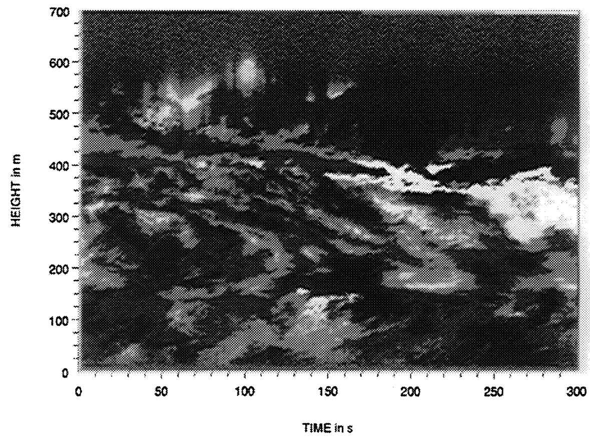

Figure 8: A turbulent atmosphere, measured under a positive elevation angle of 26 degrees over a range of 1600 m during about 320 seconds (max. altitude to end of scale: 700 m). Date October 27, 11:45.

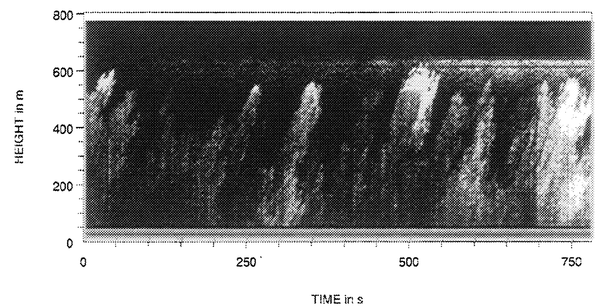

Figure 9: Lidar measurement in a convective and cloud free atmosphere during sunset. Vertical axis is from 0 to 805 m. The measuring time on the horizontal axis is 13 minutes

The results of the lidar measurements presented in Figure 9, were carried out in a cloud-free atmosphere during sunset (October 28, 16:57). The wind speed was 6.5 m/s. The maximum range is 1500 m; the measurements were carried out at an elevation angle of 32 degrees (max. altitude is 805 m). Note the huge organized convective structures. The organization becomes more and more pronounced for increasing altitude. Due to the clear conditions the scattering of the laser light is low, resulting in a low signal-to-noise ratio.

Figure 10 shows the results of lidar measurements of a plume generated by a ship. It is not clear whether the exhaust plume is mapped or the spray generated by the ship. The plume is first observed starting at a distance of about 1200 m. The maximum range to the end of the scale is 2400 m. Measurements started close to the ship. The ship moved towards the left out of the field-of-view of the lidar. The wind (9 m/s) dispersed the plume and drifted it away from the lidar.

By aiming the lidar at the sea surface at a small negative elevation angle the properties of the atmosphere in the lowest ten meters were mapped as well as the reflections of the sea surface. Lidar results of such a measurement at a wind speed of 10.5 m/s are shown in Figure 11. Sea waves are detected at a distance of about 750 m (saw tooth structures in the middle of the image) and drift away from the lidar. Repeatedly, new waves are detected. In this image, both patchy structures in the lowest 11 m of the atmosphere are mapped as well as the typically (relatively) weak reflections from the sea waves. Sometimes, two waves are detected simultaneously within one lidar return (one vertical line). Note that the structures from the sea waves, can also be found in the atmosphere above the waves. Moreover, larger structures with a smaller slope are detected in the atmosphere.

The narrow wings of the reflections from the gravity waves and of the small atmospheric patches have about the same value. This means that the speed of propagation is about the same (the waves propagate with about the wind speed). In addition to the small patches, there are very large patches with a narrower slope than that of the small patches. For the moment, we believe that these are induced by breaking of large waves. Observations of breaking waves shows that the bubble cloud in the wave, being a production source for aerosols, moves much slower than the gravity waves. The produced aerosols are taken upwards by the wind and need time to accelerate. In Figure 11, two of these effects are visible. More time and experiments are required to confirm this hypothesis.

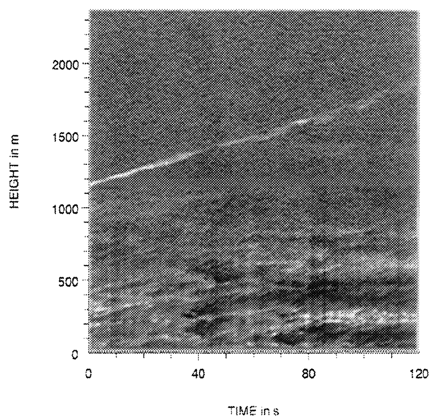

Figure 10: A ship's plume over a period of 120 s (horizontal axis) mapped with lidar. The range, from 0 to 2500 m is on the vertical axis. Measurements started in the vicinity of the ship, most left point in the figure. The ship sailed to the left and the plume is dispersed by the wind.

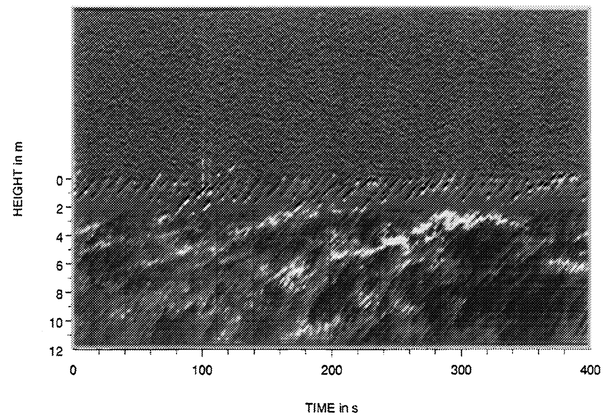

Figure 11: Results obtained from lidar measurements under a small negative elevation angle from the 12 m deck of MPN (October 25, 06:25). Atmospheric dynamics in the lowest ten meters are mapped and the reflections of the sea waves (saw tooth like patterns). Note the coherence between the atmospheric structures and the sea surface. Distance to the sea surface about 750 m; measuring time about 7 minutes.

6. CONCLUSION

Atmospheric measurements with point sensors are used to study the temporal behavior of the marine surface layer. Using micrometeorologial models based on similarity theory and assuming horizontal homogeneity the locally measured conditions are extrapolated to larger heights and areas. Lidar is the only tool that can provide the attenuation and the structural information from within the whole mixed layer over areas of several kilometers within limited time. In this work, the vertical structure of the marine atmosphere was studied both above the surf zone and within the first 10 m above the water surface over the open sea (9 km off the coast).

7. ACKNOWLEDGMENTS

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