Title	**Full-sky cloud detection by means of imaging polarimetry and polarization measurement of the cloud-base height**
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Topic	**180^o field of view, imaging polarimetry, light polarization, cloud detection, cloud-base height, artificial intelligence, 3D cloud reconstruction**

The concept

The aim of the concept is to develop a fast full-sky cloud detection system based on the patterns of skylight polarization measured by 180^o field-of-view imaging polarimetry. The primary outputs of the system will be (i) the probability distribution of clouds (from which the cloud existence can be estimated at any celestial point), and (ii) detection of the cloud-base height on the whole sky-dome. Using both primary outputs, we can derive different kinds of cloud-clustering algorithms to meet the requirements of the end-user.

Light is a transversal electromagnetic wave, that can be characterized by its wavelength (colour), intensity (brightness), direction (or angle) of linear polarization (direction of the oscillation plane of the wave's electric field vector perpendicular to the direction of propagation), degree of linear polarization (proportion of light with the major direction of linear polarization), and degree of circular polarization (proportion of light with left- or right-handed circulation of the electric field vector around the direction of propagation). The polarized skylight has a characteristic polarization pattern that depends on the position of the Sun, the albedo of the Earth's surface, the aerosol concentration in the air, the existence of clouds and the height of the cloud-base. Skylight is mainly linearly polarized. Its circularly polarized component is usually negligible, and depends on the composition and concentration of atmospheric aerosols. The traditional photographic techniques can only be used for measuring the spectrum (intensity as a function of wavelength) of skylight. For the measurement of the celestial polarization pattern a full-sky imaging polarimeter is required that is composed of a photographic camera equipped with appropriate (linear and circular) polarization filters.

The basis of our instrument is a wide (180^o) field-of-view imaging polarimeter that can take pictures of the whole sky through 3 linearly and 1 circularly polarizing filters. From these measured data a computer program can calculate the intensity, direction of polarization, linear and circular degrees of polarization of skylight in the red (650 nm), green (550 nm) and blue (450 nm) spectral ranges pixel by pixel of the full sky image. An appropriate computer algorithm can detect the clouds with the use of these polarization patterns (two-dimensional distributions), because the clouds more or less modify the polarization pattern characteristic to the clear sky.

Using the measured celestial polarization patterns, another algorithm can enhance the intensity and colour contrasts of the colour picture of the sky by reducing the blurring effect of atmospheric scattering. The contrast of clouds relative to the clear sky regions is naturally reduced by the partially linearly polarized light scattered in the air layer between the observer and the clouds that is added to the weakly polarized or unpolarized cloudlight. This disturbing partially polarized scattered light component can be subtracted from the skylight resulting in a contrast enhanced colour picture as if there were no scattering air layer (”haze”) between the observer and the clouds. This ”dehazed” picture with higher contrast can then be used by the traditional photometric cloud detection algorithms resulting in a higher accuracy of cloud detection.

The polarization data measured by full-sky imaging polarimetry can also be used to determine the relative heights of the cloud-base, because the deviation of the degree of linear polarization in a cloudy sky from that of a clear sky is proportional to the cloud-base height causing the reduced degree of linear polarization of skylight.

The relative cloud-base heights combined with the contrast-enhanced "dehazed" colour images from two or more different cloud detectors can also be converted into a three-dimensional cloud scene.

Based on the patterns of cloud probability and cloud-base height we can develop a cloud-clustering algorithm by which the type (cirrus, cumulus, etc.) of clouds can also be determined beyond the existence, size, shape, colour, texture and base height of clouds.

During our previous measurement campaigns in Budapest and the international ANT-XXVII-1-2010 expedition from Bremerhaven through the Atlantic Ocean to Capetown onboard the research vessel Polarstern organized by the German Alfred Wegener Institute for Polar and Marine Research we showed experimentally that exploiting polarization information from skylight usually improves the accuracy of cloud detection. On the other hand, cloud-base height measurements for the whole celestial hemisphere can be performed only by full-sky imaging polarimetry.

The need

- **Weather forecast**: There exist 4 major climatic models in the world that can be used for weather forecast (one of these was developed by the Max Planck Institute for Meteorology, Hamburg, Germany). These models use current and past weather data to predict the probable weather conditions in the more or less near future. One of these weather data is the cloud coverage that can be seen from a given geographical point on the Earth’s surface. The percentage and type of cloud coverage are usually estimated by human observers, introducing several problems (e.g., inaccuracy, unreliability, low spatial resolution, small temporal measurement frequency, high costs) that make it difficult to use these subjective data in climatic models. Nowadays these human observers are starting to be substituted by automatic cloud detectors.
- **Ultra short-term weather forecast**: This is a special area of weather forecast, in which very accurate and reliable short-term (about 1 hour) predictions are needed for a limited geographical area. Such forecast is used, for instance, by airports, sport and other open-air events, and so on. In these applications the real-time detection of the spatiotemporal change of the cloud coverage is essential. This task can be performed by automatic cloud detectors.

The market of automatic cloud detectors is very young (approximately one decade old), thus the available instruments are not accurate and fast enough. These problems have to be solved before a reliable cloud detector network can be created, the results of which can be successfully incorporated into the climatic models and can be used for short-term weather forecast purposes. Our new instrument, being more accurate than the existing cloud detectors, will help to solve these problems.

The solution

We use full-sky imaging polarimetry to achieve the desired result, that is, to enhance the accuracy of cloud detection and to measure the relative cloud-base height distribution on the whole sky. By measuring the intensity patterns of skylight through linear and circular polarization filters with different transmission axes, the polarization state of skylight can be determined along the sky-dome. The polarization pattern of the clear sky is well known and primarily depends on the position of the sun. This robust polarization pattern, however, is altered by clouds. The changes in the celestial polarization pattern induced by clouds can be used to detect the clouds in the sky as well as to estimate the height of the cloud-base above the ground. On the other hand, imaging polarimetry can also be used to increase the intensity and colour contrasts of sky photographs by the polarization-based dehazing procedure, which improves the accuracy and reliability of traditional photometric cloud detection algorithms.

State-of-the-Art

- **Intensity- and colour-based cloud detection**: Currently, the cloud detectors available from the market are exclusively based on the measured intensity of skylight in different (usually red, green and blue) parts of the spectrum. This means that for a given direction in the sky only the intensities of skylight are measured in the red, green and blue spectral ranges. Using these 3 data, a simple algorithm calculates the colour of skylight coming from a given celestial direction. If the sky colour deviates from the white smaller than a threshold, the algorithm assumes that in the investigated celestial point a colourless cloud exists, otherwise the sky pixel is considered clear. One of the disadvantages of this method is that the sky regions around the sun and anti-sun as well as near the horizon are usually whitish, i.e. more or less colourless, thus they may be detected as colourless clouds by an algorithm based exclusively on a colour picture of the sky. On the other hand, clouds illuminated by the red-orange rising or setting sun are reddish, thus they are not recognized as clouds by an algorithm looking for colourless celestial points. Similar problem occurs for high-altitude or far clouds, which are blueish due to Rayleigh scattering in the air layer between the clouds and the observer (cloud detector). The chance of such misdetections can be decreased with the use of additional optical data, namely the state of polarization of skylight, that can be measured by our full-sky imaging polarimeter. **LIDAR** is a LASER-based RADAR equipment used to measure the cloud profile. It measures the back-scattering of the emitted LASER beam and derives the water content distribution along the direction of the LASER beam. The disadvantage of this instrument for cloud detection is that it can measure the cloud profile only in one direction of the sky (usually in the zenith) at a give point of time. The so-called scanning LIDARs measure cloud profiles along a line or even in a small area of the sky. These measurements performed by periodical rotating/turning of the laser beam that requires some time, during which the sky scene can change. Thus, clouds can be detected and cloud-base height can be measured by LIDAR only in a very limited sky region. On the other hand, our polarization cloud detector based on full-sky imaging polarimetry can detect clouds and can measure the relative cloud-base height in numerous celestial directions, the number of which depends on the spatial resolution of the digital camera used.

Beyond the State-of-the-Art

- **Accurate and reliable cloud detection with the use of polarization data**: By using 4 times more information (degrees of linear and circular polarization, direction of polarization and intensity in the red, green and blue spectral ranges) of skylight in a given celestial direction (relative to the traditional method using only the intensity of skylight in the red, green and blue parts of the spectrum), we developed more accurate algorithms to detect clouds. The reliability of this approach is evident in comparison to the subjective cloud detection by human observers. The higher accuracy of our polarization-beased cloud detection relative to the intensity- and colour-based traditional method has been shown experimentally during measurement campaings in Hungary (Budapest) and on the Atlantic Ocean (research vessel Polarstern).

- **Exploitation of machine learning techniques for cloud classification**: Novel learning techniques can be used to robustly categorize clouds based on a reduced training set. Using this methodology, the user provides a few examples of the different types of clouds. Next, the computer extracts a number of features from the images and executes a learning algorithm that clusters them in a multidimensional space, creating a set of “visual-words”. Once this visual vocabulary has been learnt by the system, we can then characterize every image by a histogram of visual-word count to decide what type of clouds appear in the image. The features extracted to create the clusters may encode information not only about gradient, texture, color, etc., but will also exploit information from polarization data (the linear and circular degrees of polarization, angle of polarization).
- **Imaging cloud-base height measurement**: Using the state-of-the-art techniques it has been a very difficult task to measure the cloud-base height. Furthermore, it was a time-consuming procedure to measure this important parameter of clouds in numerous celestial directions (by scanning LIDAR). With our polarization-based method the distribution of the relative cloud-base height can be easily measured in the full sky. Although our method provides a lower vertical resolution relative to a LIDAR measurement, this resolution is high enough for cloud-clustering purposes. Using an absolute value of the cloud-base height measured by a LIDAR in a given celestial direction, the numerous relative cloud-base-heights obtained by our polarization-based method can also be converted to absolute values.
- **High-contrast photometric cloud detection on polarization-dehazed sky pictures**: Using imaging polarimetry, we can increase the intensity and colour contrasts of sky pictures, in which the clouds can be detected by traditional photometric cloud detection algorithms much more accurately than without such a polarization-based dehazing.
- **Three-dimensional cloud scene reconstruction**: Using (i) the constrast-enhanced colour images obtained from different nearby cloud detectors at the same time, and (ii) the celestial distribution of the relative cloud-base height from these two detectors, it is possible to calculate a three-dimensional map of the cloud scene. Such a map could be far more accurate than the present state-of-the-art that does not utilize polarization-based constrast enhancment and/or relative cloud-base height data.
- **Faster and cheaper cloud detection**: The very expensive scanning LIDAR needs a long time to scan a larger sky region in order to detect clouds, but during this time period the sky scene usually changes drastically. Consequently, clouds cannot be detected by a LIDAR in the full sky. By using imaging polarimetry, we can quickly detect clouds in the whole celestial hemisphere, and measure the celestial distribution of the relative cloud-base height in a very short time (typically 1 – 10 ms), during which the change of the sky scene is practically negligible.

Why now?

High-resolution and fast CCD cameras: As detectors we use industrial high-resolution and fast CCD cameras. A few years ago these cameras were too expensive, too slow and with too low spatial resolution, furthermore they required special cooling, which made it hard to use them. Current CCD cameras are fast enough, possess an appropriately high resolution and are easily embeddable into portable instruments with standard interfaces to computers, furthermore they require no extreme cooling. On the other hand, their price is low enough to build competitive products.

High-performance computers: The evaluation of the high-resolution polarization pictures of the sky taken through linear and circular polarizers, the detection of clouds and the computation of the cloud-base height distribution on the basis of the obtained polarization data are time-consuming procedures. In order to fasten these computations, especially if the real-time detection of the spatiotemporal change of the cloud coverage is needed, a high-performance, quick computer is necessary. Such computers are nowadays already available in the market for medium prices, which is one of the prerequisites of the production of competitive polarization cloud detectors.

R&D expertise

- **Mechanical engineering**: The design of the instrument requires some fine-mechanical engineering knowledge, because the different parts of the instrument should be adjusted and fixed in such a way that they are capable of enduring the inevitable mechanical stresses during the functioning in the field. Furthermore, the instrument has to be weather-proof.
- **Electronic engineering**: The control electronics (including its firmware) is custom-built, and has to be produced during the development process.
- **Computer engineering**: The image analysis requires advanced knowledge of machine learning techniques for object categorization and classification.
- **Standard hardware knowledge**: The electronic parts of the instrument should have standard interfaces to be easily connectable to each other.
- **Physical knowledge on light polarization**: The cloud detection and cloud-base height determination use polarization data, the measurement of which needs physical (optical) knowledge and experience in the technique of imaging polarimetry.
- **Mathematical algorithms**: Several mathematical operations (e.g. Stokes vector and Mueller matrix formulae), optimizing and clustering algorithms should be used in the evaluation of the polarization pictures as well as in the cloud detection, computation of the cloud-base height and recognition of cloud types.
- **Computer programming**: The main control unit of the instrument is a computer that has to be programmed in a standard programming language like C++ or Java.

Beneficiaries

- **Estrato Ltd., Budapest** has the technical knowledge and experience in the development of polarization cloud detectors. This firm has built version 1.0 of the instrument that was tested successfully in Budapest. The 2.0 version of the instrument, built by the same firm, was tested in 2010 during the international ANT-XXVII-1-2010 expedition from Bremerhaven through the Atlantic Ocean to Capetown onboard the research vessel Polarstern organized by the German Alfred Wegener Institute for Polar and Marine Research. The 3.0 version is being designed and built presently with the use of the field experiences gathered onboard Polarstern. The scientific background of the members of the Estrato Ltd. guarantees that the company can successfully participate in the scientific part of the project as well.
- **Environmental Optics Laboratory (Department of Biological Physics, Physical Institute, Eötvös University, Budapest**) owns knowledge of light polarization in nature, especially skylight polarization, and also has good experiences in the development of imaging polarimeters

and other scientific instruments.

- **Computer Vision and Robotics Group (University of Girona, Girona, Spain)**: The participating scientists of this research group possess invaluable knowledge about light polarization, image processing and analysis as well as different mathematical and computer algorithms.
- **Max Planck Institute for Meteorology and Alfred Wegener Institute for Polar and Marine Research** are typical possible users of our polarization cloud detector and its date and service.

Impact

- **Estrato Ltd.** is interested both in the producing and selling of the developed polarization cloud detector.
- **Environmental Optics Laboratory (Department of Biological Physics, Physical Institute, Eötvös University**) is interested in making atmospheric optical and biophysical researches with the use of the developed instrument.
- **Computer Vision and Robotics Group (University of Girona, Girona, Spain**) is interested in researches using the instrument, extending the use of machine learning techniques for advanced object recognition and classification using polarimetric images to complement non-polarized imaging classifiers.
- **Max Planck Institute for Meteorology and Alfred Wegener Institute for Polar and Marine Research** can use the results obtained by the instrument by incorporating the measured data into their clima models and using the cloud data for different meteorological and oceanographical purposes.

EU priority

For a successful research and development project we need to gather the best experts in the fields of polarimetry, meteorology, image processing, atmospheric optics, computer methods and development of scientific instruments. This justifies the demand to involve the above-mentioned consortium partners from the European Union in order to achieve successfully the planned research and development during the proposed project.