Stereo-Monitoring of Cloud Fields: A new Task for Spaceborne Remote Sensing

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Abstract: Cloud screening and tracking by geostationary satellites (GEO) is presently the main source for estimating cloud coverage and drift for weather forecast and climate research. The coarse pixel size of GEO misses essential details of the 3D cloud distribution, governing radiation transfer and energy balance. Optically thin cirrus clouds and especially aircraft contrails are rarely detected from GEO. Height is assigned only to optically thick clouds based on TIR radiation temperatures requiring auxiliary vertical sounding profiles of the temperature. The missing tasks can be solved by along track stereoscopic cloud observation from low Earth orbiting satellites (LEO), either in a Tandem satellite configuration or in combination with imaging differential absorption spectroscopy in the A-band of molecular oxygen at 760 nm wavelength. The development of suitable algorithms for the last method is a joint effort of the UCL London, DLR, FU Berlin and ETHZ Zurich and is supported by the European Commission. A scientific evaluation of the application potential will be performed by the Dutch Weather Forecast Service KNMI.

1 TASKS AND PROBLEMS OF CLOUD MONITORING

Cloud monitoring from space is not only a routine task for every day's weather forecast, but also for climate analysis and modeling since clouds play a major role for the Earth's energy balance, as a result of their large area extent and their variability on all scales. Current climate models are severely limited by the poor knowledge of the feedback processes associated with changes of cloud amount and cloud properties (WCRP-Report 86, 1994). Even optically thin Cirrus layers must be considered, as was demonstrated first for the 1987 El Nino ocean warming (RAMANATHAN and COLLINS, 1991).

It is important to estimate the impact of anthropogenic activities on cloudiness at all height levels, including contributions by air traffic, directly by the associated contrails and indirectly by the additional amount of water vapour injected into the upper troposphere. It is believed that rising temperatures will increase atmospheric humidity and global cloud amount.

Cloud screening and tracking by geostationary satellites is presently the main information source for deriving 3D-cloud coverage and wind estimates on a global base.

The horizontal and especially the vertical resolution of present space-borne imagers for meteorology is hardly sufficient for an accurate estimation of cloud cover due to the broken and scattered nature of most cloud fields (WIELICKI and PARKER, 1992) and it is insufficient to reveal the complex structural and statistical properties of cloud fields, that dominate their interaction with the radiation field (WISCOMBE et al., 1995).

An accurate assignment of absolute height to cloud layers and their drift vectors is an important issue in all this cases. Presently height is derived only for optically thick clouds based on their infrared radiation temperatures, requiring simultaneous vertical sounding profiles of atmospheric temperature.

The estimation of optically transparent clouds over land and coastal waters is completely based on models of spectral signatures and suffers from a lack of independent validation.

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2 THE CAPABILITY OF STEREO OBSERVATION

2.1 Stereo Observation from Geostationary Orbit GEO

In 1981 Hasler published results of an experimental stereo observation of clouds by a pair of geostationary satellites (GEO). For this purpose the imagers of the geostationary satellites GOES East and GOES West positioned at 75° and 135° western longitude were synchronised (HASLER 1981, HASLER et al. 1982). The stereo observation angle was 60° in the overlapping part of both fields of view. The ground pixel size was 0.9 km in the visible channel and 8 km in the thermal infrared regime. The achieved height resolution ranged from 0.1 to 0.5 km for the visible channel, depending on image contrast of the cloud scenes. The absolute accuracy of cloud top height CTH was about ± 0.5 km. Stereo matching of the TIR-channel turned out to be too coarse for practical applications. In spite of the demonstrated value of stereoscopic monitoring of severe storms in the visible channels the method did not become operational.

2.2 Stereo Observation from Low Earth Orbit LEO

Compared to GEO, the much smaller pixel size available by along track stereoscopic imagers at low Earth orbiting satellites (LEO) makes those instruments a quite ideal tool for visualising the 3D-distribution of clouds. Within the quite short time gaps of about 20 to 100 seconds associated with the stereoscopic observation at different viewing directions, the cloud shape is changing only in the small scale (10 to 100 m range). Clouds can hence be stereoscopically monitored at a much better resolution than from GEO, that is at a pixel sizes down to less than 100 m. Any systematic reduction of the accuracy of stereoscopic image correlation for small pixels (of less than 100 m) could be interpreted as a measure for the level of turbulence on the upper cloud boundary.

2.2.1 Stereo Observation with Conical Scanners

Presently stereoscopic cloud observations are provided by the conical scanners ATSR-2 on ERS-2 and MMS-UK on the Russian satellite RESURS. AATSR on ENVISAT will provide this type of data in the future. However, the swath width of only 200 to 500 km of these conical sensors is not sufficient to provide data on a daily global base. Also the ground pixel between 0.17 and 1 km does not give much improvement for the derivation of cross track cloud drift or for a detailed analysis of the 3D-structure of cloud fields. A further drawback of conical scanners is the severe reduction of the stereoscopic base length and of the associated time gap from the sub-satellite track towards the swath boarder.

2.2.2 Stereo Observation with Multiply Stereoscopic Line Scanners

A constant base length and time gap across the whole swath was or will be offered at high spatial resolution by the German cameras MOMS on MIR and HRSC and WAOSS developed for the Russian Mars 96 Mission as also by the American MISR on EOS and by SPOT-V. All these instruments are CCD line-scan cameras operating in the visible/near IR spectral regime and applying three or more different view angles in the along track direction. This multiple observation technology provides a highly improved redundancy for stereoscopic image matching of clouds. MOMS, HRSC and SPOT are high-resolution cameras with pixel sizes in the 5 to 20 m range, but with a small swath width of only 50 to 150 km. Applied on Earth at an 750 km orbit WAOSS could provide 1500 km swath width and 250 m pixel size resulting in global coverage every two days. The American MISR on

EOS will provide a 275 m ground pixel size at 400 km swath width and global coverage only every nine days.

2.3 Height Estimation for Optically Thin Clouds

The discrimination of the signals of transparent clouds from the signal of the Earth surface in monoscopic images in the VIS/NIR spectral channels is presently based on intensity thresholds and colour ratios. Cloud detection can be enhanced by thresholding of radiation temperatures, if an additional TIR-channel is available These procedures are of limited value over land and coastal sea surfaces and can nearly not be applied to separate signals of upper level cirrus clouds or contrails from lower level clouds.

DLR intends to solve this problem by development of a special cirrus detection algorithm, based on modelling of their textural properties by stochastic processes (allowing for diffuse boundaries), applying fuzzy measures and fusion of different properties by a fuzzy integral (HETZHEIM, 1993).

The systematic spatial displacement (parallax) of the spectral and textural signatures of transparent clouds relative to those of the surface provided by stereo image pairs will help to strengthen their discrimination in comparison to the monoscopic case.

3 Ambiguity of Height and Along Track Drift of Cloud Stereoscopy from Leo

The time gap of about 100 s introduced between the fore- and the Nadir- or aft-looking stereo-view direction unambiguously allows deriving the cross track drift component of clouds. Unfortunately on a circular orbit the base to height ratio B:H of the stereo observation and the associated time gap is (nearly) independent of the applied viewing angles. For that reason the along track stereoscopy cannot discriminate the parallaxes of (true) cloud height from those parallaxes generated by the along track drift component of the same clouds. This ”ambiguity problem” of cloud stereoscopy requires an independent measurement of either cloud height or drift. This fact has inhibited the development of dedicated stereoscopic line-scanners for purely meteorological application from LEO (DRESCHER, 1986).

3.1 True Cloud Height by Synoptic Wind Estimates

One solution for the ambiguity will be to apply daily wind estimates provided from weather forecast to correct the apparent stereo cloud height to "true values". The method will work on a global and regional scales as wind is spatially very homgeneous at these scales with the accuracy of the synoptic wind estimates. The method will have sysematic errors in complex situations and completely fail with for clouds associated with orography and waves.

3.2 True Stereo Cloud Height by Earth Surface Curvature

The American MISR on EOS was especially developed for studies of the bidirectional reflectance distribution function BRDF of the Earth. MISR is a nine camera assembly applying ground based along track viewing angles of 0°, ±26.1°, ±45.6°, ±60.0° and ±70.5° with four spectral channels per camera at 443, 555, 670, and 865 nm wavelength providing 360 km overlapping swath from a 705 km polar orbit at 275 m ground pixel size. Global coverage is reached every nine days.

By the curvature of the Earth surface the B:H ratio is faster growing with the view angle than the associated time gap and the height contribution to the image parallaxes is exaggerated in comparison to the wind contribution. By comparing parallaxes of stereo image pairs close to nadir with image pairs of extreme view angle it is possible to discriminate both effects and to assign absolute values to height and along track drift, but only with an absolute accuracy of many pixel.

The expected relative and absolute accuracy for cloud height and drift is given in **Table III**, normalised for one pixel accuracy of stereo image correlation. However, the achievable accuracy of image correlation at the extreme view angles of MISR may only be several pixel.

camera Nr.	A	B	C	D	E	
view angle	$\pm$70,5	$\pm$60,0	$\pm$45,6	$\pm$26,1	0,00	°
ground elevation	19,5	30,0	44,4	63,9	90,0	°
time gap to Nadir	205	144	91,6	45,5	0,00	s
B:H ratio (with Nadir)	2,82	1,73	1,02	0,49	0,00	ratio
windparallax	1,34	1,91	3,00	6,04	n.a.	m/s
height-parallax	97,4	159	269	561	n.a.	m
combination of stereo-pairs	AB/DF	BC/DF	CD/DE	AB/CG	BC/CG	
absolute accuracy for wind	8,16	18,11	99,17	5,35	15,13	m/s
absolute accuracy for height	515	1.462	8.713	393	1.286	m

3.3 True Cloud Height by Stereoscopic Tandem Missions at LEO

The ambiguity problem of in line cloud stereoscopy can be solved perfectly by two satellites flying in a "TANDEM-Configuration" on the same orbit, simultaneously applying stereoscopy in ”real time” and at ”time delay”. Any already existing main satellite with a nadir-looking scanner (NOAA/ AVHRR or IRS-P3/WIFS) could be combined with a second satellite equipped with a two- or threefold stereoscopic line-scan camera, following the main satellite at a distance of about one base length (DRESCHER, 1988). Tandem configurations of small satellites are also considered as an cost effective alternative to large universal satellites as NOAA or ENVISAT (RANEY et al., 1996). Suitable stereo cameras could be developed on the technical base of the German HRSC and WAOSS cameras or by extending the Indian Wide Field Sensor WIFS with one or two panchromatic stereo channels. The three spectral bands at 0.62-0.68, 0.77-0.86 and 1.55-1.75 µmof the WIFS would essentially facilitate the discrimination of water and ice phase of clouds and of cloud from surface features.

3.4 True Cloud Height by Differential Spectroscopy

The true height of cloud top surfaces can be derived based on differential absorption measurement in the A-band of molecular oxygen at a wavelength of 760 nm. The method will provide independent information on cloud optical thickness, a mean particle radius in the upper cloud layer and the total mass of molecular oxygen above the clouds. The true cloud top height can be inferred from the oxygen mass requiring just a correction for the actual ground pressure and no further data as temperature or humidity soundings (FISCHER and KOLLEWE, 1994). Suitable data are provided by the German MOS-A on the Indian satellite IRS-P3, and by MERIS on ENVISAT.

3.5 Advantages of A Combined Approach

Combining along track stereoscopic cloud observation with imaging absorption spectroscopy in the A-band of molecular oxygen on one satellite, for exemple an IRS-P3 follow on mission, in a tandem configuration with METOP or ENVISAT will allow to simultaneously derive the detailed 3D structure of cloud fields, absolute cloud top height and cloud drift values and further important cloud-physical parameters essential for their interaction with the radiation field and cloud climatology.

The development of evaluation algorithms for the combined method is presently a joint effort of the University College London UCL, the German Aerospace Centre DLR the Free University of Berlin and the Technical University of Zurich ETHZ and is supported by the European Commission. An scientific evaluation of the application potential will be performed by the Dutch Weather Forecast Service KNMI.

The combined approach could prove to be of great value also for natural disaster prediction. For example In 1998 and 1999 several severe storm conditions over South East Asia and Germany were not correctly predicted by the national weather agencies.

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