NEW CONCEPTS FOR SPACEBORNE MONITORING OF DRIFT AND 3D-MORPHOLOGY OF CLOUD FIELDS FOR WEATHER FORECAST AND CLIMATE RESEARCH

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ABSTRACT

Cloud screening and tracking by geostationary satellites (GEO) is presently the main information source for estimating cloud coverage and drift for weather forecast and climate research. The coarse pixel size from GEO misses essential details of the 3D cloud distribution that are important for their interaction with the radiation field and hence for the energy balance of the Earth. Height is assigned only to optically thick clouds based on their radiation temperatures requiring auxiliary vertical sounding profiles of the atmospheric temperature. Optically thin clouds, as for example the nearly permanent tropical cirrus layer, and especially for aircraft contrails are rarely detected by observations from GEO.
We discus here three methods for improved 3D monitoring of cloud structure and drift, including optically thin clouds and aircraft contrails, from low Earth orbiting satellites (LEO).

- Threefold along track stereoscopy at an eccentric orbit, as it was envisaged for the Russian Mars 96 mission.
- Stereoscopic imager on a dedicated Smalsat in a controlled TANDEM-configuration with a monoscopic imager (for example AVHRR) on a main-satellite, and finally
- Combining along track stereoscopic cloud observation with imaging differential absorption spectroscopy in the A-band of molecular oxygen at 760 nm wavelength from LEO (Low Earth Orbiting) satellites.

The development of algorithms for the last 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. A scientific evaluation of the application potential will be performed by the Dutch Weather Forecast Service KNMI.
DLR intends to solve the problem of cirrus discrimination by the development of special cirrus detection algorithm, based on the stochastic of their intensity and of their textural properties (allowing for diffuse boundaries), applying fuzzy measures and fusion of different kinds of properties by a fuzzy integral.

ZUSAMMENFASSUNG

Gegenwärtig werden Wolkendrift und Wolkenbedeckungsgrad für Wettervorhersage und Klimaforschung vor allem aus Bildsequenzen geostationärer Satelliten (GEO) abgeleitet. das grobe Bild aus GEO übersieht entscheidende Details der 3D-Verteilung von Wolkenfeldern, die für die Wechselwirkung mit dem Strahlungsfeld und die Energiebilanz wesentlich sind. Eine Höheninformation kann gegenwärtig nur optisch dichten Wolken über deren Strahlungstemperatur zugeordnet werden, gestützt auf eine zusätzliche Vertikalsondierung der Atmosphärentemperatur.
Wir diskutieren hier drei Methoden zur Ermittlung von 3D-Struktur und Drift der Wolken einschließlich Cirren und Flugzeugkondensstreifen von tief umlaufenden Satelliten (LEO) aus:

- Dreifachstereoskopie in Flugrichtung von einer exzentrischen Bahn aus, wie im russischen Mars 96 Projekt vorgesehen,
- einem Stereobildaufnehmer auf einem Kleinsatelliten in Tandem-Konfiguration mit einem mono- oder stereoskopischen Bildaufnehmer auf einem Hauptsatelliten (z.B. AVHRR auf NOAA) und
- eine Kombination von Wolkenstereoskopie mit abbildender differentieller Spektroskopie in der A-Bande des molekularen Sauerstoffs bei 760 nm Wellenlänge.

Die Entwicklung geeigneter Algorithmen für die letzte Methode stellt ein Gemeinschaftsvorhaben des University College London UCL, des Deutschen Zentrums für Luft- und Raumfahrt DLR der Freien Universität Berlin und der Technischen Universität Zürich ETHZ dar und wird von der Europäischen Kommission gefördert. Eine wissenschaftliche Bewertung des Anwendungspotentials der Daten wird vom Holländischen Wetterdienst KNMI vorgenommen werden. Das DLR plant die Entwicklung eines auf Texturmerkmalen basierenden Algorithmus für Cirrenerkennung unter Verwendung von Fuzzy-Maßen für die verschiedenen stochastischen Eigenschaften und deren Integration über das Fuzzy Integral.

1. INTRODUCTION

1.1 Problems of Cloud Monitoring from Space

Clouds play a major role in governing the Earth's energy balance, as a result of their large area extent and their variability on all scales. Cloud screening and tracking by geostationary satellites is presently the main information source for deriving 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 of cloud layers 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.

Special problems arise with the necessity to detect even optically thin clouds, as for example the nearly permanent tropical cirrus layer, that may cause wrong estimates of radiation temperatures and the associated height of lower cloud layers (and finally of the energy balance) or even of the drift vectors of the lower cloud layers. Cirrus clouds influence the radiation budget in a way that enhances the greenhouse effect.

Current models of Earth's climate are severely limited by the low knowledge on the feedback processes associated with changes of cloud amount and cloud properties [Intergoverm. Panel on Climate Change, 1992]. Even the optically thin clouds (Cirrus layers) must be considered within this respect, as was demonstrated by for the 1987 El Nino ocean warming. [Ramanathan and Collins, 1991]

It is further of major importance to estimate the impact of anthropogenic activities on cloudiness at all height levels. It is believed that a rising atmospheric temperature will lead to an increase in atmospheric humidity and thus also in the global cloud amount.

A continuous observation of cirrus clouds is urgently needed to study their role in the Earth's climate system. Especially we need to quantify direct contributions to cloudiness in the upper troposphere related to sub-sonic air traffic, either directly by the associated contrails ore more indirectly by the additional amount of water vapour resulting from the continuous injection by sub-sonic air traffic.

1.2 Cloud Screening Capability of Spaceborne Sensors

Geostationary cloud imagers operate with a ground pixel size of 5 and 10 km (METEOSAT) and 1-8 km (GEOS-8/9) and at repetition times of 15 to 60 minutes. AVHRR on the polar orbiting NOAA satellite provides a better resolution with 1 and 4 km pixel, but only twice per day. The accuracy of cloud drift monitoring from geostationary image sequences is estimated as 6 to 7 m/s for the upper Troposphere from a comparison with radio-sond data. [H. Woik, EUMETSAT, (p.c.)]. Estimates of the accuracy of height assignment to clouds and their drift vectors are presented in **Table I.**

Platform Sensor	Technique	IFOV [m]	Z rms [m]
GOES-VAS	CO2/TIR	8,000	500
NOAA-HIRS	CO2/TIR	50,000	180-440
EOS-MODIS	CO2/TIR	1,000	310-360
MIR-MOS-A	O2 A-band	1,000	~ 300
ERS-ATSR	CO2/TIR	1,000	~ 500
EOS-MISR	stereo	275	500-1000
MIR-MOMS	stereo	18	~ 50

Table I: Estimates of the mean error Z rms for cloud top height CTH of some selected space-borne sensors

2 ADVANCED TOOLS FOR CLOUD MONITORING FROM SPACE

2.1 Experimental Stereo Observation from Geostationary Orbit

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 01 to 05 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 severe storm monitoring in the visible channels the method did not become operational.

2.2 Stereo Observation by from Low Earth Orbiting Satellites

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.

2.1.2 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 basis. 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.

2.1.2 Threefold Stereoscopic Line Scanners

A constant base length and time gap across the whole swath is 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 ranges, but with small swath width of 50 to 150 km dependent on orbit height. On Earth WAOSS could provide (more than) global coverage every two days with 1500 km swath and 250 m pixel at an 750 km orbit. The American MISR on EOS will provide a 275-m ground pixel size at 400-km swath width.

2.2 Stereo-Ambiguity of Height and Along Track Drift Component of Clouds

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 on LEO [Drescher, 1986].

2.3 Non-Ambiguity of Threefold along Track Stereoscopy from an Eccentric Orbit

On a circular orbit the base to height ratio 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.

If threefold stereoscopic imaging will be applied on the up-or down-bound branches of an eccentric orbit, the time gap will be faster growing with the height of the spacecraft, than the base to height ratio. This fact introduces an asymmetric contribution of height and along track drift to the parallaxes of the forward to nadir image pair in comparison to the backward/nadir pair.

The ratios (TAN of the ground based view angle to time gap) between the forward to Nadir and the Nadir to backward stereo image pairs. This asymmetry allows to discriminate between cloud height and its along track drift and to assign true values to both of them. However, this absolute accuracy is always systematically much worse than the (relative) resolution.

Table II shows the theoretical relative and absolute resolution for cloud height and along and cross track drift expected for the HRSC camera on the Russian Mars 96 mission. All values are given in steps of 5° of true anomaly (Mars centre angle between spacecraft and periapsis position) assuming negligible error contributions from the orbit and attitude measurements.

true anom. [°]	S/C height [km]	stereo pixel [m]	resolution veloc. [m/s]	resolution height [m]	absolute x-drift [m/s]	absolute y-drift [m/s]	absol. height [m]
0	297,5	11,90	0,2487	16,12	0,249	1/0	1/0
5	304,1	12,16	0,2476	16,45	0,248	22,76	1.486
10	323,9	12,95	0,2447	17,44	0,245	11,19	783,0
15	357,2	14,29	0,2399	19,10	0,240	7,194	561,3
20	404,5	16,18	0,2334	21,40	0,233	5,163	462,6
25	466,4	18,66	0,2253	24,35	0,225	3,915	412,1
30	543,9	21,75	0,2156	27,94	0,216	3,036	381,6
35	638,0	25,52	0,2044	32,17	0,204	2,387	362,0
40	750,3	30,01	0,1919	37,02	0,192	1,887	348,4
45	882,4	35,30	0,1781	42,51	0,178	1,486	336,3
50	1.037	41,46	0,1629	48,65	0,163	1,162	324,9
55	1.215	48,61	0,1464	55,15	0,146	0,891	311,5
60	1.422	56,88	0,1279	63,16	0,128	0,662	294,3
65	1.660	66,41	0,1054	72,00	0,105	0,457	269,7

Table II indicates the theoretical resolution and accuracy for the case of HRSC in steps of 5° of true anomaly and normalised for one pixel accuracy of stereo image correlation:

- true anomaly (in steps of 5°),
- height of the spacecraft,
- ground pixel size,
- resolution for cloud velocity vectors and cloud heights,
- absolute accuracy for the cross track cloud drift and
- absolute accuracy for the along track cloud drift.

The table shows, that the instrumental resolution for drift velocity and height of clouds is excellent for the case of HRSC on Mars. The relative and absolute accuracy of the cross track drift of clouds is the result of neglecting here the errors from orbit and attitude measurements. The achievable absolute accuracy for height and along track drift is acceptable, if the anomaly is > 20°.

2.4 Non-Ambiguity by Application of Extreme Stereo View Angles

The American MISR on EOS is a special instrument developed for studies of the bidirectional reflectance distribution function BRDF of the Earth. For this purpose MISR is composed of nine independent cameras applying ground based along track viewing angles of 0°, +26.1°, +45.6°, +60.0°, and +70.5°. Each camera uses four spectral channels of 1520 pixel at 443, 555, 670, and 865 nm wavelength.. With 360 km overlapping swath width from a 705 km polar orbit MISR will provide global coverage every nine days. The ground pixel size is 275 m.

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 parallxes of stereo imge pairs close to nadir with image pairs of extreme view angle it is possible to assign absolute values to height and along track drift of clouds in a similar way as in the case of excentric orbits.

The expected relative and absolute accuracy for cloud height and drift are presented in **Table III**, normalised for one pixel accuracy of stereo image correlation.

camera Nr.	A	B	C	D	E	
view angle	±70,5	±60,0	±45,6	±26,1	0,00	°
ground elev.	19,5	30,0	44,4	63,9	90,0	°
time gap	205	144	91,6	45,5	0,00	s
B:H ratio	2,82	1,73	1,02	0,49	0,00	ratio
windparallax	1,34	1,91	3,00	6,04	n.a.	m/s
z-parallax	97,4	159	269	561	n.a.	m
stereo-pair	2ab/df	2bc/df	2cd/de	2ab/cg	2bc/cg	
σ Wind	8,16	18,11	99,17	5,35	15,13	m/s
σ Height	515	1.462	8.713	393	1.286	m

2.5 Solving for the Ambiguity by Tandem Missions

The ambiguity problem can be solved perfectly if we simultaneously apply stereoscopy in "real time" and at "time delay". We propose here to fly two satellites in a "TANDEM-Configuration" on the same orbit, with an already existing main satellite bearing a nadir-looking scanner (as for example AVHRR on NOAA) followed by a second satellite equipped with a two- or threefold stereoscopic linescan camera at a distance of roughly one base-length [Drescher 1988].

Tandem configurations of small satellites are discussed as an cost effective alternative to large universal satellites as NOAA or ENVISAT [Raney et al. 1996].

Suitable stereo cameras can be developed on the technical base of the German HRSC and WAOSS cameras or the Indian Wide Field Sensor WIFS with 188 m pixel at 770 km swath width.

By its three spectral bands at 0.62-0.68, 0.77-0.86 and 1.55-1.75 micrometer wavelength a stereoscopic WIFS would essentially facilitate the discrimination of water and ice phase of clouds and of cloud from surface features. Application of the first two spectral channels of WIFS at Nadir and additionally on a strongly inclined view angle would provide two different ratios between vegetation and soil signal, this wise adding a further dimension to the derivation of the Net Differential Vegetation Index NDVI, as already demonstrated with the data of ATSR-2 [Gemmell and Millington, 1997]. The NDVI is presently derived globally with only one view direction from the first two channels of AVHRR on the NOAA satellites.

2.6 Solving for the Ambiguity via Cloud Height Estimation by Differential Spectroscopy in the OxygenA-Band

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. Measurements with an airborne spectrometer have shown that spectroscopic measurements at three ore more positions in the oxygen A-band will provide independent information on cloud top height, cloud optical thickness, a mean penetration depth of the backscattered radiation and of the total mass of molecular oxygen above the cloud [Fischer and Kollewe, 1994]. True cloud top height can be inferred from the last information requiring just a correction for actual ground pressure and no further data as temperature or humidity soundings.

Combining along track stereoscopic cloud observation with imaging absorption spectroscopy in the A-band of molecular oxygen wiil allow to derive simultaneously absolute values on cloud top height and cloud drift. Suitable data can be provided by imaging spectrometers as the German MOS-A presently flown on the MIR station and also on the Indian satellite IRS-P3, by GOME on ERS-2 and in the future by MERIS on ENVISAT. MOS-A on IRS-P3 applies 500 m ground pixel size at 200 km swath width. MERIS will apply a 2.5 by 5 km ground pixel at 1450 km swath. The GOME pixel of 40 by 40 or 40 by 320 km is to coarse for an application on clouds.

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

The algorithms will be tested with data from existing imaging spectrometers as GOME on ERS-2 and MOS-A on MIR and IRS-P3 and stereoscopic instruments as ATSR-2 on ERS-2, the German high resolution camera MOMS on MIR and in the future with also with data of the along track stereo module of SPOT-V An operational application is envisaged with MERIS and AATSR on ENVISAT and MISR on EOS.

3 MONITORING OF CIRRUS AND AIRCRAFT CONTRAILS BASED ON THEIR STOCHASTIC PROPERTIES

The discrimination of clouds from the signal of the Earth surface in monoscopic images is taken in the VIS/NIR spectral channel presently based on intensity thresholds and colour effects. Cloud detection can be enhanced by thresholding of radiation temperatures, if an additional TIR-channel is available The problem of separating signals of upper level cirrus clouds or young and aged aircraft contrails from lower level clouds can not be solved reliably by these procedures.

DLR intends to solve this problem by development of a special cirrus detection algorithm, based on the stochastic of their intensity and of their textural properties (allowing for diffuse boundaries), applying fuzzy measures and fusion of different kinds of properties by a fuzzy integral [Hetzheim, 1995].

The detection of cirrus clouds is difficult, because they are optically very thin, the grey values are hard to distinguish from the background, and their boundaries are diffuse. A fusion of different stochastic properties can be used for their detection, for example: a selected intensity distribution, and the missing of boundaries.

An effective method to collect such different kinds of properties, which are mainly stochastic, is the application of the fuzzy integral related to image processing [Hetzheim 1993].

With the help of the fuzzy measure the properties described by different kinds of relationships are all mapped in the closed interval [0,1]. The fuzzy measure, first defined by Sugeno [Sugeno 1974], allows the representation of the importance of special properties by a different weight factor l. In such a way the additivity of the measure is lost and the coupling of the fuzzy measures g is given by:

$$g(A \cup B) = g(A) + g(B) + \lambda\, g(A)\, g(B)$$

Where the coupling parameter l is calculated by solving the equation:

$$1 + \lambda = \left[\prod_{x_i \in A} \left(1 + \lambda g(x_i)\right) \right]$$

with x_i = a specific property of cirrus clouds

The following properties can be used to identify cirrus clouds:
a) Repetition of differences in the grey values,
b) parameters describing the stochastic in density
c) the direction of similar grey values,
d) the differences of values in a given distance and combination of this properties.

All these different properties can be summed up for an improved decision process by representing the process by a characteristic number, determined by a projection of the property onto the same interval [0,1].

All this properties of different kind have a relationship to the description of the cirrus clouds. These effects can be summed up for a better decision making by the representation of a number, given by the projection of the property on the interval [0,1]. Using such fuzzy measure, different parts of properties can be summed up by the fuzzy integral. The fuzzy integral

$(F)\int_A$ is defined by

$$(F)\int_A h_\alpha(x) \otimes dg := \sup_{\alpha \in [0,1]} \left\{ \min\left[\alpha, g(A \cap H_\alpha)\right] \right\},$$

$$H_\alpha = \left\{ x \mid h_\alpha(x) \geq \alpha \right\}$$

Here is h_α a function of the fuzzy value x over the area A with the cut value a.

The fuzzy integral connects the properties represented as a fuzzy function with the corresponding fuzzy measure of another property. The fuzzy integral has the property of a fuzzy measure. In such a way the cirrus clouds can be discriminated from other clouds by a hierarchical application of fuzzy integration. Here the new fuzzy function is given by the value of the fuzzy integral.

For the detection of cirrus clouds the boundary is represented by optical thickness. By this parameter a cirrus clouds can be distinguished from other clouds. For the fuzzy function are used properties such as:
a) differences of grey values in different distances,
b) weak change of the grey values at the boundary,
c) difference of the stochastic in different directions.

By the fuzzy integrals this fuzzy functions are coupled with the fuzzy measure. For example can be combined the weak change of the grey values at the boundary with the fuzzy measure of the direction of similar grey values. This integral can be used as a new fuzzy measure g_1. The coupling of g_1 and the fuzzy function for the differences of grey values in different distances by the fuzzy integral gives a new fuzzy measure g2. By such a hierarchical process it is possible the weak information of the cirrus clouds to collect for a better decision making. This procedure has been successfully applied to find cirrus clouds.

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