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FOUR DIMENSIONAL OBSERVATIONS OF CLOUDS FROM GEOSYNCHRONOUS ORBIT USING STEREO DISPLAY AND MEASUREMENT TECHNIQUES ON AN INTERACTIVE INFORMATION PROCESSING SYSTEM

A. F. Hasler, M. desJardins, W. E. Shenk, *Goddard Space Flight Center, Greenbelt, Maryland*

ABSTRACT

Simultaneous Geosynchronous Operational Environmental Satellite (GOES) 1 km resolution visible image pairs can provide quantitative three dimensional measurements of clouds. These data have great potential for severe storms research and as a basic parameter measurement source for other areas of meteorology (e.g. climate). These stereo cloud height measurements are not subject to the errors and ambiguities caused by unknown cloud emissivity and temperature profiles that are associated with infrared techniques. Previous work by Minzner et al. (1978a) has demonstrated the validity of stereo measurements from geostationary satellites using techniques based on conventional analogue stereography. This effort describes the display and measurement of stereo data using digital processing techniques.

Computer remapping of digital GOES image pairs allows the interactive display (on the Atmospheric and Oceanographic Information Processing System, AOIPS) of time sequences of stereo images: a true four dimensional representation of cloud structures. A description of similar work at the University of Wisconsin is given by Bryson (1978). Interactive manual and semi-automatic height measuring techniques have also been developed on AOIPS. Capabilities under development include: 1) measurement of multilevel wind fields with accurate height assignment; 2) estimation of thunderstorm intensity from horizontal and vertical cloud growth rates; and 3) measurement of four dimensional cloud structure for comparison with numerical models and radar observations. Stereo height verification and error analyses were conducted using computer crosscorrelation on AOIPS. Accuracies of ±0.5 km appear to be possible for geographical features and clouds with precisions (relative accuracies) approaching ±0.1 km.

INTRODUCTION

The quantitative three-dimensional geometric descriptions of cloud structure as a function of time is extremely important in severe storm research as well as other areas of meteorology. A few of the many uses include: 1) height assignment for satellite cloud winds; 2) cloud growth rate measurements for storm intensity estimation; and 3) input and verification for radiation models. This paper describes the stereo display and measurement of the four dimensional cloud structure using digital data on an interactive image processing system (AOIPS) which has many inherent advantages over previously used techniques.

The only method routinely used over the U.S. for measuring cloud heights at frequent intervals depends on infrared equivalent blackbody temperatures (T_{BB}'s) from the Geosynchronous Operational Environmental Satellites (GOES). Stereo cloud height measuring techniques have the following advantages over the infrared techniques: 1) The GOES visible resolution is 8 times greater than the IR resolution, making it possible to measure the height of much smaller clouds and cloud features. 2) The infrared techniques require a knowledge of cloud emissivity which cannot be determined accurately from GOES images so that thin clouds (especially cirrus) often have large height errors. 3) The infrared techniques require an atmospheric temperature profile which is generally not available and in the case of isothermal layers cannot be accurately used for height assignment. 4) The stereo representation allows the operator to scan large areas while observing height differences, whereas with infrared techniques, height is generally shown only as a T_{BB} change which is not as easily interpreted. 5) Multilevel height determination is possible using stereo including measurements beneath thin cirrus which are impossible using the infrared.

Previous stereo analyses from geostationary satellites by Minzner et al. (1978a, 1978b) involves the use of hard copy images and optical mechanical systems. The processing techniques used in this work operate directly on the digital data in its most pure form. The measurements made directly from the digital data do not differ from the degradation and inaccuracies inherent in all image display systems and optical mechanical devices. Computer remapping of the images gives a three dimensional view of a large area with no apparent distortion. When time sequences of remapped stereo image pairs are displayed on AOIPS the 3-dimensional evolution of clouds can be observed: a true 4-dimensional representation. The unique image shift capabilities of AOIPS allow the interactive manual measurements of height as well as automatic computer cross correlation height measurement and interactive image enhancement.

Another paper in this volume by Minzner et al. (1978b) describes: 1) The useful area of coverage for the two operational GOES satellites; 2) Stereo cloud height errors caused by imprecise image pair scan synchronization; and 3) Theoretical error limits for satellites with various longitude separations.

TECHNIQUES

Basic Remapping, Display and Height Measurement

Image sequences from the two GOES satellites are precisely navigated. A 512 X 512 visible picture element (pixel) area of interest from one satellite is chosen. A somewhat larger area from the second GOES satellite is then remapped digitally* into the coordinate system of the first satellite such that sea level features are superimposed. Features above or below sea level will be displaced to the left or right. This parallax gives a three-dimensional view when the image pair is projected through the red and green channels of a color television system and viewed through red and green glasses. The magnitude of the parallax is a function

*See Moik (1977) for remapping programs used on the IBM 360-91.

of the altitude and is used to calculate the height. Time sequences of remapped image pairs are then displayed on AOIPS. The heights are measured on AOIPS using the following procedure: a cursor or box is moved under joystick control to the cloud or geographical feature to be measured. One of the images is shifted also using the joystick (a unique AOIPS function) until the parallax for that feature is eliminated. Observed through the stereo glasses the cursor appears to move up or down until it is at the height of the feature. This manual measurement of the parallax can only be made to the nearest pixel, therefore a cross correlation algorithm must be used when subpixel accuracy is required. The parallax is used to calculate the height taking into consideration the positions and attitudes of the satellites.

Cloud Motion and Height Measuring Techniques

Software is under development at GSFC on AOIPS to allow the measurement of cloud motion and height simultaneously from stereo image sequences. Observation of three-dimensional cloud motion fields makes it much easier to measure winds at many levels and to minimize confusion between cloud tracers, because even small altitude differences between cloud layers are observed. This software will also aid in the measurement of cloud height variations as a function of time. Methods are also being developed to contour cloud height as a function of time on AOIPS. These methods will be adapted for the cloud growth techniques used to estimate vertical velocities and storm intensity which is now done using infrared techniques by Adler & Fenn (1978a, 1978b).

STEREO HEIGHT VERIFICATION AND ERROR ANALYSIS

Measurements of the altitude of known geographical features, repeatibility studies on cloud heights, and stereo vs. IR height comparisons have been made to evaluate the stereo cloud height accuracy. The altitude of the coastline over a 5° latitude by 5° longitude area of the Gulf of Baja California was measured to determine bias errors and to estimate altitude measurement variability. The average bias error was $\overline{Z} = -0.67$ km with a standard deviation $\sigma_Z = 0.29$ km as shown in Table 1. Over a small 5 x 5 pixel area the standard deviation $\sigma_Z = 0.10$ km. The coastline altitude bias error was also measured in central California and near Lake Titicaca in South America where $\overline{Z} = 0.11$ km and 0.26 km respectively (also shown in Table 1).

Also, the altitude of several lakes in and near California, and Lake Titicaca were used for verification. The differences between the stereo heights and the known (map) altitudes ranged from 0.01km to 0.29 km once the sea level bias error was removed. Although we have no rigorous verification of cloud top height we conclude from these terrestrial data comparisons that the absolute accuracy of the cloud height measurements is about ±0.5 km and if a feature of known altitude is available in the image, measurements of precision approaching ±0.1 km are possible (relative accuracy). The absolute accuracy is dependent upon having a very accurate navigation solution. Repeatibility measurements of heights of various cloud types indicate that cloud layer altitudes can be measured within about 0.1 km even for very thin cirrus as shown by the standard deviation values ranging from $\sigma_Z = 0.08$ to $\sigma_Z = 0.19$ in Table 2. Repeatibility over a few pixels (σ_Z local) is also excellent. All measurements were made using a crosscorrelation algorithm which can measure to subpixel precision. For maximum precision it is necessary to have a fairly large, high contrast feature oriented in a north south direction.

Table 1. AOIPS digital stereo error analysis based on geographical feature height verification from GOES East (75°W) and GOES West (135°W)

	Altitude (km)				
	Z_{MAP}	$\overline{Z}$	$\overline{Z}_{CORRECTED}$	σ_Z	$Z_{MAP} - \overline{Z}_{CORRECTED}$
BAJA (1 km ≈ 1.5 pixels)					
5° Lat. X 5° Long. area	0	-0.67		0.29	
5 X 5 pixel area	0	-0.46		0.10	
CALIFORNIA (Lake Tahoe Area/ 1 km ≈ 2 pixels)					
Coast Line	0	0.11		0.25	
Walker Lake	1.21	1.03	0.92	0.17	0.29
Pyramid Lake	1.16	1.20	1.09		0.07
Lake Tahoe	1.90	2.0	1.89		0.01
Mono Lake	1.95	2.0	1.89		0.06
SOUTH AMERICA (Lake Titicaca area/ 1 km ≈ 5 pixels)					
Coast Line	0	0.26	–	0.11	
Lake Titicaca	3.82	4.21	3.95	0.19	0.13

Table 2. AOIPS digital stereo error analysis based on cloud height measurements from GOES East (75°W) and GOES West (135°W)

	(km)				
	$\overline{Z}$	σ_Z	σ_Z (LOCAL)	Z_{IR}	$\overline{Z} - Z_{IR}$
REPEATIBILITY (Baja area/1 km ≈ 1.5 pixels)					
Stratocumulus	1.2	0.19	0.01		
Cirrus	8.2	0.12	0.06		
Very Thin Cirrus	7.8	0.08			
STEREO/IR COMPARISON (Florida area/1 km ≈ 3 pixels)					
Stratocumulus	0.7			0.1	0.6
Middle Level Cumulus	4.9			4.9	0.0
	5.8			6.1	-0.3
Small Cumulonimbus Tower	9.1			10.6	-1.5
Cumulonimbus Cirrus Anvil	11.1			12.4	-1.3

Manual measurements made on the 1 km resolution displays used for this study and on features of about 1 pixel area can be made only to the nearest pixel. For the four areas used in this study the ratio of horizontal parallax to vertical resolution ranged from 1.5 to 5 pixels per km. Therefore measurements to 1 pixel would give precision ranging from 0.67 to 0.2 km. For large features where the cross correlation was used subpixel measurements with precision of 0.15 to 0.5 pixels would be required to give the approximately 0.1 km vertical resolution indicated by the data. Comparison of stereo cloud height with IR cloud height on high emissivity clouds show agreement to approximately 1 km as shown in Table 2. Since only a climatological atmospheric temperature profile was used for determining the infrared derived heights this gives only an order of magnitude verification.

RECOMMENDATIONS AND FUTURE WORK

Tests using 8 km resolution infrared images from GOES indicate that stereo techniques work equally well in the infrared, but since the resolution is low it is likely that little useful height information may be obtained over other methods. It is recommended that future geosynchronous satellites have an infrared resolution of 1 km so that this extremely powerful stereo technique is available 24 hrs/day.

It is also extremely important that 5 minute interval synchronized stereo image pairs be obtained in the future, since this is required for cloud growth and motion measurements in the complicated weather situations where stereo has its greatest impact. These intervals are needed because many clouds and cloud features have such short lifetimes that the continuity provided by 5 minute intervals is absolutely necessary to measure their motion or growth.

Techniques are proposed to display mesoscale and submesoscale numerical model results on AOIPS in a graphical four-dimensional manner. When combined with the four-dimensional representation of cloud structures from the GOES satellites this should provide a powerful diagnostic tool for understanding the model output and comparing it with observed weather.

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