Update on Accurate Cloud Motion and Heights Using Time Adjusted Stereo

G. Garrett Campbell [2], James F.W. Purdom [1,2] and Carol E. Vaughn [2]

[1]Regional and Mesoscale Meteorology Branch NOAA/NESDIS
[2]Cooperative Institute for Research in the Atmosphere
Colorado State University
Fort Collins, Colorado 80523

USA

Third International Wind Workshop, June 1996

ABSTRACT

At the last winds conference, Purdom and Dills (1993) presented a framework for deriving highly accurate cloud heights using a method they termed "time adjusted stereo." With time adjusted stereo, very accurate cloud heights are derived using cloud observations from different satellites, not taken at the same time, provided that the motion of the cloud in question is well known. Further research at CIRA has developed a method to derive both cloud height and velocity simultaneously. The method requires that the cloud be viewed from two or more different perspectives with at least two of the views being at different times. With the new method time coincidence is a disadvantage, and higher accuracy is obtained when all views are at different times. For height verification, improvements have been made in the cloud height by shadow method. Full automation has not been our goal: manual interaction is required to select clouds which are distinct and change shape slowly in time. Accuracies of better than 1 km height and 0.5 m/sec are typical of the results.

1. INTRODUCTION

As pointed out in the February 20-21, 1992 Workshop on Cloud Motion Winds, the need exists to improve the accuracy and number of cloud motion winds, globally in coverage and eventually mesoscale in resolution. This need continued to be stressed almost two years later at the Second International Wind Workshop that was held in Tokyo from 13--15 December, 1993. Today many of the major problems remain at operational wind production centers. Foremost is assigning an accurate height for the tracer in question. At the last winds conference, Purdom and Dills (1993) presented a framework for deriving highly accurate cloud heights using a method they termed "time adjusted stereo." Since that initial work, research at CIRA has developed an improved method which allows for the determination of both cloud height and velocity simultaneously. The new method is a least squares fit for the position of the cloud as a function of time from many observations. The method requires that the cloud be viewed from two or more different perspectives with at least two of the views being at different times. With the new method time coincidence proves to be a disadvantage, with higher accuracy obtained when all views are at different times. In addition, accuracy is improved as the number of observations of the cloud increases (either from multiple satellites, or more views from a single satellite at other times).

Using internal consistency and comparison between nearby clouds, accuracies can be estimated. With 1 km resolution visible imagery, cloud motions remain very accurate (to within 0.5 m/s) while cloud height accuracies of better than 1 km are being realized. For height verification, improvements have been made in the cloud height by shadow method to give an independent verification method.

This paper addresses improvements in cloud motion accuracy, both velocity and height which have been major culprits inhibiting progress in wind improvement. After the methodology is presented, the accuracy factors will be discussed and results will be shown.

2.0. REVIEW OF PAST CLOUD HEIGHT ASSIGNMENT

2.1 Infrared based techniques

From satellites, both high resolution visible and infrared imagery are used for the tracking of clouds, while infrared imagery is used for cloud height assignment. Two major problems encountered when using infrared imagery for cloud height assignment are: 1) cloud emissivity; and, 2) knowledge of the lapse rate to which the cloud's temperature will be matched. A technique known as CO_2 slicing that uses multi-spectral aspects of GOES-VAS was developed to aid in cloud height assignment. That technique eliminates some of the uncertainties due to cirrus emissivity, however, the problem of a representative lapse rate in the vicinity of the cloud remains. In addition, CO_2 slicing is not be possible with the new GOES series of spacecraft since one of the needed channels is not included on those spacecraft's imagers. Instead, a technique that is not as accurate as CO_2 slicing will be employed: water vapor slicing.

2.2 Geometric techniques

Since geometry does not rely on cloud properties, that methodology may be preferable for use in deriving cloud heights. Recognizing the problem encountered using infrared imagery for cloud height assignment stereographic techniques were developed to very accurately determine cloud heights using imagery from two geostationary satellites. Early stereo techniques provided accurate cloud height assignment, however, there was a requirement for the satellites to observe the cloud at the same time or height errors would be introduced due to the cloud's motion. For instance for a 10 m/sec speed, the cloud will move one GOES pixel in one minute leading to height errors of similar size. The requirement for time synchronous viewing was eliminated with "time adjusted stereo," however, that technique required the cloud velocity be very well known. In addition, time adjusted stereo was a two step process, and (as with normal stereo) accuracy was not improved with multiple observations.

A geometrically based technique that overcomes the requirement for two satellites the calculation of cloud height using shadows (Purdom and Dills,1993). That technique is limited to daytime and performs best early or late in the day when the satellite, cloud shadow perspective is optimized (long shadows).

2.3 Stereo errors from different platforms

An initial study of the accuracy of stereo height estimation from different view points was prepared. This considered different satellite view points and resolutions. Figure 1 shows the height errors from observation from the current GOES 8 and 9 satellite view points (75° West and 135° West). These were estimated by adding random errors to the a set of reference view angles. Then the root mean square deviation of the resulting height

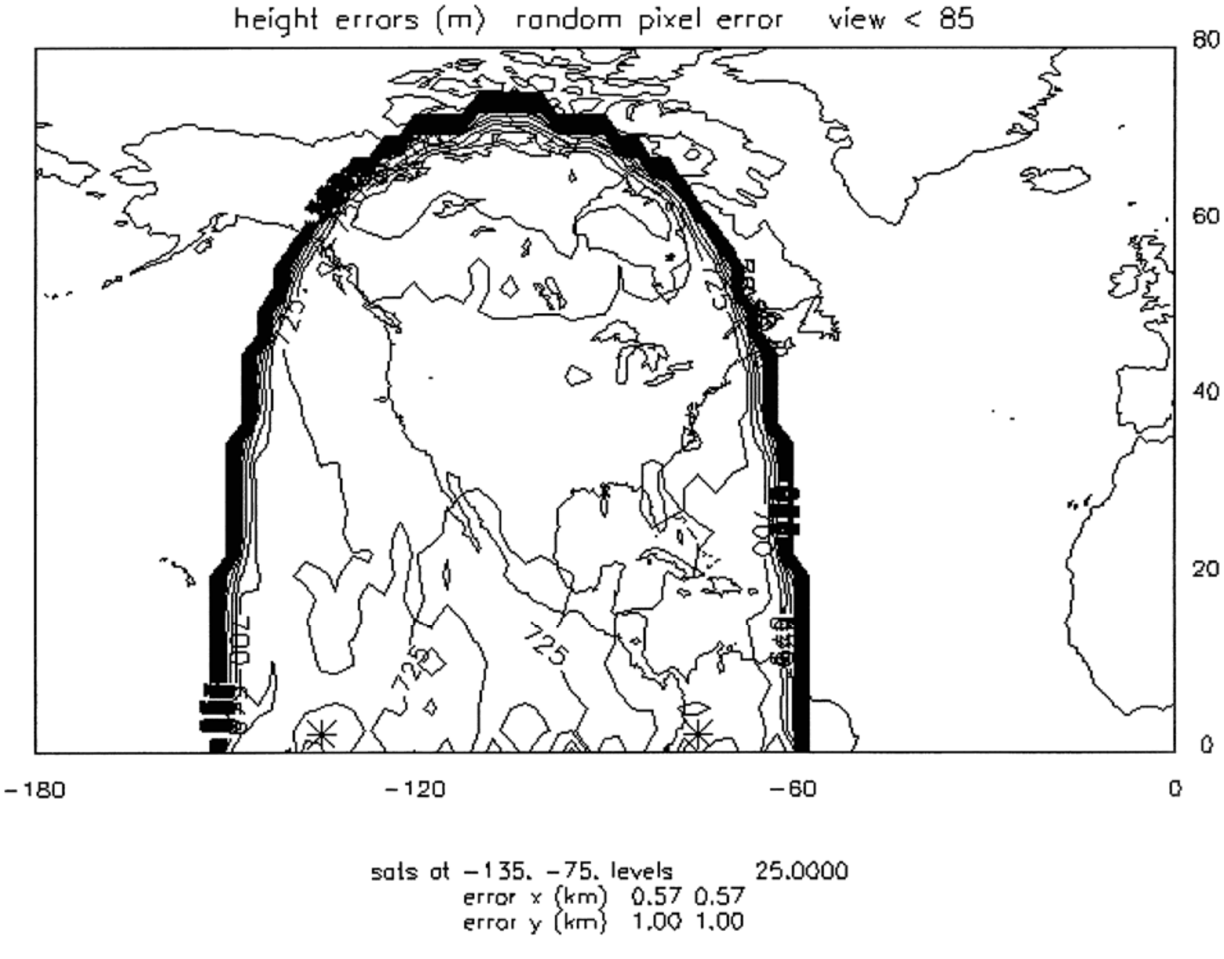


Figure 1 Pure stereo errors from GOES at 75° West and 135° West. The geometric height errors are very uniform across the area seen by both satellites.

analysis relative to the reference heights represents the uncertainty of the heights. Errors were added with Gausian random noise with variance of 1 pixel (± .57 km East West or 1 km North South for GOES).

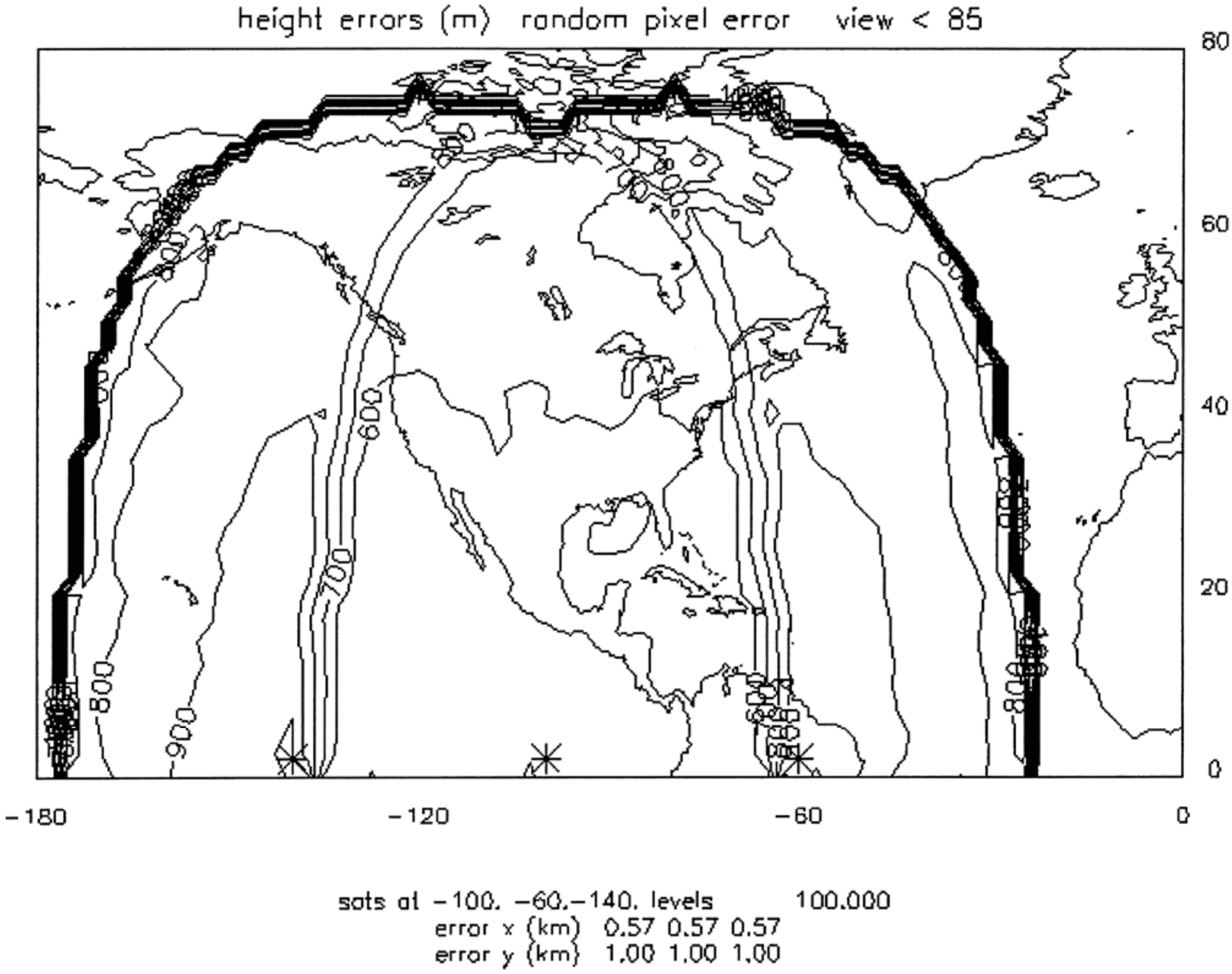


Figure 2. Pure stereo errors from GOES at 60º West and 140º West and 100º West. In the central region, errors are reduced because the redundant observations average out some of the noise. To the west and east, useful results are still obtained with just two measurements. This situation is proposed when the U.S. has 3 GOES operational

Figures 2 and 3 show that improvements occur with the introduction of a third satellite. Good results can be obtained with the mixture of Polar and Geosynchronous satellites. This last idea has been very difficult to implement until now because simpler algorithms require simultaneity. Finally some useful results can be obtained by mixing GOES and METEOSAT with its lower spatial resolution (figure 4). Small errors like these are possible with the mixed height/wind estimation discussed below.

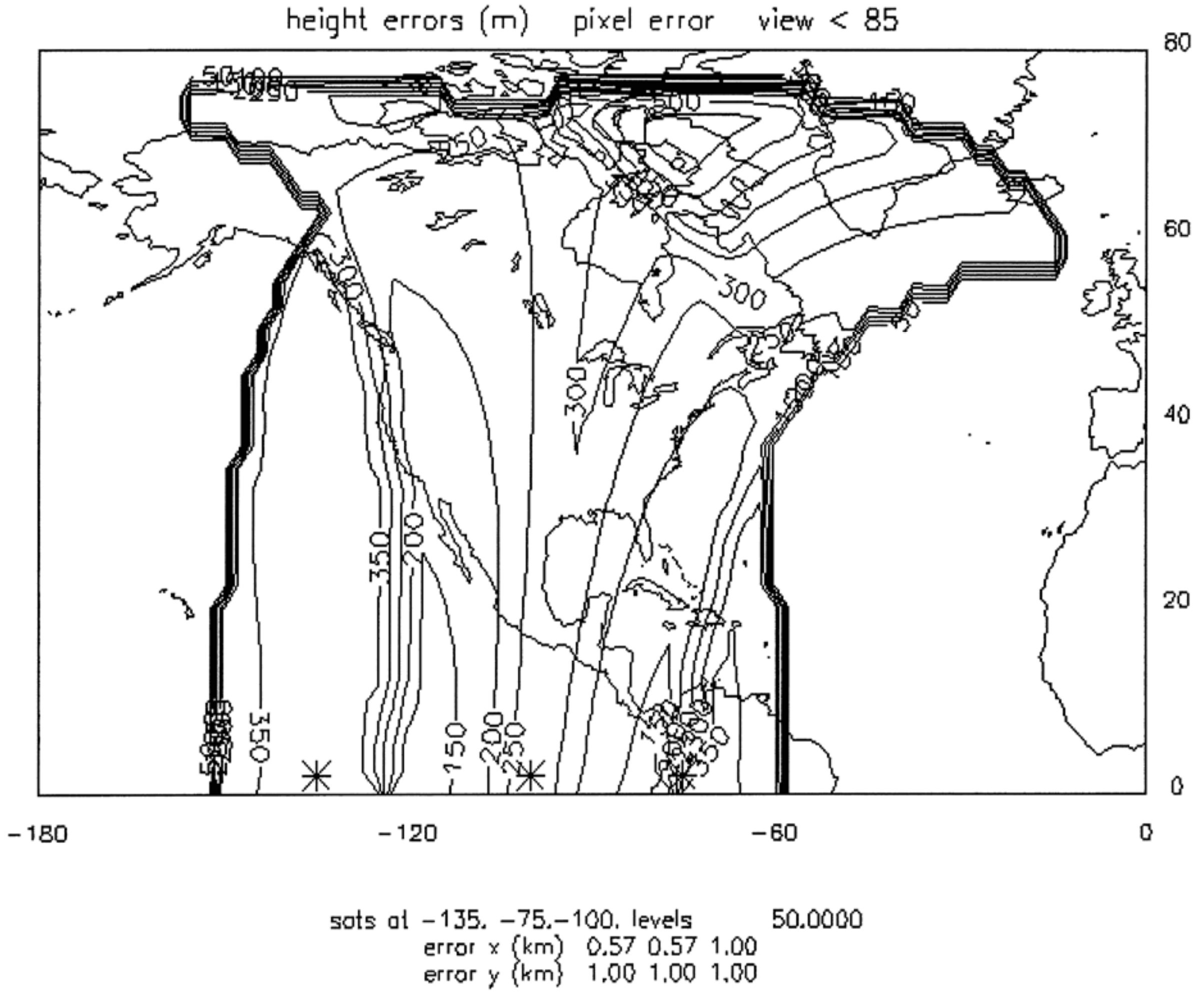


Figure 3 Pure stereo errors from GOES at 75° West and 135° West with one AVHRR 1 km resolution data (one orbit). The errors are reduced by the inclusion of more observations with three satellites in comparison to figure 1.

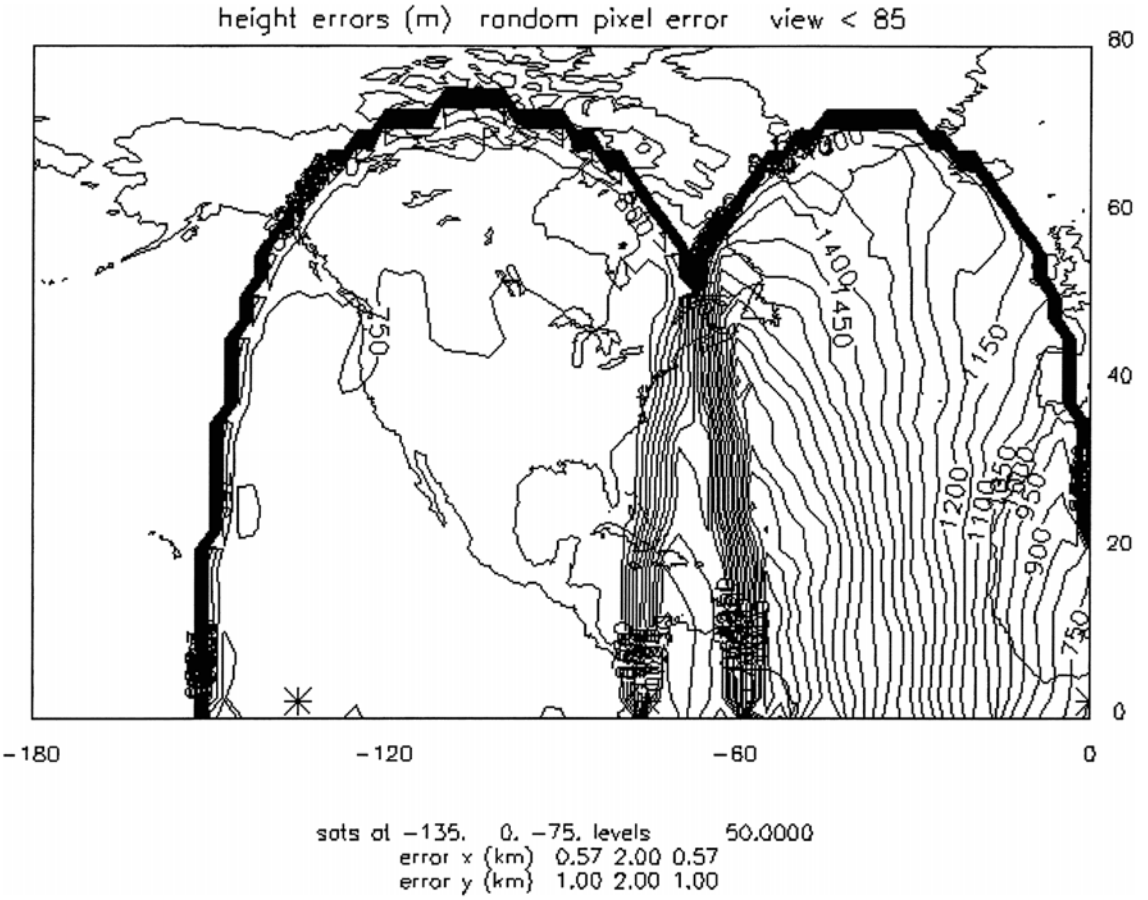


Figure 4 Mixture of GOES and METEOSAT whose resolution is 2 km at best. The use of 2 km resolution data does provide useful results across the Atlantic.

3.0 ASYNCHRONOUS STEREO HEIGHT AND MOTION ESTIMATION

The essence of the method is a least squares fit to all observations minimizing the difference between the apparent position from the observing satellites and an ideal vector which moves in time. By assuming constant velocity many measurements over time can be combined to decrease random noise due to quantized pixel locations.

Let **R**(t) represent the vector position of the cloud in time, t, then equation 1 represents the cloud position with a starting point **R**(0), a velocity **V**(0) and a acceleration, **S**:

1. $$\mathbf{R}(t) = \mathbf{R}(0) + \mathbf{V}(0)\, t + 1/2\, \mathbf{S}\, t^2$$

At first we considered the solution for constant velocity, but then we realized that a cloud would rise significantly over one hour for high winds (100 km/hour >.7 km rise/hour).

The acceleration term was added to tip the wind into approximately horizontal motion. **S** is approximated by centripetal acceleration (V^2/Rearth) pointing toward the center of the earth. This still allows the potential to measure vertical motion.

For the angles of observation from a satellite, $\mathbf{R}s$, the apparent location, $\mathbf{P}(t)$, of the cloud is derived for a point on the Earth's geoid from standard navigation software. The true location is located on the line of sight between the satellite and the apparent location, equation 2.

$$\mathbf{R}(t) - \mathbf{R}s = f\,(\mathbf{P}(t) - \mathbf{R}s) \qquad (2)$$

The factor f is unknown and is different for every observation event. Rearranging this and recognizing that no measurement is perfect, eq. 3 represents the error vector between the ideal and the real measurement:

$$\mathbf{E}(t) = \mathbf{R}(t) - \mathbf{R}s - f\,(\mathbf{P}(t) - \mathbf{R}s_i) \qquad (3)$$

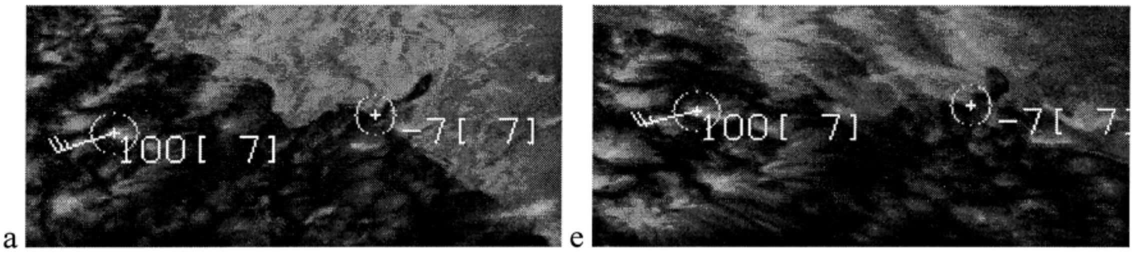
By summing over many observations, a minimum of the $\Sigma\,(\mathbf{E}(t) \bullet \mathbf{E}(t))$ provides an estimate of the initial position and initial velocity. The subscript has been added to the satellite view point because more than one viewpoint is needed to solve the equations. The smallest number of observations is two times from one view point and one observation from a different view point. As long as a single cloud facet can be identified, it is best not to have time coincidence between the two view points. This formalism is general enough to accommodate mixtures of Geosynchronous and Polar orbiter observations.

3.1 Implementation

Practically this has been implemented in the MCIDAS system using the operator to manually select a target cloud. Then a small region around the target is correlated to later images in a time loop to derive the sequence of $\mathbf{P}(t)$ observations relative to view point $\mathbf{R}s_1$. The operator also selects a point near the cloud later in the time loop as a first guess for the cloud motion. The other geosynchronous image is remapped to the projection of the first and the target patch is correlated to it to find the best match cloud for the other satellite view. A small region around this matched location is correlated in a second time loop from the other satellite providing more $\mathbf{P}(t)$ observations relative to the second satellite $\mathbf{R}s_2$. The manual operations might be eliminated in the future but it has been much more practical to deal with selected targets for algorithm development and testing.

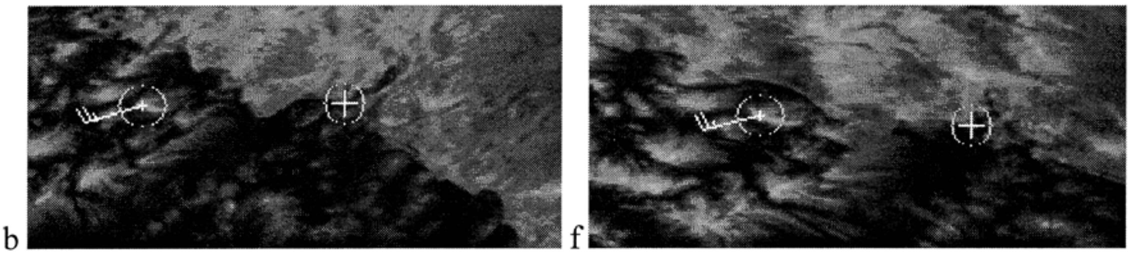
3.3 Example 1: Cloud off Baja California

For example we will discuss the detailed analysis procedure for a case from March 3, 1996 between 17 and 18 Z with GOES 8 at 75° West and GOES 9 at 135° West. There was cirrus moving rapidly over the Baja California peninsula. Figures 5 a, b and c show the view of these clouds from GOES 8.



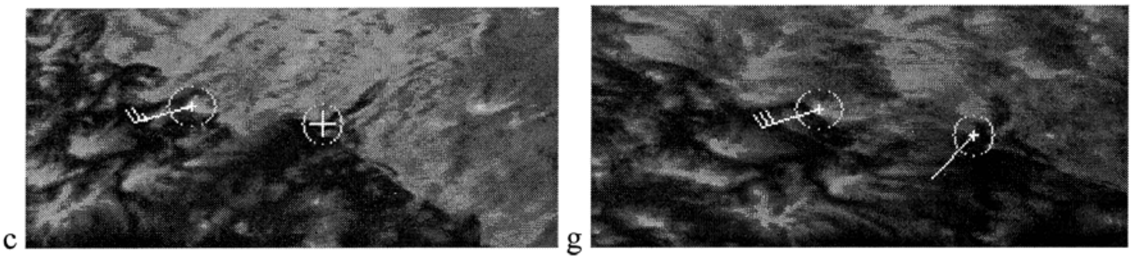
GOES 8 17:20 at the cloud

GOES 9 17:19 at the cloud



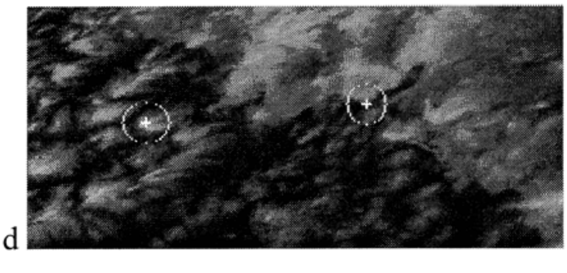
GOES 8 17:34 at the cloud

GOES 9 17:35 at the cloud



GOES 8 17:52 at the cloud

GOES 9 17:49 at the cloud



Remapped GOES 9 image into GOES 8 projection.

Figure 5: March 3, 1996 clouds near Baja California, Mexico. a,b,c,d from GOES 8 view point and e,f and g from GOES 8 view point.

The operator selected the cloud (or surface point) in the first image in the sequence from the GOES 8 view point (figure 5 a). Then a guess end point location was selected in last image in the loop (figure 5 c). Correlations were performed for times b and c to improved the cloud location matches. Next the program searched the remapped image to find a match to the patch from the first time. This is the essence of any stereo method, find the object from the two view points. Finally the object is tracked in the second time loop (figure e,f, and g). The + sign indicates the correlation center, the circles show the correlation region, the wind barb shows the estimated wind and the height is displayed in hectometers (l00 meters). The number in brackets shows the error estimate obtained by random perturbations added to the pixel locations. Notice that the observation times at the clouds can be different by several minutes because of the different operational scan modes used with GOES (Menzel and Purdom, 1994).

There are two wind and height estimates displayed, one for a cloud and the other for a surface point which should not move and should have 0.0 height (sea level):

Cloud:	u	23.9	±0.57 m/s	Surface	u	.38	±0.56 m/s
	v	11.1	±0.61 m/s		v	.08	±0.61 m/s
	h	9986.	±696. m		h	-711.	±702. m

To give a larger view of this example, Figure 6 shows many cloud height and winds estimated for a 500 km region.

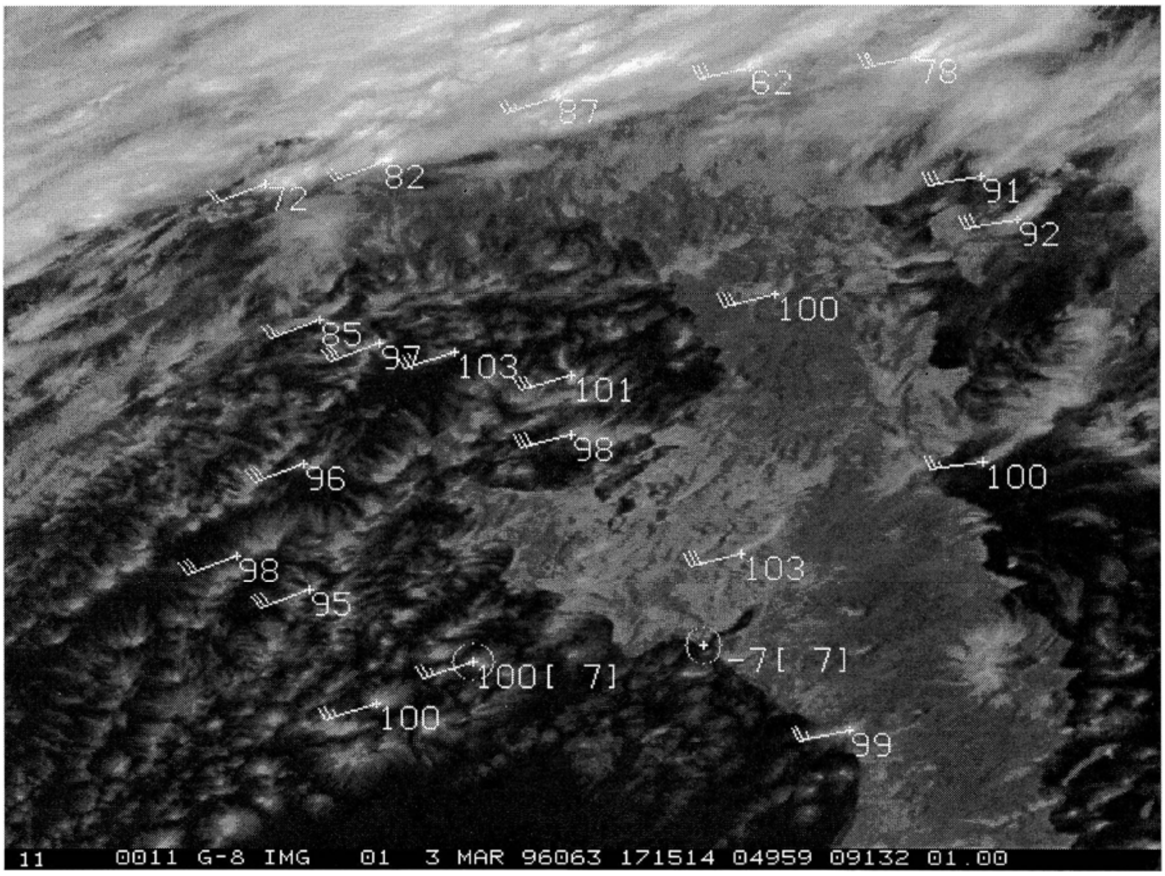


Figure 6, March 3, 1996 analysis, heights shown in hectometers.

3.4 Example 2: Cloud over Texas with 1 minute sampling.

As a second example, one minute interval data was collected over Texas on May 23, 1996 from GOES 8. The GOES 9 data transmitted data at a 7.5 minute interval. Figure 7 shows one image from that sequence with clouds at different heights. The numbers up and the right of the + are the cloud heights based upon the cloud's shadow. The lower numbers come from the composite analysis from 20 to 20:45 Z with the asynchronous stereo height and motion analysis. The two height analyses generally agree on the cloud heights to .5 km accuracy. The shadow height estimate is less accurate because it involves the analysis on only one image and typically the edges of shadows are not distinct.

In more detail, table 1 shows a list of the measurements which went into the asynchronous analysis. One can get an estimate of the cloud motion from each pair of images analyzed. The asynchronous analysis uses the times and apparent locations from all the times.

GOES 8 observations, apparent locations and image to image winds.

200458 *	31.245	98.077	0.	0.
200602	31.257	98.067	15.71	19.54
200706	31.268	98.056	15.72	19.55
200810	31.279	98.046	15.72	19.55
200913	31.290	98.035	15.96	19.86
201017	31.302	98.032	5.23	20.00
201121	31.313	98.028	5.23	20.00
201225	31.325	98.025	5.23	20.01
201909	31.369	97.968	13.27	12.26
202558	31.426	97.915	12.28	15.33
203236 *	31.471	97.866	11.77	12.54
203558	31.493	97.838	13.25	12.29
203701	31.504	97.827	15.93	19.93
203805	31.516	97.816	15.68	19.63
203909	31.527	97.813	5.22	20.07
204013	31.527	97.806	10.45	-.44
204117	31.527	97.799	10.45	-.44
204220	31.538	97.795	5.30	20.40
204324	31.549	97.785	15.67	19.64
205036 *	31.606	97.718	14.70	14.42
GOES 9 observations				
200421 *	31.242	97.893	0.	0.
201219	31.304	97.841	10.24	14.33
201948 *	31.366	97.772	14.71	15.52
202439	31.391	97.740	10.27	9.66
203419	31.466	97.663	12.57	14.37
204218 *	31.517	97.609	10.77	11.66
204947	31.567	97.545	13.43	12.57
hr/min/sec	latitude	- longitude	u (m/sec)	v (m/sec)

Final analysis	Conventional wind estimate (first to last GOES 8 image)
u 12.3 ± 0.2 m/sec	13. to 15. m/sec
v 13.7 ± 0.3 m/sec	14. to 16. m/sec
h 9838. ± 491. m	

9.3 km shadow height estimate for the 200458 image.

Table 1: Detailed data on one particular cloud.

There is considerable fluctuation in the image to image wind estimate. These use the conventional method of estimating the motion: just difference the apparent position and divide by the time interval. The fluctuations occur because the time interval is very short and the cloud does not move very far. For a 5 m/sec motions, the cloud will only move 300 meters in one minute or less than one GOES pixel. In the current version of the program, clouds centers are located at pixel centers. This introduces some round off error which might be reduced by an analysis of the shape of the correlation function used to measure the movement of the cloud. We are studying this problem now, especially in view of the applications with lower resolution data (IR).

The conventional motion method can also be applied to the beginning and ending cloud giving a variety of results depending upon which facet of the cloud is tracked. In fact this particular cloud under goes some change in shape so there is some ambiguity in cloud motion or development.

To look at the impact of numerous observations, just a few selected observations were extracted for the sequence of observations above. For just the 6 observations with a * in the table, the analysis gives:

u 12.4 ± 0.4 m/sec
v 14.4 ± 0.5 m/sec
h 10473. ± 664. m

The biggest impact of the extra observations is to reduce the uncertainty of the result.
The analysis with just 6 observations is useful.

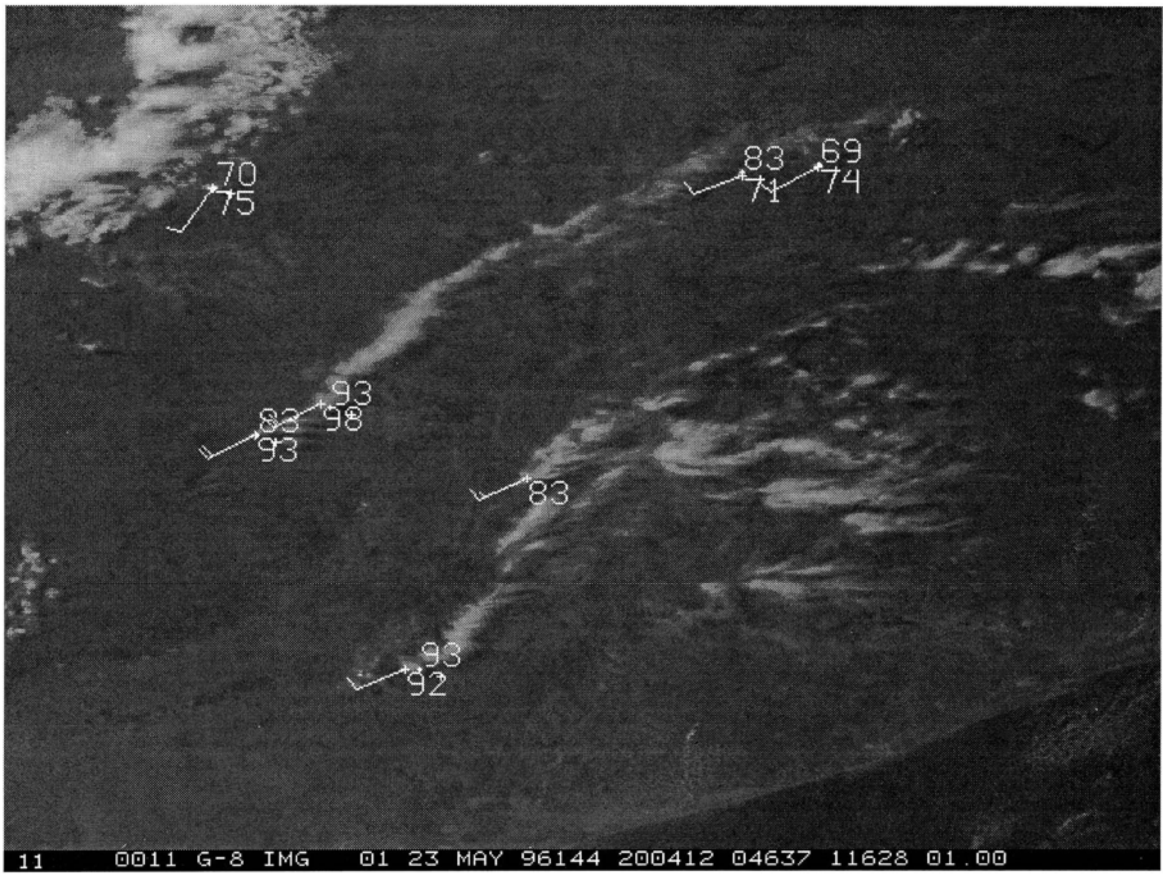


Figure 7: May 23, 1996 GOES 8 image with cloud height estimated by shadow (upper right) and asynchronous stereo (lower right). Heights in hectometers (100m).

4. VERIFICATION

4.1 Internal or regional consistency

Looking back at figure 6, one sees two types of clouds and two groups of cloud heights: around 10 km and around 8 km. These are not grouped randomly, but are associated with the particular cloud type. Trying to derive cloud height for the cirrus cloud in the southern part of this image from IR data would be difficult because none of these clouds would completely fill the 4 km IR field of view and also the emissivity of the clouds would be less than 1.0. Finally the fact that the land height was near zero height verifies the analysis.

4.2 Shadow heights

Dills and Purdom (1993) discussed a shadow height estimation method at the last winds conference. This method has been improved by selecting the shadow and allowing the computer to search for the cloud. Since the cloud edge is more distinct than the shadow, it is easier to find. This provides an independent geometrical cloud height to be used to verify the results shown above. Distinct shadows are more difficult to find than clouds so the multi-satellite cloud height methods is more widely applicable. Also the shadow method is less accurate at certain times of the day (near local noon). Still as shown in example 2 above shadows provide some useful results.

4.3 Ground Truth

A final opinion on the accuracy of our technique must await a comparison between a cloud and some ground based height measurement. There will be a special experiment over Oklahoma in June 1996, Cloud Layer Experiment (CLEX) sponsored by the Center for Geosciences at CSU. This will provide detailed cloud observations by airplanes and ground based measurements. The asynchronous stereo analysis will be carried out for comparison to these “ground truth” observations

5.0 FACTORS AFFECTING ACCURACY

The asynchronous algorithm now calculates height and motion together so improvements in one component generate improvements in the other component.

5.1 Remapping and Registration

Among the factors which affect the cloud height accuracy is precise remapping and registration between images. With the GOES 8 and 9 this is a smaller problem than older satellites, but can still be a significant. For special observation series like 5 minute or 1 minute sequences where clouds do not move very far between sequential images, and for slow moving clouds in 15 and 30 minute interval sequences, registration accuracy becomes more important. For special studies, adjustment of the navigation is fairly easy in the MCIDAS environment. For automated unsupervised estimates, poor navigation will cause larger problems.

For cloud motion measurements, the cloud can be identified by hand or by a correlation technique. Similarly for the height estimate to work correctly, some method is needed to match a cloud feature between the different view points. Our current algorithm does this by remapping an image from one view point into the other and then correlating the selected cloud feature. Then the cloud feature is tracked automatically in the image sequences from both satellites (one or more times). This transfer is critical and systematic navigation errors will amplify the errors.

Notice that the correlation between satellites is identical to the time coincident stereo method. But the information about the times of the two images is now included in the analysis. Inherent in all cloud tracking is the assumption that the cloud does not change it shape over the time interval of correlation. For clouds which change shape more rapidly than the observation interval, neither velocity or height would be accurate. This fact shows the advantage of rapid sequences of observations.

There is a related problem, cloud motion and height can not be determined for horizontally homogeneous clouds like some cirrus or stratocumulus clouds. Ultimately geometry methods can only analyze cloud edges in contrast to the temperature lapse rate technique which assumes horizontal homogeneity and fails when there are many cloud edges.

5.2 Number of observations

Improvements in cloud velocity and height accuracy occur with the new method with the inclusion of more observations of the same cloud facet. We have tested several cases with as many as 20 observations (within a one hour period) to derive an initial height and velocity. Cloud continuity in time can be improved by frequent viewing. If a cloud is changing shape rapidly in time, it can still be tracked by successive pair correlations. Suppose one has a sequence of 4 images 5 minutes apart. The simplest correlation method compares 1 to 2, 1 to 3 1 to 4, but a better method would be to correlate 1 to 2. Then compare the best match location in 2 to 3 and similarly the best location in 3 to 4. This shows the advantage of frequent viewing, 1 or 5 minute observations allow many more targets to be tracked than 15 minute or 30 minute interval observations. This will happen either because the target cloud changes shape or gets lost in a field of many similar clouds.

5.3 Is cloud motion wind?

The motion of the correlation center may or may not represent the wind, but it can still be used to measure height. For instance wave cloud height can be measured even though the cloud motion does not represent the wind. The problem of connecting cloud motion to wind has been discussed extensively at this workshop by others, and is beyond the scope of this study.

5.4 Resolution

Estimation of the height of clouds and their motions depends fundamentally on how well a cloud patch can be aligned with one later in time (or from the other view point). This is limited to zero order by the pixel resolution of the images. By matching extended patches it may be possible to estimate subpixel scale latitude longitude differences in the position of the patches by careful examination of the shape of the correlation function in space. This would especially be needed for the analysis of IR data which at best has resolution of 4 km from current geosynchronous platforms. Mixing different resolutions appears possible and the simulation study results shown in figure 4 show promise that 2 and 1 km resolution data can be used together.

6.0 GOES OPERATIONAL ISSUES.

Many new opportunities exist with the GOES 8 and 9 satellites because of the diverse observation schedule. Generally the western continental U.S. is sampled every 15 minutes from both view points. Thus given a typical 30 minute cloud life time, 6 or more observations can be incorporated into one height wind analysis. For servere weather events, observations from 1 to 5 minute interval is routinely available. Precise navigation is a continuing problem, but is being improved by NESDIS. The possibility of a third GOES satellite next year makes the opportunities for short interval multiple measurements even more wide spread. Routine observations from 3 geosynchronous satellites will improve the precision of the winds and heights.

7.0 CONCLUSIONS

Asynchronous stereo and motion analysis uses stereo graphic techniques, but does not require time synchronization between the different satellite images. Also the inclusion of many measurements improves the accuracy of the height and the motion. It is hoped that asynchronous stereo and motion analysis will replace temperature dependent methods with geometric calculations where the opportunity exists, and help refine temperature dependent methods in other situations. Cloud optical properties like emissivity could also be derived from the temperature lapse rate analysis given the geometric height of the cloud.

CIRA plans to undertake the following activities as resources permit:

1) Develop multiple-satellite (polar/geostationary and polar/polar) stereo algorithms;
2) Develop interactive computer techniques to relieve most of the (manual) burden in deriving accurate cloud drift winds and their heights without sacrificing accuracy.
3) Develop methods to utilize the lower resolution data like IR (4 km) or METEOSAT-GOES analyses perhaps with subpixel resolution correlation analysis.

8.0 ACKNOWLEDGMENTS

Portions of this research were supported by NOAA grant number NA37RJ0202-10. The Center for Geosciences at Colorado State University also provided support.

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