1.4 MONITORING OF AIR MOTION USING LIDAR AND VIDEO OBSERVATIONS

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1. INTRODUCTION

For the past five years we have conducted a series of experiments on the use of a ground-based, scanning holographic lidar system HARLIE (Holographic Airborne Rotating Lidar Instrument Experiment) for meteorological measurements, particularly for monitoring air motion in the troposphere. Currently this lidar operates by recording the Mie backscatter of laser light at 1047 nm, and thus measures horizontal winds *via* timed records of the motion of aerosols and cloud patterns across the line of sight. Altitude profiles of the backscatter, and therefore the wind velocity, are obtained by virtue of the range resolution inherent in the lidar method. Experiments with this method include organized campaigns in which HARLIE results are compared with other wind measurements.

In addition, we have developed passive imagery methods for observing cloud motion that include the automated analysis of cloud patterns for clouds that either have well defined boundaries or are diffuse with no clear boundary. We track tropospheric clouds primarily by their patterns that do not require a boundary analysis. Coupling these measurements with lidar, we obtain checks on the consistency of passive and active wind observations. Chemical release clouds, on the other hand, require a more detailed analysis of cloud shape and evolution for comparison with meteorological models. High speed, real time data on cloud boundaries and shape parameters is vital for delineation of hazardous clouds and for optimizing the use of additional sensors such as lidar.

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2. HOLOGRAPHIC LIDAR

Figure 1 shows the both the principle of a holographic lidar and its embodiment in the HARLIE instrument (Schwemmer, 1993a,b; Guerra *et al.*, 1999). A rotating holographic optical element (HOE) transmits the laser beam vertically at an angle of about 45° to its optic

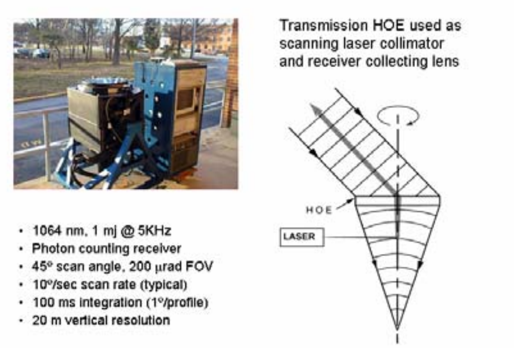

Figure 1. Holographic lidar principle (right) and HARLIE lidar apparatus (left)

axis. The laser light backscattered at 180° is focused to an on-axis detector whose output is recorded as a function of lidar range and rotation angle. The shorter of the two boxes in the photograph is the HARLIE transceiver, where the HOE is seen as the shiny 0.4 meter diameter disk on top. Rotation of the HOE provides a complete 360° scan on a 45° conical surface projecting vertically into the atmosphere. At every altitude, the HARLIE field of regard on the clouds traces out a cycloid in the direction opposite to that of the horizontal cloud motion.

Figure 2 shows a sample HARLIE data record of lidar backscatter intensity for a particular altitude, taken over about 150 rotations (25 minutes)**.** The phase of these sinusoidal patterns provides the direction of the horizontal wind at the given altitude, and the amplitude of the sinusoids is inversely proportional to the cloud velocity (Sanders, 2000; Wilkerson, Sanders and Andrus, 2003). We have used both manual and automated curve-fitting methods to obtain wind velocity from these “wave images”. Manual reduction is so far the best method when the patterns are fragmentary. Promising work continues on the use of the Hough transform (Cornelsen, 2004a) to recognize partial sinusoids against a grainy background.

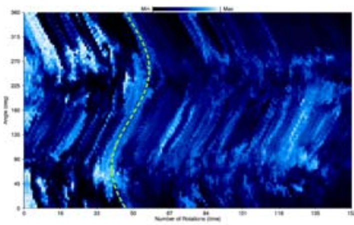

Figure 2. Wind velocity derived from rotational lidar scan

The wave image method has been tested over the past five years in six joint USU-NASA campaigns involving various comparisons of HARLIE data with other methods such as radiosondes, cloud videos, and Doppler lidar. Figure 3 lists these campaigns.

March 1999	Logan, UT	HOLO-1
June 1999	Manchester, NH	HOLO-2
Sept./Oct. 2000	DoE ARM/SGP Site, OK	WVIOP
November 2001	Wallops Island, VA	HARGLO-2
April 2002	Ft. Bliss, TX (with D.R.I.)	SERDP
May/June 2002	DoE ARM/Homestead, OK	IHOP-2002

Instruments:
HARLIE holographic scan lidar & SkyCam for cloud video imagery
AROL-2 profiler for HOLO-1
GLOW Doppler lidar for HARGLO-2 & IHOP

Figure 3. Joint USU / NASA lidar campaigns

A typical comparison obtained during the WVIOP (ARM) campaign in 2000 is shown in Figure 4 (Schwemmer et al., 2002). The HARLIE data are 10-minute averages of wind speed and direction over an altitude range of 1600 – 7000 meters, compared to two radiosonde profiles in a period of highly variable conditions.

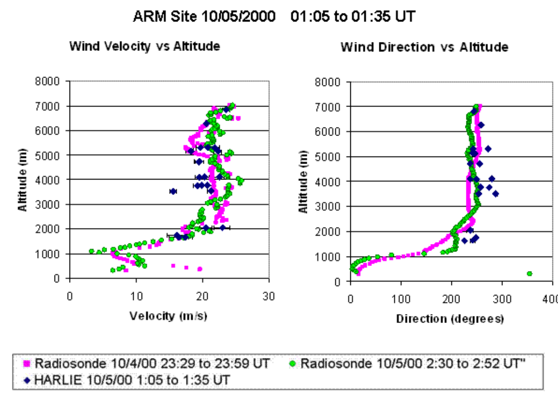

Figure 4. HARLIE and radiosonde profiles of wind speed and direction during WVIOP

Figure 5 shows results obtained during IHOP-2002 for all selected periods during this campaign when we could compare lidar and

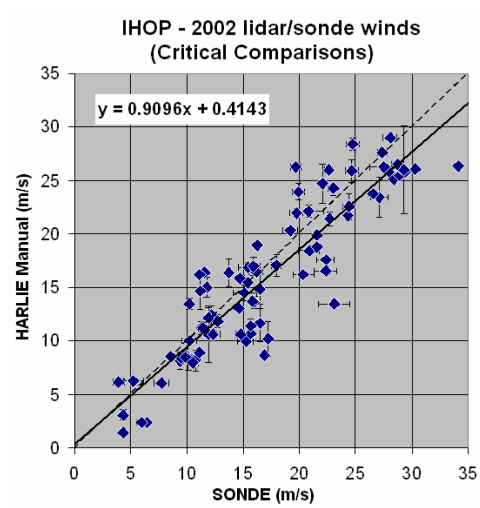

Figure 5. Comparison of wind speeds between HARLIE and radiosonde, May/June 2002

sonde data for the same altitude and time intervals within 200 meters and 15 minutes respectively. Our experience with HARLIE shows that one can obtain altitude profiles of aerosols and clouds for long continuous periods on a 24/7 basis, and that profiles of wind speed and direction are readily derivable from these data.

3. CLOUD IMAGERY FOR SLOWLY CHANGING CLOUDS

Long records of overhead cloud motion are also obtainable from time-lapse images, and can be used for wind measurements if the altitude of the cloud patterns can be established (Pal, Pribluda and Carswell, 1994). We employ this method, making use of either a lidar that stares vertically (the AROL lidar mentioned in Figure 3) or just the *altitude* part of the HARLIE data record. Cloud images are recorded with a digital camera or a Panasonic SkyCam wide angle video camera. Automation of the image interpretation is essential for practical use. Our first developed method, MCP (Moving Cloud Patterns), is based on a progressive frame-by-frame comparison of selected parts of the cloud pattern, using "block matching" and other image processing techniques (Anderson, 2002; Wilkerson *et al*., 2002; Cornelsen, 2004b) together with automatic inclusion of the camera's angle-image relationship and lens distortion parameters Another method, to be described below, differs in that it uses the *boundaries* of clouds rather their interior patterns and thereby addresses average or overall cloud parameters such as shape and extent.

Figure 6 shows a sample of SkyCam / MCP wind data (open squares) overlaid on profiles of wind speed and direction obtained by means of radiosonde (yellow) and HARLIE (red, green) for May 28, 2002. Because of the automation of the MCP system, it is able to passively detect the differing angular velocities of the two cloud layers occurring at 1000 and 5000 meters. Currently, MCP runs as a real time system in IDL to maintain a running statistical record of the angular velocity of overhead clouds at rates of order 10 frames per second. Coupled to a simple ranging system such as a Vaisala ceilometer, it can provide continuous, real time summaries of wind speed and direction at altitudes where clouds can be detected.

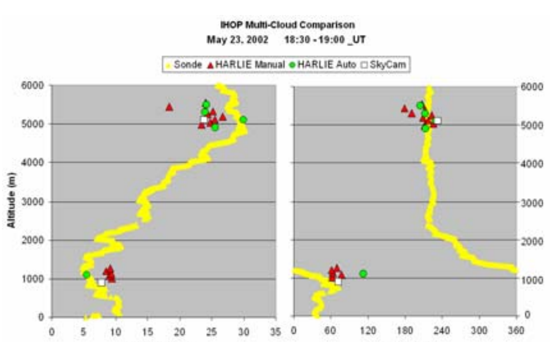

Figure 6. MCP detection of two cloud decks, and consistency with HARLIE and radiosonde winds

4. IMAGE ANALYSIS AND TRACKING OF RAPIDLY CHANGING CLOUDS

The analysis of rapidly changing clouds is important because of military and civilian applications to atmospheric releases of hazardous particles and gases. In addition to 2D and 3D imagery *per se*, time-resolved passive cloud images can provide guidance to other threat sensors such as lidar, as well as empirical data to assist in the meteorological modeling of chemical releases. The 2D work reported here will be carried forward to 3D applications.

In view of the difficulty of completely describing complex cloud shapes, we have developed a parametrization of cloud shape that provides a set of useful observables sufficient for most purposes. Frame by frame, this system (1) warns of the appearance of a new cloud in a camera's image field, (2) distinguishes the cloud and its boundary from its surroundings, (3) measures the area, (4) locates the cloud centroid, (5) fits an ellipse to the boundary, (6) lists all the elliptical parameters, and (7) calculates the "complexity index" of the cloud boundary. Initially this capability was developed in IDL (Anderson, 2003). Currently the new system, SIP (Surveillance Image Processing) runs on C++ (Call, 2004) and computes all parameters at rates exceeding 50 frames per second, so that the motions of the cloud centroid and boundary are tracked and predicted in real time. Many clouds can be tracked at once, including the amalgamation of cloud masses and the emergence of new clouds from old.

Figure 7 illustrates the image processing steps required to identify a cloud and segment it from its surroundings. This is a daylight visible image of an explosively driven cloud of plaster of Paris.

We have also demonstrated the extension of our analysis method to chemical clouds visualized by infrared absorption. Figure 8 shows the expansion of propane from a ruptured balloon, imaged with an SBF 125 focal plane camera filtered so that the background IR emission is absorbed by the "C-H stretch" band at 3.4 microns. The SIP processing creates the cloud boundary (blue), the ellipse fit (red), a box to define a scan zone for other sensors (blue), and

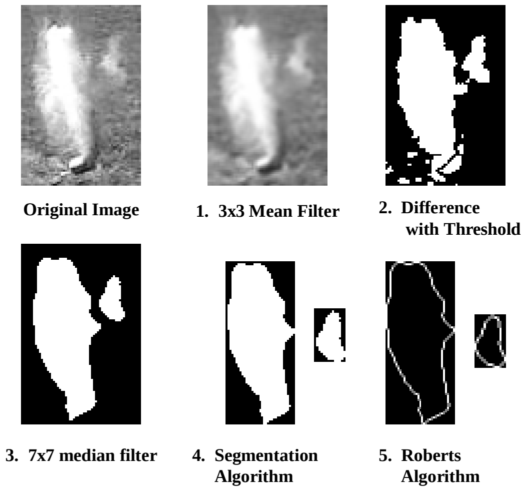

Figure 7. Cloud segmentation steps

a first-cloud warning frame (red). In addition, a frame-by-frame summary of all of the shape parameters is listed next to the images.

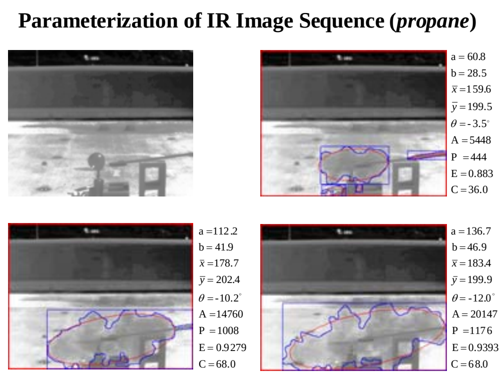

Figure 8. IR images of propane expansion, with complete record of shape parameters

Figure 9 summarizes the evolution of the cloud area, perimeter and "complexity", a descriptive dimensionless parameter [(perimeter)^2/area]. Complexity distinguishes simple convex *vs.* complicated cloud shapes and may be used to categorize types of explosions in real time. Another capability being explored in this program is the real time prediction of the arrival of a toxic cloud boundary at any point in the image field. SIP has also been applied for rapid analysis of the images of large scale chemical releases at Dugway Proving Ground. Further details of this work have recently been published (Anderson *et al.*, 2004).

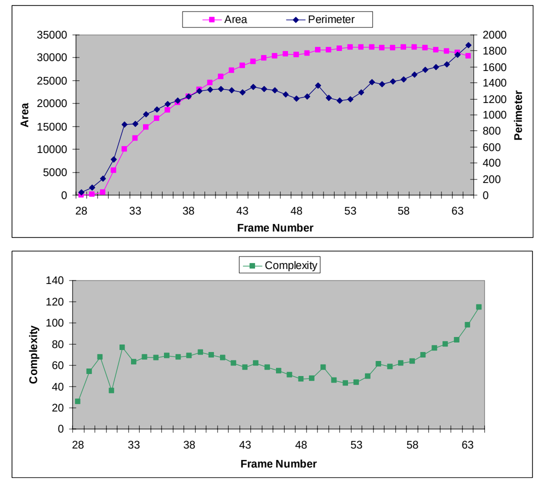

Figure 9. Time evolution of shape parameters for propane cloud shown in Figure 8

5. SUMMARY

We have shown that the present HARLIE lidar provides a good 24/7 wind monitoring capability for the troposphere when aerosols and clouds are present. The holographic scan system provides an attractive alternative to complex, multi-mirror lidar designs. Its reliability indicates that, as a sky scanner for ground-based and airborne applications, it should operate equally well as a "front end" for direct detection Doppler wind lidars.

Our meteorological application of passive tracking of diffuse clouds provides real time, automated data on the wind-borne motion of overhead clouds and diffuse clouds of aerosols.

Another important application of high speed analysis of passive images arises when lidars will be used to probe hazardous clouds. Delineation of the cloud boundary and other shape parameters, in real time at frame rates > 50 per second, provides (1) guidance to the lidar scanning strategy for optimal coverage of the danger zone and (2) the capability to predict the arrival of hazards at specific targets.

6. ACKNOWLEDGEMENTS

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6. REFERENCES

Anderson, M.E, 2002: MCP (Moving Cloud Patterns): A program for detecting and measuring the speed and direction of cloud motion and wind, SDL/02-270, 22pp.

Anderson, M.E., 2003: Analysis of dynamic particle and gas cloud imagery at visible and infrared wavelengths, SDL/03-244, 14 pp.

Anderson, M.E., J.C. Larsen, S.S. Cornelsen, S.T. Call, S.T. Stokes, C.L. Earl, T. M Hayes, T. D. Wilkerson, 2004: Dynamics of gas and particulate clouds: parametric analysis of cloud motion, *Proc. SPIE* **5547**, 79 – 90.

Call, S., 2004: SIP (Surveillance Image Processing): A software application using statistics to dynamically track the motion of clouds and other objects, SDL/04-184, 13 pp.

Cornelsen, S., 2004a: HAN (HARLIE-AutoNew): A program for the automatic analysis of data from the HARLIE instrument, SDL/04-030, 21 pp.

Cornelsen, S., 2004b: MCP (Moving Cloud Patterns) analysis: A program for the filtering and analysis of MCP output, SDL/03-234, 8 pp.

Guerra, D.V., A.D. Wooten, S.S. Chaudhuri, G.K. Schwemmer, T.D. Wilkerson, 1999: Prototype holographic atmospheric scanner for environmental remote sensing, *J. Geophys. Res.,* **104,** 22,287 – 22,292.

Pal, S.R., I. Pribluda, A.I. Carswell, 1994: Lidar measurements of cloud-tracked winds, *J.Appl. Meteor.* **35**, 35–44.

Sanders, J.A., 2000: Lidar tropospheric wind vector measurements, *MS thesis, Department of Physics, Utah State University.*

Schwemmer, G.K., 1993a: Conically scanned holographic lidar telescope, U.S. Patent No. 5,255,065.

Schwemmer, G.K., 1993b: Conically scanned holographic LIDAR telescope, *NASA Tech. Briefs* **17**, 61–62.

Schwemmer, G.K., D.O. Miller, T.D. Wilkerson, I.Q. Andrus, 2002: Time resolved 3D mapping of atmospheric aerosols and clouds during the recent ARM water vapor intensive operating period, *Proc SPIE* **4484**, 58 – 63.

Wilkerson, T.D, J.A. Sanders, I.Q. Andrus, 2003: Kinematic analysis of conically scanned environmental properties, U.S. Patent No. 6,535,158.

Wilkerson, T.D., C.Q. Egbert, I.Q. Andrus, M.E. Anderson, 2002: Advances in wind profiling by means of lidar and video imagery of clouds and aerosols, *Proc. SPIE* **4723**, 130 – 146.