# The HOLO Series: Critical Ground-Based Demonstrations of Holographic Scanning Lidars

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## ABSTRACT

Results of two lidar measurement campaigns are presented, HOLO-1 (Utah, March 1999) and HOLO-2 (New Hampshire, June 1999). These tests demonstrate the ability of lidars utilizing holographic optical elements (HOEs) to determine tropospheric wind velocity and direction at cloud altitude. Several instruments were employed. HOLO-1 used the 1.064 mm transmission-HOE lidar (HARLIE, Goddard Space Flight Center), a zenith-staring 532 nm lidar (AROL-2, Utah State University), and a wide-field video camera (SkyCam) for imagery of clouds overhead. HOLO-2 included these instruments plus the 532 nm reflection-HOE lidar (PHASERS, St. Anselm College). HARLIE and PHASERS scan the sky at constant cone angles of 45° and 42° from normal, respectively. The progress of clouds and entire cloud fields across the sky is tracked by the repetitive conical scans of the HOE lidars. AROL-2 provides the altitude information enabling the SkyCam cloud images to be analyzed for independent data on cloud motion. Data from the HOE lidars are reduced by means of correlations, visualization by animation techniques, and kinematic diagrams of cloud feature motion. Excellent agreement is observed between the HOE lidar results and those obtained with video imagery and lidar ranging.

**KEYWORDS:** Scanning lidar, Wind velocity, HARLIE, AROL-2, HOLO, Cloud tracking, Holographic lidar, Velocity comparisons, Wind profiles

## 1. INTRODUCTION

Two one-week lidar research campaigns were conducted in 1999 to evaluate three new lidar instruments. The goal of the measurements was to assess the instruments' performance, develop data reduction routines, and explore scanning lidar applications. This paper emphasizes the measurement of the wind speed vector from the collected data.

The HOLO-1 campaign was conducted March 7-13, 1999 at Utah State University's Space Dynamics Lab (SDL), in Logan, Utah. Three instruments were involved: the Holographic Airborne Rotating Lidar Instrument (HARLIE), Army Research Lidar (AROL-2), and a wide-angle monochrome CCD camera (SkyCam). The actual arrangement on the roof of SDL for HOLO-1 is shown in FIG. 1. The two lidars and the camera were set up as indicated in FIG. 2 for the HOLO series.


**Figure 1**: Equipment arrangement at USU's Space Dynamics Laboratory during HOLO-1.

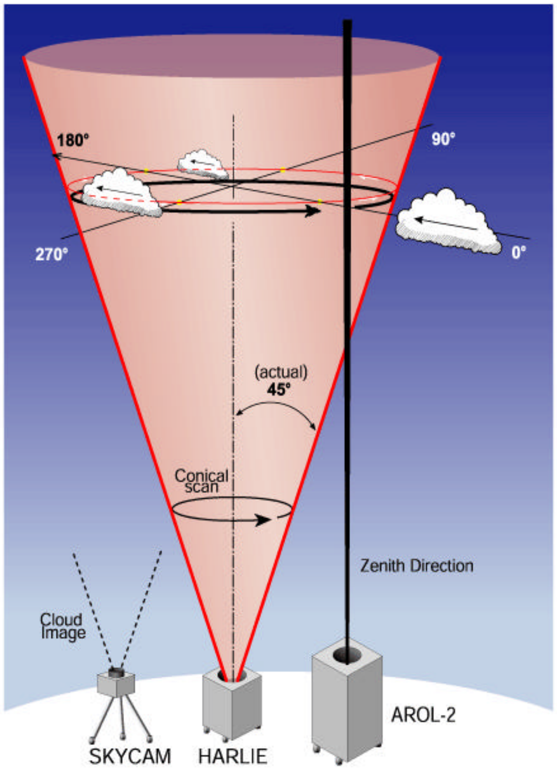


**Figure 2**: Concept of HOLO series equipment layout.

HOLO-2 was conducted June 5-12, 1999 at St. Anselm College near Manchester, New Hampshire. A third lidar instrument also took part in HOLO-2, namely the Prototype Holographic Atmospheric Scanner for Environmental Remote Sensing (PHASERS) described by Guerra (1998) and Guerra *et al.* (1999). AROL-2, HARLIE, and the SkyCam were situated at the college's observatory, about 1/4 mile from the main campus, while PHASERS is now permanently installed on the roof of the Science Center on the St. Anselm campus. PHASERS was the original holographic lidar; measurements made with this lidar during the HOLO campaigns will be described in subsequent papers.

Over the course of these campaigns, all three instruments operated about 50-70% of the time, with most of the "down time" attributed to precipitation, operator errors, and periods for relaxation and rest. Instrument malfunctions were rare. The mobile systems AROL-2 and HARLIE proved to be rugged and reliable enough to be used in field missions with a high probability of meeting investigators' objectives and commitments.

Numerous technology and science objectives for the HOLO tests have been summarized by Schwemmer *et al.* (2000). The primary objectives were technology oriented, to test the hardware and its measurement characteristics in the field, and to develop new data analysis algorithms in preparation for future scientific field investigations. Moreover, we wanted to develop a new application for conically scanned aerosol and cloud lidar systems, namely the profiling of atmospheric winds *via* cross-beam tracking of aerosol and cloud structures.

## 2. BACKGROUND

### 2.1 Lidar wind velocity measurements

Lidar wind vector measurements are based on the laser backscatter from clouds and aerosols. Several methods to measure the wind vector in this manner have been devised. Eloranta *et al.* (1975) used an elevation-scanning lidar pointed upwind to capture the shape and motions of aerosols and clouds as they pass through the lidar. Sasano *et al.* (1982) developed a scanning lidar method that determines the horizontal wind vector by matching aerosol distribution patterns. Sroga and Eloranta (1980) tracked aerosol particle distributions by scanning a lidar between three closely spaced small elevation azimuth angles. Pal *et al.* (1994) measured the wind speed from displacements in cloud features obtained from time-lapse video and simultaneous lidar altitude measurements. This method is also used in the present work by combining SkyCam and AROL-2 data.

**Table 1**. HARLIE and AROL-2 lidar properties.

| | AROL-2 | HARLIE |
|---|---|---|
| Wavelength (nm) | 532 | 1064 |
| Energy/Pulse (mJ) | 100 | 2 |
| Pulse Rate (Hz) | 20 | 5000 |
| Telescope Diameter (cm) | 20 | 40 |
| Range Resolution (m) | 15 | 30 |
| Data Channels | 4 | 1 |
| FOV Direction | Vertical (fixed) | 45° elevation (rotating) |

### 2.2 Instruments

Our wind speed measurements were derived from data taken with the AROL-2, HARLIE, and SkyCam instruments. Table 1 lists the main properties of the two lidar systems.


**Figure 3**: Tom Wilkerson with the AROL-2 lidar during HOLO-2.

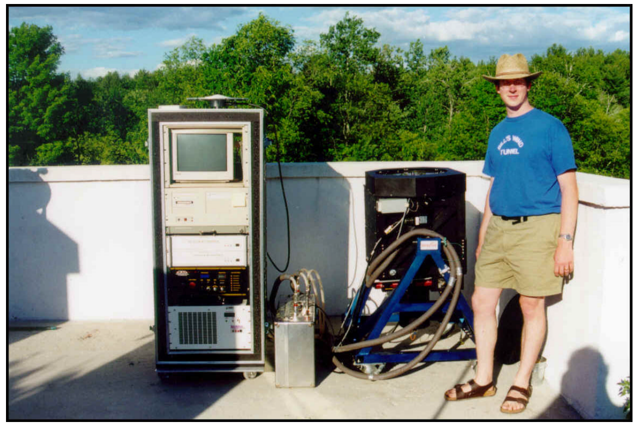

**Figure 4**: David Miller with the HARLIE scanning lidar system during HOLO-2.

Orca Photonic Systems, Inc. built AROL-2 for Utah State University (see FIG. 3) under a two-phase grant from the United States Army Research Office. Their work is described in a separate paper at this meeting by Moody, *et al.* (2000).

AROL-2 is a portable, ground based, zenith-viewing-only lidar, emitting an average power of 2 Watts at 532 nm. It has analog and photon counting photomultipliers for each of its parallel and cross-polarized receiver channels. AROL-2 was the only hermetically enclosed instrument used in the HOLO campaigns, but it was usually moved indoors during periods of precipitation along with the other instruments.

HARLIE, a holographic scanning lidar, was built for NASA's Goddard Space Flight Center and has been described by Schwemmer (1998) and Schwemmer *et al.* (2000). HARLIE scanned the sky overhead at a cone angle of 45° from the zenith. Its rotation axis can be tilted at any angle to the vertical, *including nadir viewing from aircraft*, its original design and application. The scanner and supporting electronics for HARLIE are shown in Figure 4.

## 3. METHODS

### 3.1 SkyCam /AROL-2 method

Two methods were used to calculate the wind speed from the data collected during the two campaigns. The SkyCam and the AROL-2 lidar were used together to establish the absolute size, direction of motion, and velocity of clouds during daytime observations (Pal *et al*. 1994). FIG. 5 is a representative gray-scale display of AROL-2 cloud backscatter intensity, with altitude plotted vertically and time plotted to the right, for a three and a half hour period during HOLO-2 on June 7, 1999. Such cloud altitude data were combined with overhead cloud video images from SkyCam to produce wind speed vector measurements. Only daytime observations are feasible with this method because the SkyCam is not sufficiently sensitive for nighttime cloud photography. FIG. 6 shows a representative pair of SkyCam video frames used to obtain the *angular* velocity of clouds above the AROL-2 lidar.

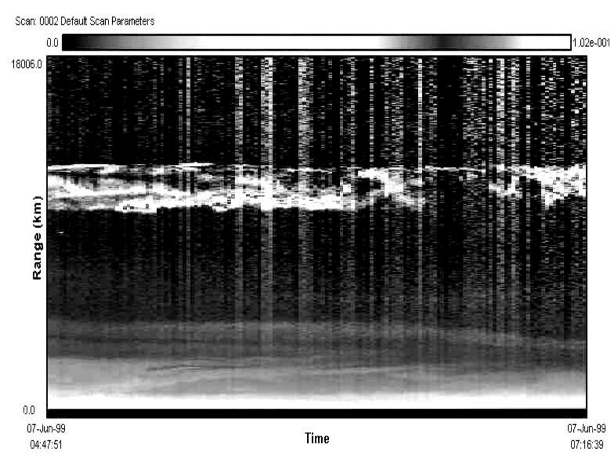


**Figure 5**: AROL-2 data visualization plotting backscatter intensity as a function of range and time. Data taken from 04:47:51 A.M. to 07:16:39 A.M. on June 7, 1999, during the HOLO-2 campaign.

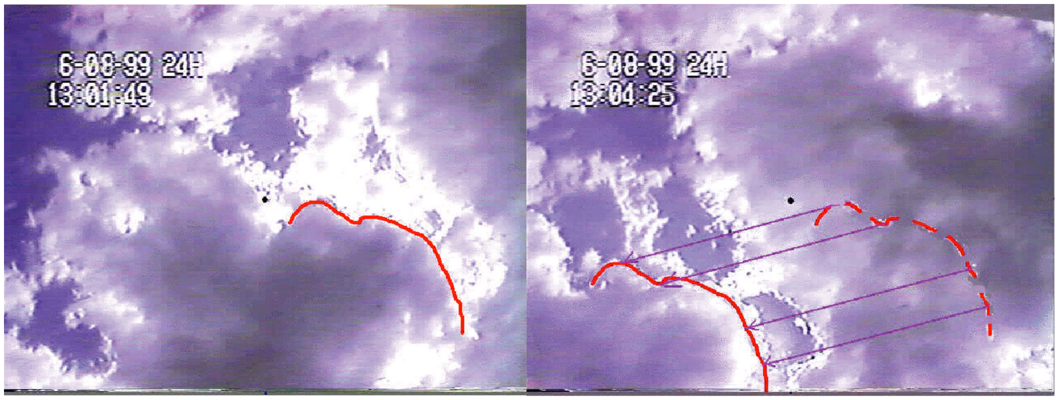


**Figure 6**: Tracking cloud features with SkyCam

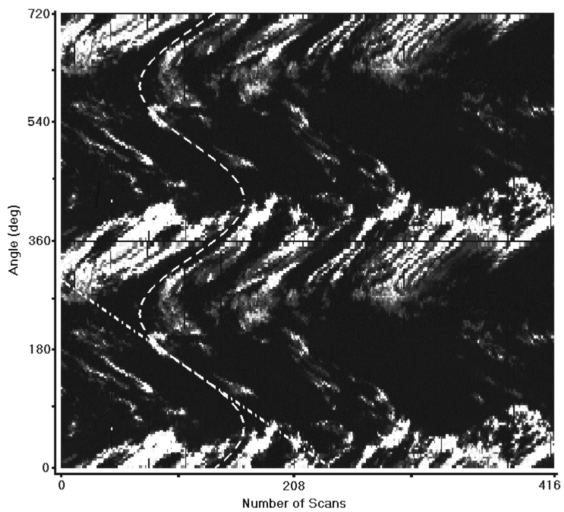


**Figure 7**: HARLIE wave image at 2480-2650m altitude, taken during HOLO-2 on June 5, 13:42 to 14:51.

### 3.2 HARLIE method

The second method derives the wind speed vector from the HARLIE lidar data. FIG. 7 is a gray scale representation of the cloud backscatter data at an altitude of approximately 2550 m collected by HARLIE during a 416-revolution scanning period lasting about 69 minutes on June 5, 1999, during HOLO-2. Time is in terms of the number of scan revolutions to the right, and the azimuthal angle (or scan angle) of observation is plotted vertically. In fact the full azimuthal extent is shown twice here for redundancy, so that the progress of cloud features across HARLIE's "cone of regard" can be visualized without having to match features occurring at 0° with those occurring at 360°.

The use of such kinematic diagrams or "wave-images" facilitates the identification of the wind direction and the calculation of the wind speed. This calculation is aided by analyzing the simulated cloud field shown in FIG. 8, and its corresponding wave-image in FIG. 9.

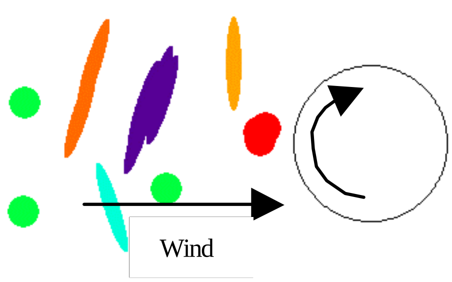


**Figure 8**: A simulated cloud-field approaching a circle that represents the intersection of a HARLIE scan cone with the cloud altitude. The wind vector and scanner rotation direction are shown.

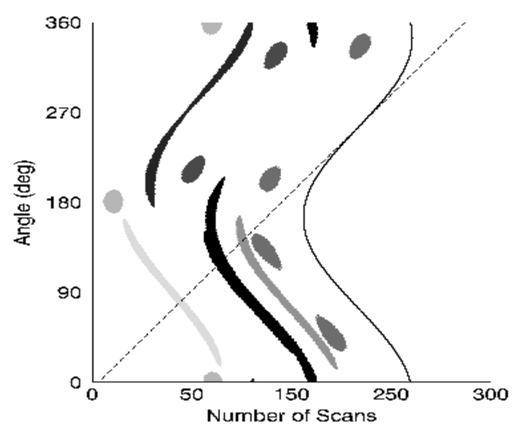


**Figure 9**: The simulated wave-image corresponding to the cloud-field in FIG. 8. Note the wave-like behavior of the cloud features. A comparison arccosine function is plotted at the right. The dashed line, at the inflection point of the arccosine, provides the wind speed.

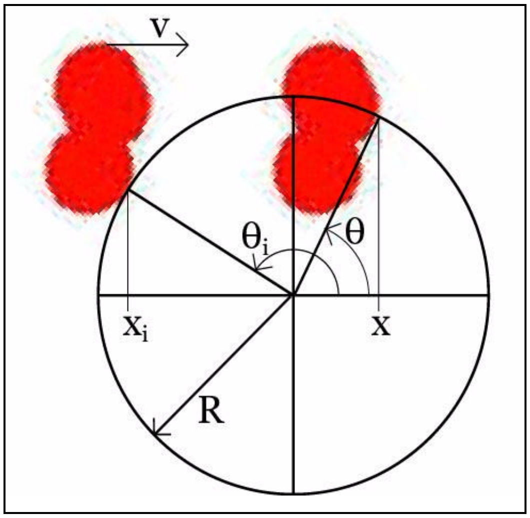


**Figure 10**: Coordinate system for the derivation of wind speed from traces in the "wave image" of a cloud.

Referring to FIG. 10, clouds passing through the circle of a conical scanner with a speed ***v*** produce an arccosine curve in a wave image given by

$$q(n,v) = \arccos[(\frac{v \cdot n}{f \cdot R}) + \cos(q_i)] \qquad (1)$$

where $n$ is the number of revolutions, $f$ is the frequency of revolution, $R$ is the scanner radius, and $q_i$ is the initial scan angle. It is assumed that the cloud shapes are convex and not large compared to the size of the lidar's "circle of regard". The arccosine function is plotted alongside the simulated wave-image in FIG. 9.

The wind speed of a cloud as it passes through the HARLIE scanning cone is derived from the slope of (1) at the inflection point, namely

$$\frac{dq}{dn} = \frac{-v}{f \cdot R} \qquad (2)$$

The slope of the simulated wave-image is also plotted as a dashed line in FIG. 9.

Wind direction is indicated by the location of the apex or peak of the arccosine wave on the vertical axis.

## 4. RESULTS

Sample results of measuring the wind speed with both the SkyCam /AROL-2 and the HARLIE-based methods are shown in FIGS. 11 - 16 for data taken during HOLO-1 and HOLO-2.

The progression from FIG. 11 to FIG. 14 is in cloud altitude, namely 2.4, 3.8, 5.0 and 10.0 kilometers for June 8, March 10, June 6, and June 5 respectively. Within each graph the time period is shown and ranges from ½ to 2 hours. The time-error bars indicate the averaging times used in each measurement. Wind speed error bars for HARLIE are obtained from the average deviation of results obtained in 5-10 observations per event. For AROL/SkyCam measurements there are two sources of error. The error of angular displacement within the video image was at most 2 degrees, while the altitude error

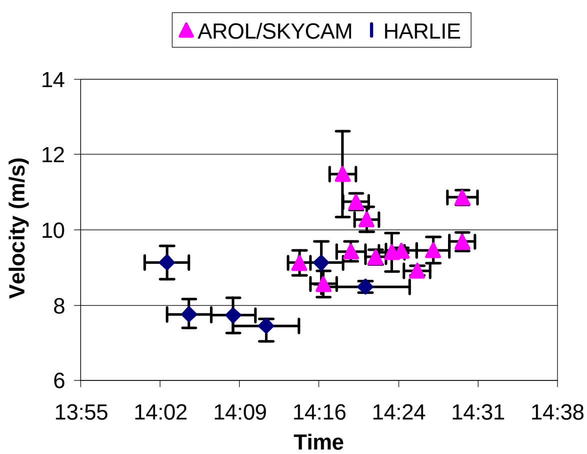


**Figure 11**: HARLIE and AROL/SkyCam wind measurement comparison chart for 8 June, 1999, 13:55 - 14:30 hrs, ~2400 m altitude.

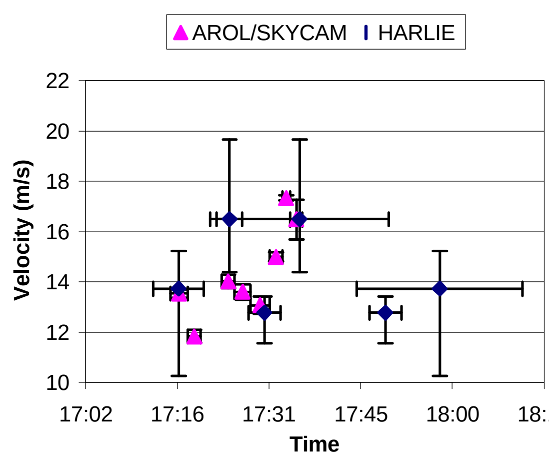


**Figure 12:** HARLIE and AROL/SkyCam wind measurement comparison chart for 10 March, 1999, 17:00 - 18:00 hrs, ~3800 m altitude.

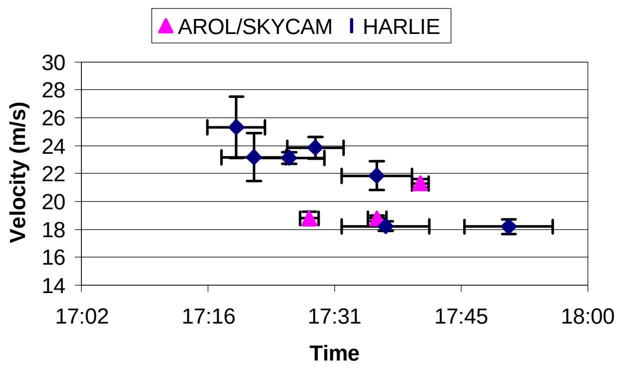


**Figure 13**: HARLIE and AROL/SkyCam wind measurement comparison chart for 6 June, 1999, 17:00 - 18:00 hrs, ~5000 m altitude.

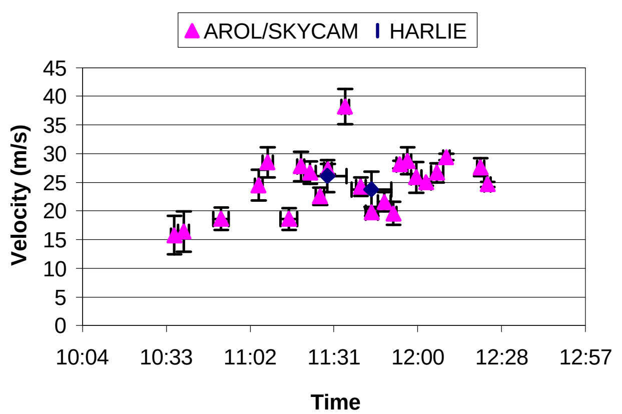


**Figure 14:** HARLIE and AROL/SkyCam wind measurement comparison chart for 5 June, 1999, 10:30 - 12:30 hrs, ~10 000 m altitude.

was determined from the average deviation of the cloud bottom altitude during the given time interval. The two methods of wind speed measurement are in good agreement over the speed range 5-40 meters/second.

FIG. 15 summarizes the altitude variation of wind speed for the entire day of June 5 when both instruments were operating (10:30-15:00). The lowest cloud level was at 1.5-2.5 km AGL and higher clouds were tracked over a range of altitudes 7.0-15.0 km AGL. There is clearly a predominant trend in speed vs. altitude in these data, even over the 4 hours observing time.

Two points of departure from this trend are noteworthy, as they illustrate difficulties occasionally encountered with the measurement method employed: (1) The inaccurate AROL/SkyCam data point at 7 km altitude reflects the ambiguity that can arise in assigning a lidar altitude to a vertically extended cloud structure whose silhouette, and hence edge motion, seem very clear in the SkyCam video frame. To overcome this problem, one needs to have the AROL-type lidar tightly bore-sighted to the moving cloud features being recorded in the video. (2) The outlying HARLIE point at 14 km and 24 meters/second may reflect the fact that the HARLIE "circle of regard" is almost 30 km in diameter at this altitude, a size that could well include a significant horizontal gradient in wind speed. A basis for this supposition is seen in FIG. 16 (June 5, early afternoon) where HARLIE speeds (~30 m/s) are seen to vary markedly and intermittently from the AROL speeds.

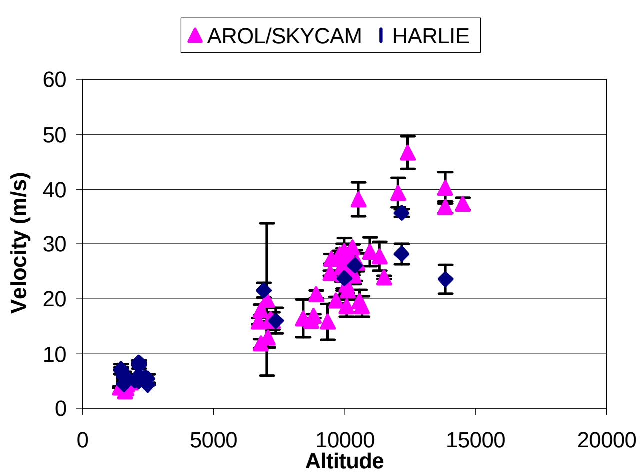


**Figure 15:** HARLIE and AROL/SkyCam wind measurement comparison chart for 5 June, 1999, note that this displays the velocity as a function of altitude.

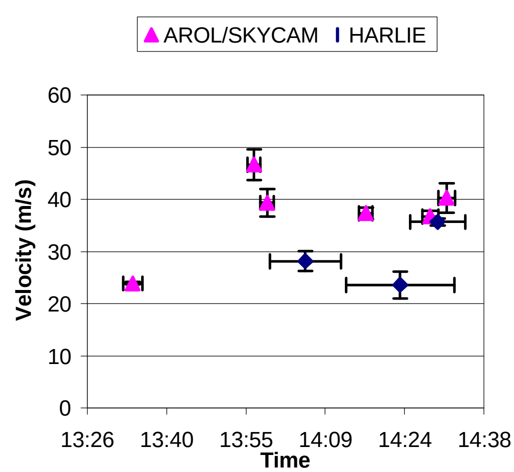


**Figure 16**: HARLIE and AROL/SkyCam wind measurement comparison chart for 5 June, 1999, 13:30 - 14:40 hrs, ~12 500 m altitude.

## 5. CONCLUSIONS

The main objective of the HOLO campaigns was met by showing that the holographic lidar HARLIE can be used to obtain horizontal wind velocities over a range of altitudes and weather conditions. A new algorithm was developed for analyzing the horizontal motion of atmospheric features observed with a conical scanner. We have observed velocities over a range of 1-40 meters/sec, and the altitudes covered are 500 meters to 15 kilometers. The precision of the HARLIE wind speeds varies between 0.5 and 2 meters/sec, and the AROL-2 precision is comparable. The results of the two methods usually agree to within 1 or 2 meters/second, depending on altitude and the evident variability of the wind field.

The favorable correlation leads us to believe that the HARLIE type measurements could be extended to work with aerosol or sub-visible cloud structures, providing a fairly simple alternative to Doppler methods of obtaining local wind profiles. Instances were observed when atmospheric variability and the different observing geometries of HARLIE and AROL-2 could have been responsible for results that differ between the two types of measurement. Future tests of these optical methods should be accompanied by rawinsonde measurements of the vertical profile of the horizontal wind field.

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