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Performance of a VME-based Parallel Processing LIDAR Data Acquisition System (Summary)

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Abstract

It may be possible to make accurate real time, autonomous, 2 and 3 dimensional wind measurements remotely with an elastic backscatter LIght Detection and Ranging (LIDAR) system by incorporating digital parallel processing hardware into the data acquisition system. In this paper, we report the performance of a commercially available digital parallel processing system in implementing the maximum correlation technique for wind sensing using actual LIDAR data. Timing and numerical accuracy are benchmarked against a standard microprocessor implementation.

Introduction

An elastic backscatter LIght Detection and Ranging (LIDAR) system can remotely detect a variety of naturally occurring clouds and aerosols that move with the wind. If the spatial motion of these clouds and aerosols can be remotely sensed, time interval measurements can be used to determine their velocities, and hence the associated local wind velocities. The elastic backscatter LIDAR technique consists of emitting laser pulses and measuring the laser signal returns as a function of time (or, equivalently, spatial range from the laser). Laser light is reflected by the clouds and aerosols and causes enhanced signal returns. A current LIDAR data analysis approach to the wind sensing problem is to measure correlations in multiple returns from different spatial orientations of the LIDAR in an attempt to track the motions of the naturally occurring fiducials.

Current LIDAR systems have lasers that operate at a repetition rates of a few tens of Hertz. Direct digitization of these LIDAR returns can generate considerable amounts of data which currently requires days to process on a host computer to extract wind information. With ever increasing data rates, the raw data must be processed in the data acquisition system to extract the relatively sparse winds information before transmission back to the host computer. We discuss the performance increase obtained by using a parallel processor for the wind sensing algorithm to the current host computer performance.

LIDAR: The Sensor

A lidar is a type of laser radar. A short, intense pulse of laser light is emitted into the atmosphere. The various constituents of the atmosphere interact with that beam and scatters part of the emitted light back to a receiving telescope. At the back of the telescope, the returning light is separated by wavelength and converted to an electrical signal. This electrical signal is sampled and converted to digital data at rates approaching 100 MHz (approximately 1.5 m resolution) and stored in memory. Because the time of flight of the light from the lidar to a particular atmospheric constituent and back is recorded, its distance from the lidar can be calculated. Lidars are specialized to particular applications depending on the laser wavelength.

Analyzing a time series of horizontal and vertical scans (such as Fig. 1) allows us to infer the main atmospheric movements of aerosols within the volume of atmosphere scanned. In fact, we obtain a description of the circulatory patterns of atmospheric aerosols. By sensing the spatial movements of these aerosols and recording
The following pairs of vertical and horizontal scans were acquired between the 0900 and 1400 hours on September 11, 1994 (Buttler et al. 1995).

Ringing, a type of detector noise, is visible in the two vertical scans. The red colors in the horizontal and vertical scans correspond to regions of high backscatter return. These high returns could be caused by dust, water, or other particulate matter—which could be pollutants emitted by smokestacks or car exhausts. The elastic backscatter lidar, as stated earlier, cannot distinguish aerosol species. And, although it is clear that large amounts of aerosols are flowing into New Mexico from Mexico, knowing what those aerosols are without sampling them is impossible. It is also clear that aerosols are flowing into New Mexico from Texas, but not at the volumes seen flowing in from Mexico.
Time, the wind speed and direction in planes or volumes of the atmosphere can be calculated. Thus, elastic backscatter LIDAR can be used to remotely sense 3 dimensional wind fields that are more difficult or impossible to measure using conventional in situ or Doppler techniques (Buttler et al. 1995).

Wind Sensing Technique: Maximum Correlation

Mathematically, correlation is a measure of the deviation about the mean square between two distributions. When one distribution, whose variables are time or space, lags another, the maximum in the correlation between the two distributions will occur at the temporal or spatial separation between the two data sets. For instance, the lag between \( \cos(x) \) and the \( \sin(x) \) over one period is \( \pi/2 \) radians. Correlations can also be performed in more than one dimension as shown below (Eq. 1).

\[
\gamma(p, q) = \frac{\sum_{r,t} \left\{ \frac{[A(r,t) - \bar{A}] [B(r+p,t+q) - \bar{B}]}{\sigma_A \sigma_B} \right\}}{\left( \sum_{r,t} \left[ \sigma_A^2 \right] \left[ \sigma_B^2 \right] \right)^{1/2}}, \tag{1}
\]

where \( \gamma(p,q) \), the cross-correlation function, gives the cross correlation at lags \( p \) and \( q \) between distribution \( A(r,t) \) and lag distribution \( B(r+p,t+q) \). \( \sigma_A \) and \( \sigma_B \) are the standard deviations of the elements of distribution \( A \) and the lag distribution \( B \). \( \bar{A} \) and \( \bar{B} \) imply average values. The square root of the product of the sum of the squares of the elements of distribution \( A \) times the sum of the squares of distribution \( B \) normalizes the results of the correlation between the two distributions to a range of values between +1 and -1.

The most common type of correlation involves a comparison of the same scene at later times. One might imagine taking a satellite photo of a region of the earth at 10:00 hours, and taking another satellite photo of the same region of the earth at 10:10 hours. If there are clouds present in the images, and pixel intensities between the two images are correlated, then the result of the pixel correlations will be a position lag between the two images. It is possible to extract the direction and distance the clouds have traveled by calculating a distance vector between the original pixel position and the lagged pixel position. A mean velocity is extracted by dividing the distance traveled by the change in time, 10 minutes in our satellite photo example.

Problems can occur when directly correlating full images. If there are a large number of stationary objects in the images being correlated, then these objects will add a type of noise to the resulting lags; i.e. the stationary objects in the images skew the deviation about the mean square between the two data sets toward zero lag. Fine scale detail, which may be moving, cannot be resolved above the zero lags of the stationary parts between the two images. Fine scale motions can be recovered by removing stationary components in images to be correlated, or by performing a maximum cross-correlation between images of interest.

The maximum cross correlation consists of subdividing one of the images into smaller subimages and correlating the subimages with the remaining full image. The increased computational time is offset by the reduced effects of bulk-image features and the explicit velocities dependence on structure size. This type of technique has been used to measure sea-surface velocities (Emery et al. 1986) and (Garcia et al. 1989), ice pack motions (Ninnis et al. 1986) and cloud motions (Leese et al. 1970).

Our maximum cross-correlation application differs from the basic technique described above in that the lidar surveys different scenes (different look angles) during the same time period, whereas most correlation techniques survey the same scene at later times. As a result, correlations are performed in the temporal and spatial domains to yield a range lag and a time lag between the adjacent look angles. The lags and the spatial separation between the locations of maximum correlation of the two look angles are
then used to calculate a velocity vector. The wind fields and velocity distributions observed by the lidar are shown in Fig. 2.

Fig. 2. Wind Fields Above the Rio Grande River Valley (September 11, 1995, 0900 to 1000 hours) (Buttler et al. 1995)
The Parallel Processor

Current LIDAR data acquisition systems are not capable of measuring 3 dimensional winds in real time. Typically, analysis may require weeks after the field experiments. Current elastic backscatter LIDAR's have lasers that fire at rates of 20 - 50 Hertz. Current data acquisition systems utilize Versa Module Eurocard (VME) bus digitizers operating at 25-100 MHz sampling rates and having resolutions of 8-12 bits. It is necessary to store 100 microseconds of return samples for each 15 km of range, so a LIDAR receiver can easily generate $10^5$-$10^6$ A/D samples per second. Archiving and displaying information at this data rate strains current data acquisition systems. As the laser repetition rates increase into the KHz regime, transmitting the raw digitized data from the A/D converter in the VME crate over a network link, such as Ethernet, to a host computer for display becomes unfeasible, and doing analysis with the host computer is out of the question. Introducing a parallel processor into the data acquisition system can transform the LIDAR into a wind sensing LIDAR and the data acquisition system into a digital signal processing system.

The CNAPS parallel processor, a commercially available product from Adaptive Solutions of Beaverton Oregon, is especially well suited to the processing requirements of the maximum correlation algorithm (Skinner 1995) performed in the data pipeline. The linear processing array is in a Single Instruction Multiple Data (SIMD) configuration with fixed point data representation. These parallel processors are available in the VME form factor for integration into existing LIDAR data acquisition systems. The VME card, with 256 processing elements running at 20 MHz, has 16 megabytes of RAM for program and data storage.

Algorithm development begins by generating the executable code with a parallel 'C' cross compiler on a SUN host and executing that code on a CNAPS development station. After development, the algorithm is migrated into the VME bus system with the CNAPS parallel processor VME card. The CNAPS control will be done from the existing single board computer (SBC) (680x0 or PowerPC) running the VxWorks real time Operating System. The SBC will not only coordinate the laser and telescope control and the digitizer timing as in current systems, but will also control the CNAPS parallel processor. After analysis with the CNAPS, the extracted wind speed data is transferred to a host computer for display and archival.

Discussion

We will implement the maximum correlation technique for wind sensing in 2 dimensions on the CNAPS parallel processing development station. The algorithm will be tested with actual elastic backscatter data and benchmarked against existing host computer time required for analysis. The results will serve as justification for integrating the parallel processor into the LIDAR data acquisition system to produce wind measurements in real time.

References


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