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Beam Pointing Stabilization for a Shipboard Volume Imaging Lidar

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A Scanning lidar has been modified to operate aboard the research vessel GLORITA in the MAST (Monterey Area Ship Track) experiment. Beam pointing stabilization was accomplished by using vertical gyros to measure the ships' attitude and a computer to control the scanning mechanism. The computer reads angles from the scanning mechanism, gyros and data acquisition computer which determines the desired pointing direction. Using orthogonal transformations, the required position of the scanning mechanism is calculated and appropriate commands are sent to it. During most of the MAST experiment the wave heights were in the 3 to 7 m range with rolls reaching 20° and pitches reaching 7°. For these conditions, pointing accuracies of 0.1° were achieved.

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Monterey area shiptrack experiment	laser radar	eulers angles	yaw
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BEAM POINTING STABILIZATION FOR A SHIPBOARD VOLUME IMAGING LIDAR

Lidar Description

A lidar (laser radar) transmits a pulse of laser light into the atmosphere, collects the light backscattered from the laser beam into the field of view of a receiving telescope, focuses the light onto a photodiode, and digitizes the analog signal from the photodiode at rates ranging from 20 MHz to 100 MHz. In addition, a volume imaging lidar (VIL) is moved in azimuth and elevation between laser pulses. By combining a series of returns from different directions, a volume image of aerosol structures is created allowing time varying 3-D images of clouds, sea spray structures and smoke plumes to be examined.

The movements of a ship's deck produce substantial pointing errors for a scanning lidar. For example, a 5° roll creates a positioning error of nearly 175 m vertical displacement from the desired position at a range of 2 km. Since ship plumes near the surface frequently have scale sizes of 10 m, pointing errors larger then a few tenths of a degree introduce unacceptable errors. This report discusses the techniques used to minimize pointing errors.

The NRL VIL[1] system recently took part in the MAST (Monterey Area Ship Track) experiment funded by the Office of Naval Research (ONR). For over 30 years, satellite images taken over the Pacific Ocean have contained features resembling "ship tracks"; long, linear cloud features apparently caused by ships[2]. The purpose of MAST was to determine the conditions under which these tracks form. The lidar was operated aboard a ship so it could be positioned near areas where tracks frequently occur. The R/V GLORITA, a Dutch-built research vessel with a length of 150 feet and a beam of 26 feet, was leased and the lidar was modified to fit on the upperdeck, see figure 1.

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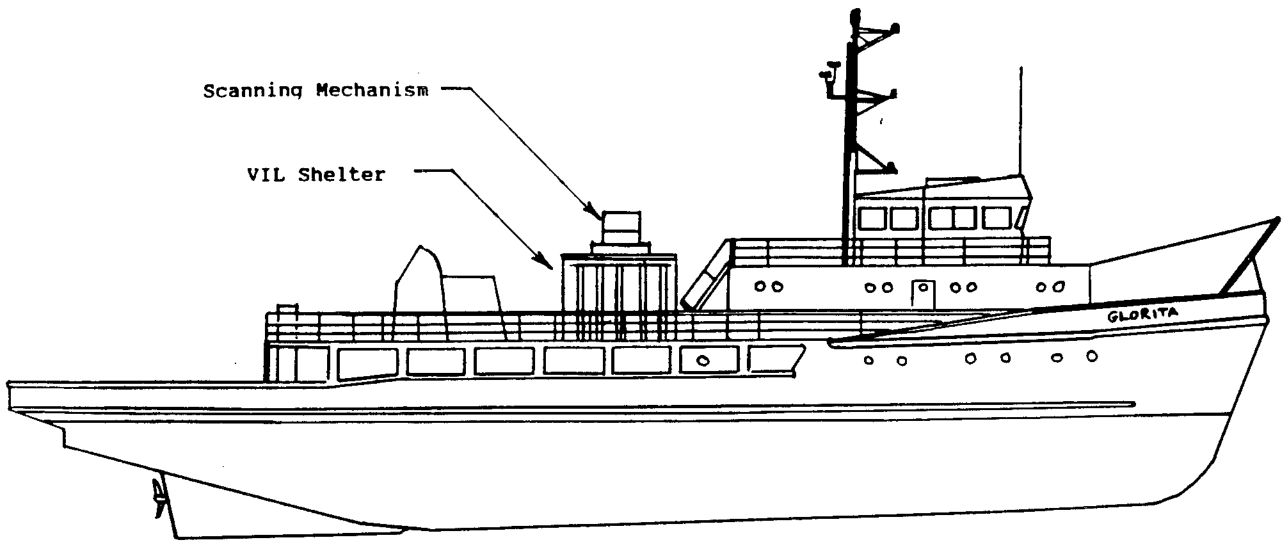

Figure 1. Location of the lidar shelter on the RV GLORITA.

The lidar has primarily been used as a ground-based measurement system at the Chesapeake Beach Detachment (CBD) located just east of Washington, DC. It was housed in a 40 foot long tractor trailer van; however for MAST, a shorter shelter was constructed to fit on the ship. This shelter, a shipping container 20 feet long by 8 feet wide by 8 feet high, was modified by Oceaneering Inc. to house the lidar. Electrical wiring, air conditioning, heat, lights and phone were added. A rectangular cutout was made in the roof and a hydraulic scissor jack was installed on the floor of the shelter so the scanning mechanism could be raised above the roof line during operations and retracted into the shelter when not in use.

Scanning and Data Acquisition Systems

The scanning mechanism consists of two rotation stages mounted at right angles to each other, one mounted horizontally and the other vertically, see figure 2. Each rotation stage supports a mirror mounted at 45° to the plane of rotation. The horizontal stage is aligned over a 20 inch hole in the lidar frame. The laser beam is aimed directly up through the hole and reflects off the mirrors out into the atmosphere. The horizontal rotation stage rotates both mirrors and controls the azimuthal pointing direction. The vertical stage rotates the vertical mirror and controls the elevation angles. Large scale (1 km) structures can be scanned and displayed in about a minute.

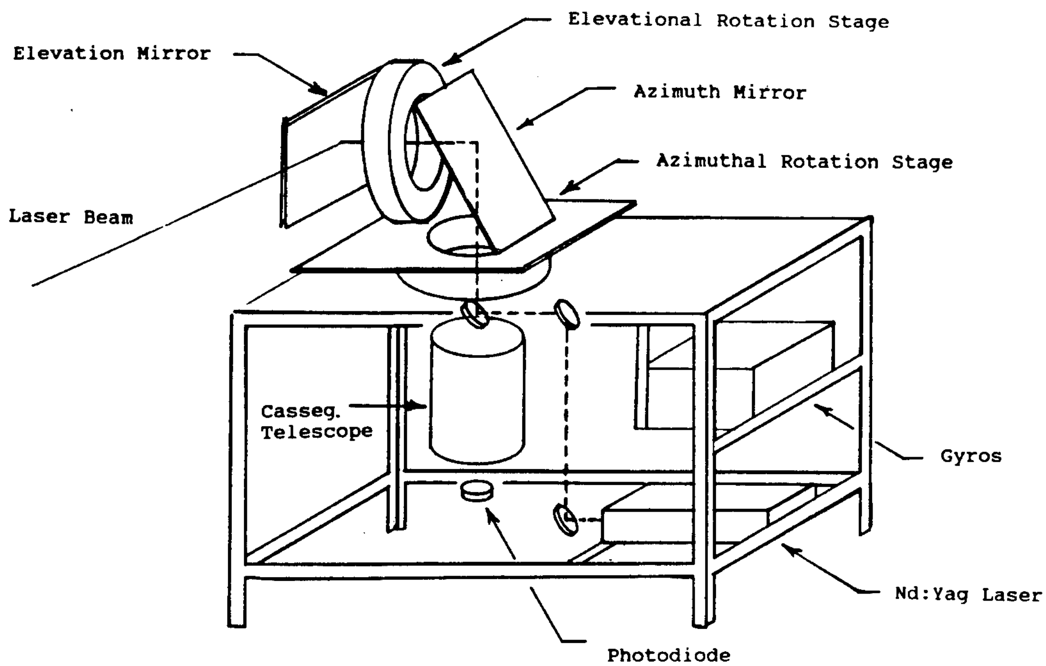

Figure 2. Locations of VIL mirrors, laser, gyros and telescope.

To compensate for the pitch, roll, and yaw motions of a ship, the hardware and software that control the lidar scanning mechanism was modified. As briefly mentioned in the introduction, a change in the ship's attitude dramatically effects the pointing direction of the lidar system and therefore the system must compensate for the ship's motions. However, pointing errors due to heave are not considered since the vertical motions are small in amplitude (approximately 1 to 2 m) and would be less than the beam width several km away thus having a negligible effect on signal return.

Three computers (a 386 PC, a Silicon Graphics workstation and a 486 PC) are used to control the scanning mechanism, acquire data, and display the data, see figure 3. The first computer ("Scanner PC") was added to the VIL data acquisition system to continually interrogate the gyro outputs, compute orthogonal transformations, and send corrected angles to the scanning mechanism. The second computer (a SGI workstation) is used to create real-time displays that show spatial cross sections and time series as well as 3-D images.

The third computer ("Lidar PC") controls the data inputs into the first two computers. Its' tasks include:

1. Sending scan parameters, azimuth and elevation, to the "Scanner PC".
2. Reading the digitized return signal from the CAMAC waveform digitizer, adding header information and transferring data to the SGI workstation.
3. Monitoring the laser output power.

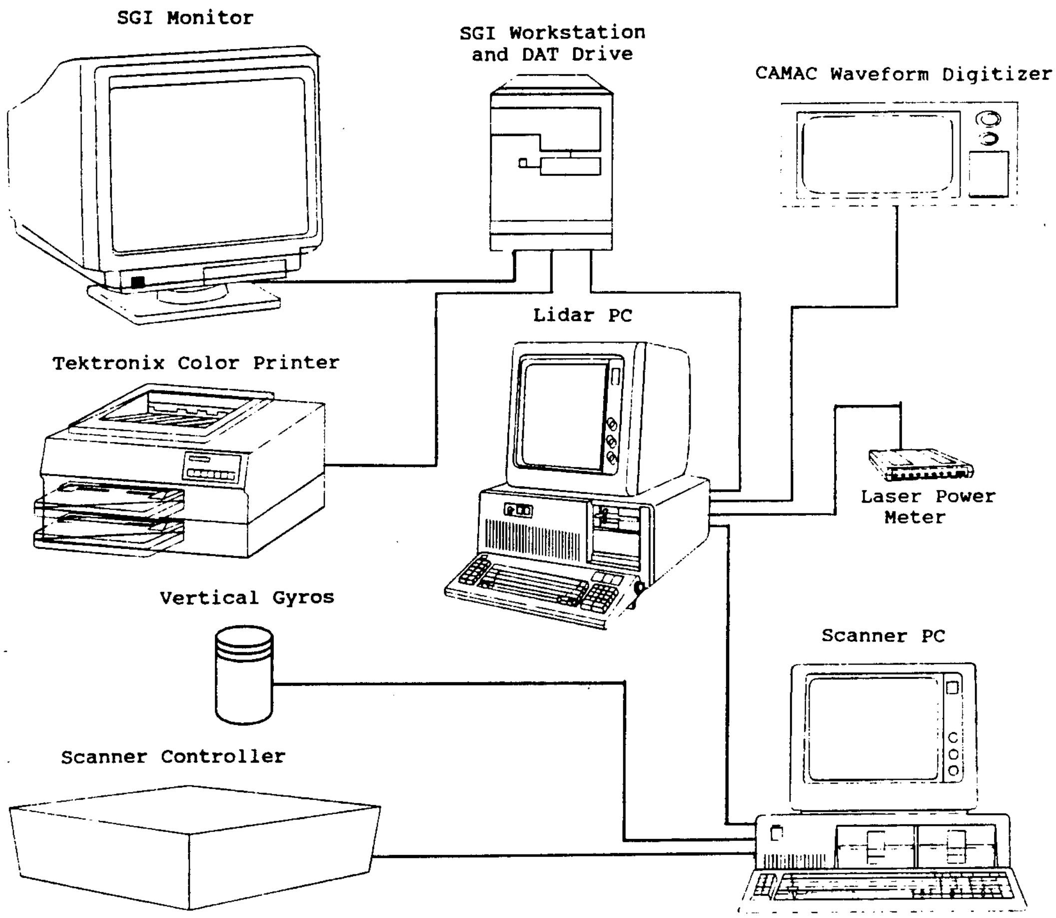

Figure 3. Interconnections of the VIL data acquisition system.

Measurement of Pitch, Roll and Yaw

A two axis vertical gyro and a directional gyro were mounted on the lidar frame inside the lidar trailer. A magnetic compass with a north seeker was mounted on an aluminum pole extending 3 m above the roof of the shelter. A pair of inclinometers were aligned along the pitch and roll axes in case of gyro failure. See table 1 for the rated accuracies of the instrumentation.

Table of Hardware

Manufacturer	Description	Accuracy
Klinger	RT660 Rotation Stage (Az)	0.001°
Klinger	RT660 Rotation Stage (Elev)	0.001°
Humphrey	NS29-0201-3 North Seeker	1.0°
Humphrey	VG24-0635-1 Vertical Gyro	0.1°
Humphrey	DG570-0602 Directional Gyro	0.2°
Sperry	Accustar Pitch Inclinometer	0.1°
Sperry	Accustar Roll Inclinometer	0.1°

Table 1. Rated accuracies of stabilization equipment.

Coordinate System Transformation

Pointing angles, azimuth and elevation, are determined and sent to the scanning mechanism. The scanning mechanism is mounted rigidly to the shelter and the shelter is mounted rigidly to the deck of the ship; therefore, the desired elevation and azimuth are biased by the pitch, roll, and yaw movement of the ship. For accurate scanning and positioning a correction must be done to account for this motion.

Two sets of axes, S and S''', are defined with S fixed to the earth and S''' fixed to the ship, see figure 4. The primes on the S''' axes correspond to the number of rotations required for the full coordinate transformation. The S axes are defined with the z axis aligned with nadir and the x axis fixed along a reference line such as magnetic north. The origin of this system is free to move with the ship and is co-located with the origin of the axes defined as S'''. The z''' axis is fixed perpendicular to the deck of the ship and the x''' axis is fixed along the centerline of the ship.

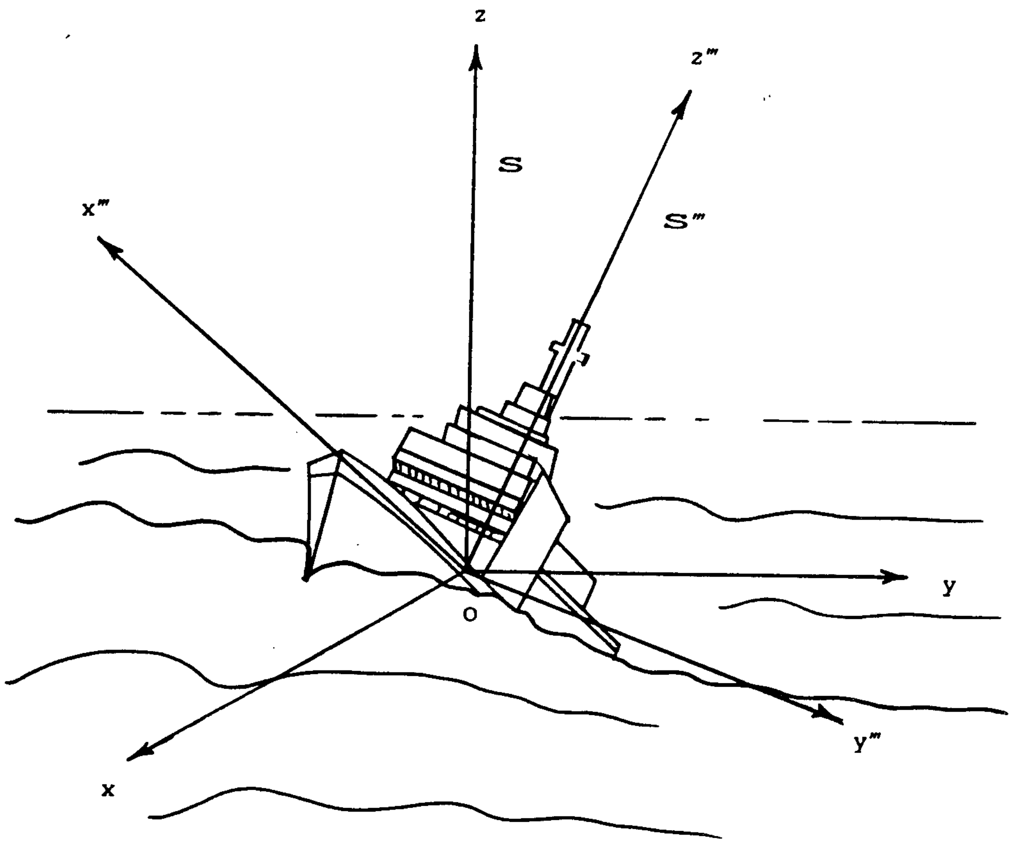

Figure 4. The orientation of the S and S''' axes.

The vertical gyros (pitch and roll) are aligned along the x''' and y''' axes, respectively. The yaw gyro is aligned with the x axis (north). The azimuth angle defines a rotation about the z axis with 0° aiming the laser beam directly aft along the centerline of the ship, 90° pointing the beam to port, and -90° pointing to starboard. The elevation angle defines a rotation perpendicular to the plane of the azimuthal rotation with 0° corresponding to the beam being parallel to the plane created by the ships' deck and 90° aiming up, perpendicular to the deck. The gyros give the angular displacements about the set of axes defined as S. A coordinate transformation to the S''' axes from the S axes using the xyz convention[3] must be done to determine the values of azimuth and elevation, see figure 5.

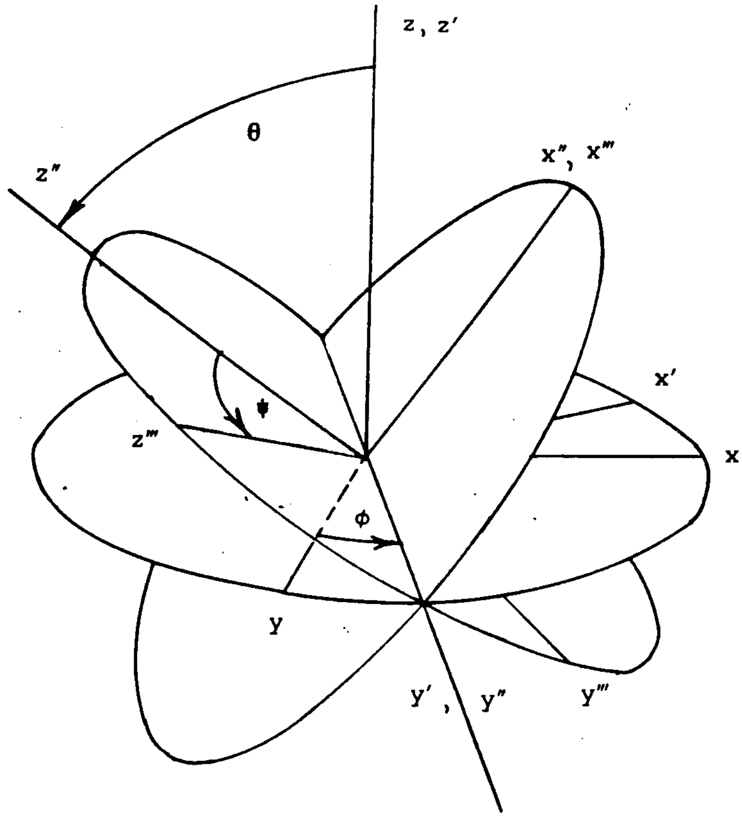

Figure 5. Graphical representation of the three rotations.

The transformation from the S to S''' axes is defined by three rotation matrices. The first rotation is through the yaw angle, ϕ:

$$\overleftrightarrow{R}_1 = \begin{vmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{vmatrix}, \tag{1}$$

where the primes denote rotation number and dyad denotes matrices. The second rotation is by the pitch angle, θ, about the y' axis:

$$\overleftrightarrow{R}_2 = \begin{vmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{vmatrix} \tag{2}$$

The third rotation is by the roll angle, ψ, about the intermediary x″ axis:

$$\vec{R}_3 = \begin{vmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & \sin\psi \\ 0 & -\sin\psi & \cos\psi \end{vmatrix} \tag{3}$$

The transformation between the two axes is given by the product of the three rotation matrices:

$$\vec{S}''' = \vec{R}_3 \, \vec{R}_2 \, \vec{R}_1 \, \vec{S} \tag{4}$$

or

$$\begin{vmatrix} x''' \\ y''' \\ z''' \end{vmatrix} = \vec{R}_3 \, \vec{R}_2 \, \vec{R}_1 \begin{vmatrix} x \\ y \\ z \end{vmatrix} =$$

$$= \begin{vmatrix} \cos\theta\cos\phi & \cos\theta\sin\phi & -\sin\theta \\ \sin\psi\sin\theta\cos\phi-\cos\psi\sin\phi & \sin\psi\sin\theta\sin\phi+\cos\psi\cos\phi & \sin\psi\cos\theta \\ \sin\psi\sin\phi+\cos\psi\sin\theta\cos\phi & \cos\psi\sin\theta\sin\phi-\sin\psi\cos\phi & \cos\psi\cos\theta \end{vmatrix} \begin{vmatrix} x \\ y \\ z \end{vmatrix}$$

The unprimed coordinates are calculated from the desired "fixed earth" pointing direction:

$$x = \cos(el)\,\cos(az), \tag{5}$$

$$y = \cos(el)\,\sin(az)\,, \tag{6}$$

$$z = \sin(el)\,, \tag{7}$$

where el and az are the elevation and azimuth angles respectively. Once the S‴ coordinates are known, the new elevation and azimuth angles (el‴ and az‴) can be defined in terms of the unit vector P, which represents the laser beams pointing direction, see figure 6:

$$z''' = \sin(el''') \tag{8}$$

$$x'''=\cos(el''')\cos(az''')\ . \tag{9}$$

Solving for the new scanner angles, el‴ and az‴, gives:

$$el'''=invsin(z''') \tag{10}$$

and

$$az'''=invcos\left(\frac{x'''}{\cos(el''')}\right) \tag{11}$$

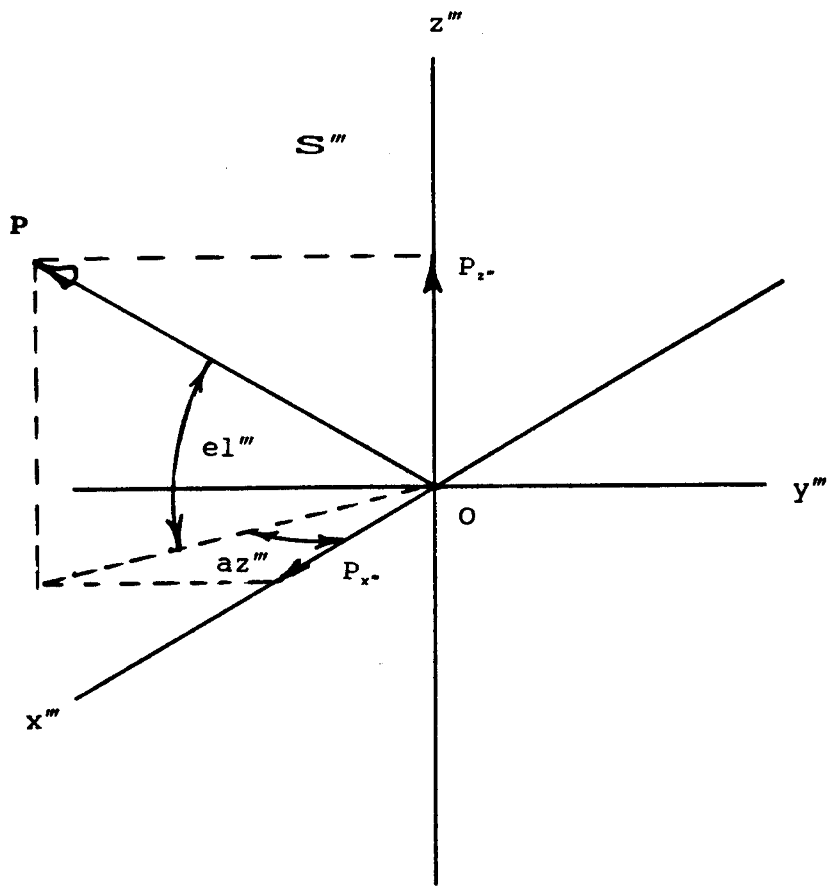

Figure 6. Geometrical analysis of beam direction.

The angles, el‴ and az‴, which correct for the pitch, roll and yaw of the ship, are (as discussed in the next section) used to control the scanning mechanism.

Scanning and Stabilization Software

The scanning mechanism used in the lidar system is manufactured by Klinger Scientific, Inc. The rotation stages are positioned by stepping motors that are controlled by a 386 personal computer ("Scanner PC"). A host of commands are available to control the acceleration, velocity and position of the scanner:

AC	Set acceleration of rotation stage.
MV	Move continuously in direction specified.
ST	Stop motion with deceleration.
VA	Set velocity of rotation stage.
TP	Report angular position of rotation stage.

To correct for the motions of the ship the scanner angles were continually adjusted according to the pitch, roll and yaw measured by the gyros. But rather than moving to the corrected position at a fixed rate, the velocity at which it was positioned was adjusted to create continuous movement. In this way, the forces required to overcome the inertia of a system at rest are greatly reduced and the high accelerations associated with sudden, large changes in velocity are removed. The adjustable rate method is a much smoother positioning method than a fixed rate angle change. The angular velocity, which must be calculated for both azimuth and elevation, is calculated as:

$$\Delta\theta/\Delta t=\alpha(\theta_i-\theta_{i-1})/\Delta t \qquad (12)$$

where Δt is a fixed time increment of about 0.1 sec (set by the "Scanner PC"),

θ_i is the destination angle determined by the scan parameters and the gyro input,
θ_{i-1} is the present scanner angle, and
α is the damping coefficient, (typically 0.95).

The damping coefficient is required to keep the angular velocity correction from overshooting the destination angle, otherwise pointing errors could grow causing undamped oscillations. In figure 7, the desired position of the scanner is at the point labeled, θ_1, and the present position is at θ_0. The angular difference, $\Delta\theta_0$, formed by these rays is computed and an angular velocity is calculated so that position θ_1 can be reached before a predetermined time period expires or some maximum speed is reached. In actuality the calculated velocity is slightly less than required to reach θ_1 because of the damping coefficient α. After the first movement, the scanner velocity is again adjusted and the scanner moves at the new velocity reaching position θ_2.

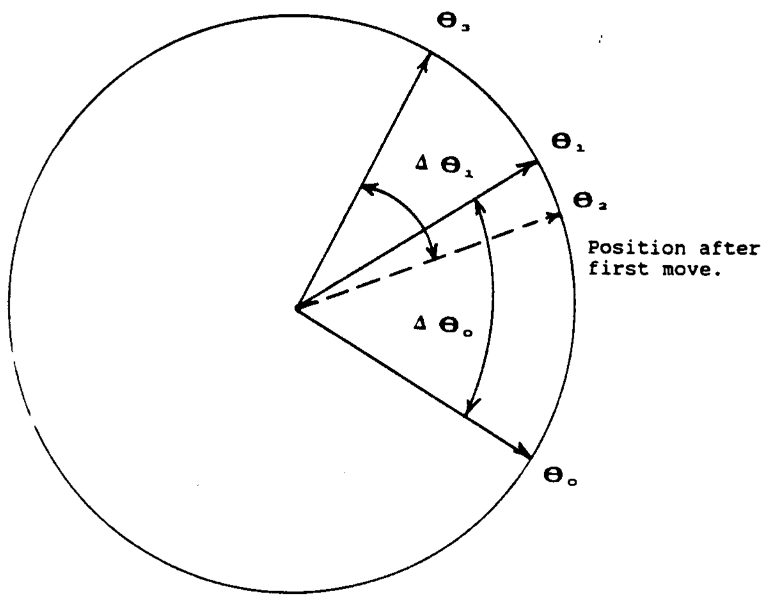

Figure 7. Description of angular positioning.

The gyros are interrogated, new position angles are determined, the velocity is calculated, and the scanner velocity is adjusted accordingly. This sequence of events is depicted in the flow chart in figure 8. The scanning angles are updated at about a 1 Hz rate by the "Lidar" PC. The "Scanner" PC reads the gyros, calculates the new velocities, and sends the commands to the scanner controller at approximately 10 Hz.

Pitch, Roll, and Yaw Test

NRL owns a pitch, roll and yaw test facility[4] located at CBD. Manufactured in 1943 by Westinghouse to test shipboard radars, the platform is a metallic structure with a deck area of about 225 ft^2 on which equipment can be mounted. The test facility provides rolls up to ±15°, pitch to ±5°, and 360° of yaw, all of which can operate simultaneously to simulate ocean swells with periods from 12 to 25 seconds.

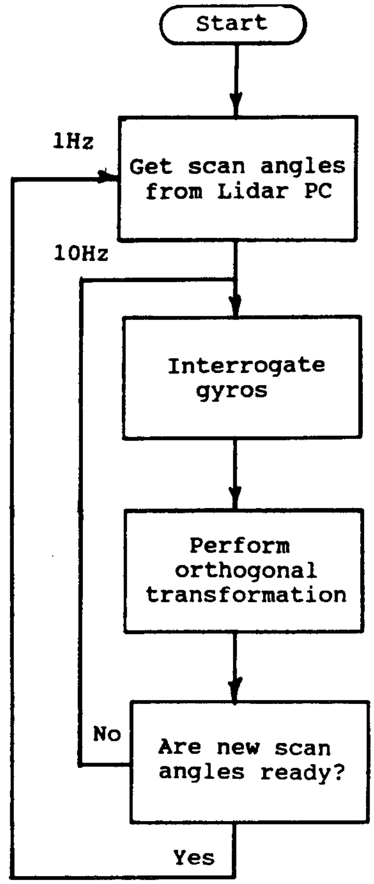

Figure 8. Order of events during scanner positioning.

The scanning system and controller, gyros, inclinometers and computers were bolted to the platform and put through a series of tests. An elevation of 10° and an azimuth of 0° was used as the desired target direction. An inclinometer mounted on the elevation stage monitored how well the corrections for pitch and roll were working. A HeNe laser operating at 632.8 ηm (a visible red beam) was attached to the elevation stage and the system was aimed at a wall approximately 30 m away. The platform was then rotated, pitched and rolled at various amplitudes and the movement of the laser upon the wall monitored.

Two problems were encountered during the testing. First, the yaw gyro did not function properly. A north seeking compass was mounted on the platform to replace the yaw gyro input. Second, the rock and roll platform generated massive, angle-dependant, magnetic fields that corrupted the output of the compass. Because of these fields, the pointing accuracy was limited to about 0.5°. The test had to be conducted without any yaw of the platform during the pitch and roll tests. The accuracy of the corrections for pitch and roll was about 0.1° without the yaw input.

MAST Experiment

During the MAST experiment[5], seas were rougher and the swell period shorter than predicted. The average wave height was 3 m with several days of waves in the 5 to 7 m range. The CBD test platform was operated at approximately a 14 to 18 s period but a shorter period of 6 s between swells was encountered throughout the cruise. At CBD the scanning system was subjected to maximum rolls of ±15° and a maximum pitch of ±5°. At sea we encountered pitches up to 15° and rolls with magnitudes of 20° or more. Despite the adverse conditions to which the scanning mechanism was subjected, the stabilization worked well. There was some occasional jitter in the scanning mechanism from noise in the gyro output caused by heavy seas, but data taken on days when the seas were above 5 m show that the scanner was well stabilized even under those conditions. Figure 9 shows typical output from the pitch and roll gyros and figure 10 depicts the correlation between the corrected scan in elevation and the pitch and roll encountered. As mentioned in the previous section, since the yaw gyro malfunctioned and compass readings were strongly contaminated by local magnetic fields, neither instrument was used on the ship to control yaw. Instead, the ships' autopilot was used to hold the ship track constant whenever possible to minimize yaw errors.

The rms error between the roll angles and the scanner elevation angles in figure 9 is 0.117° and was calculated as:

$$e_{rms} = \sqrt{\frac{1}{n}\left(\sum_{1}^{n} (Abs(\psi_n) - Abs(el_n'''))^2 \right)} \tag{13}$$

where, ψ_n is the roll angle measured by the gyros, and el'''_n is the scanner elevation angle.

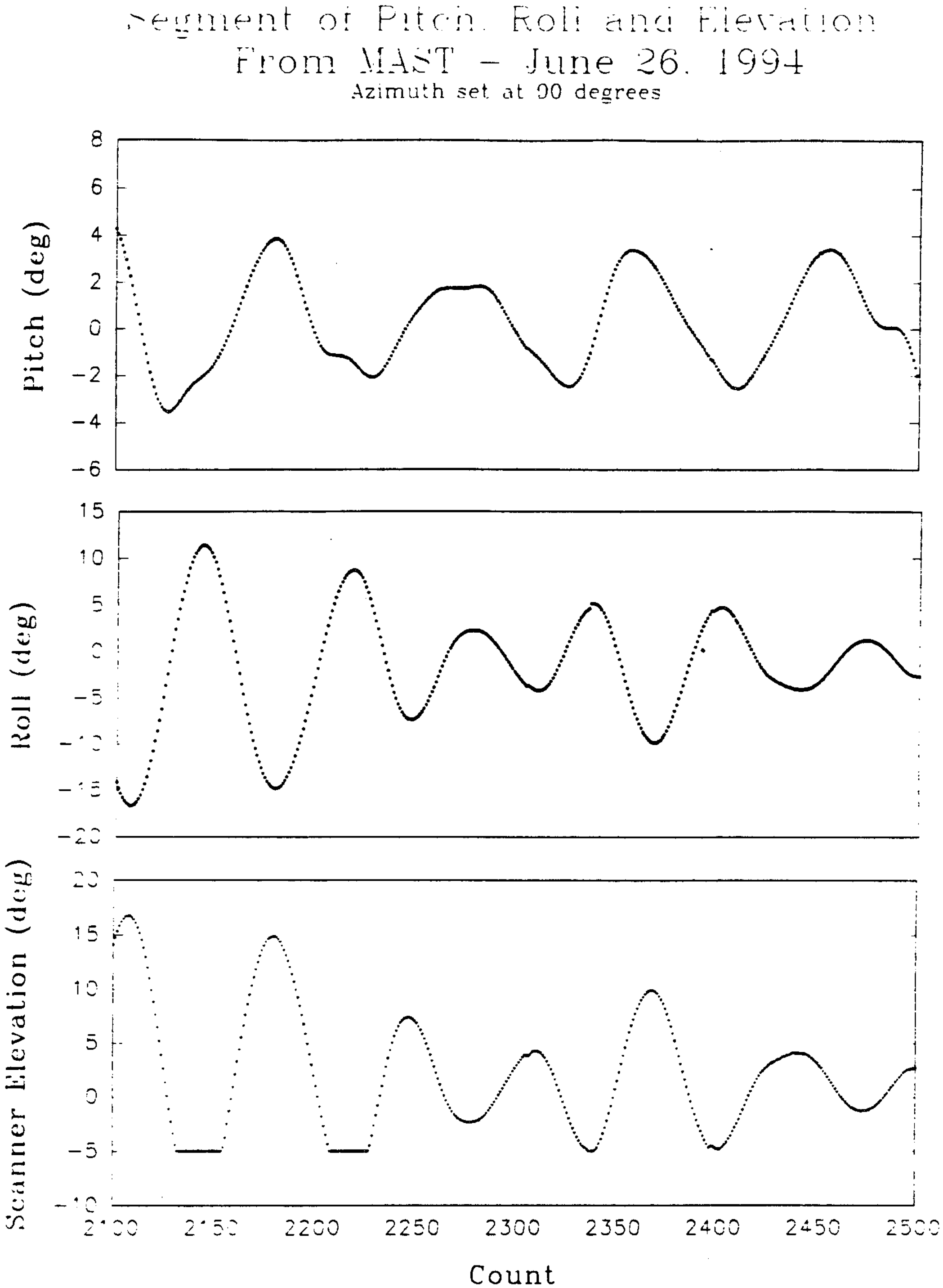

Figure 9. Pitch, roll and corrected elevation during MAST. Note: Flat sections of scanner elevation plot at -5° are from a mechanical stop on the elevation stage. The horizontal axis is the row number of the data point. There are ~0.1 s per count.

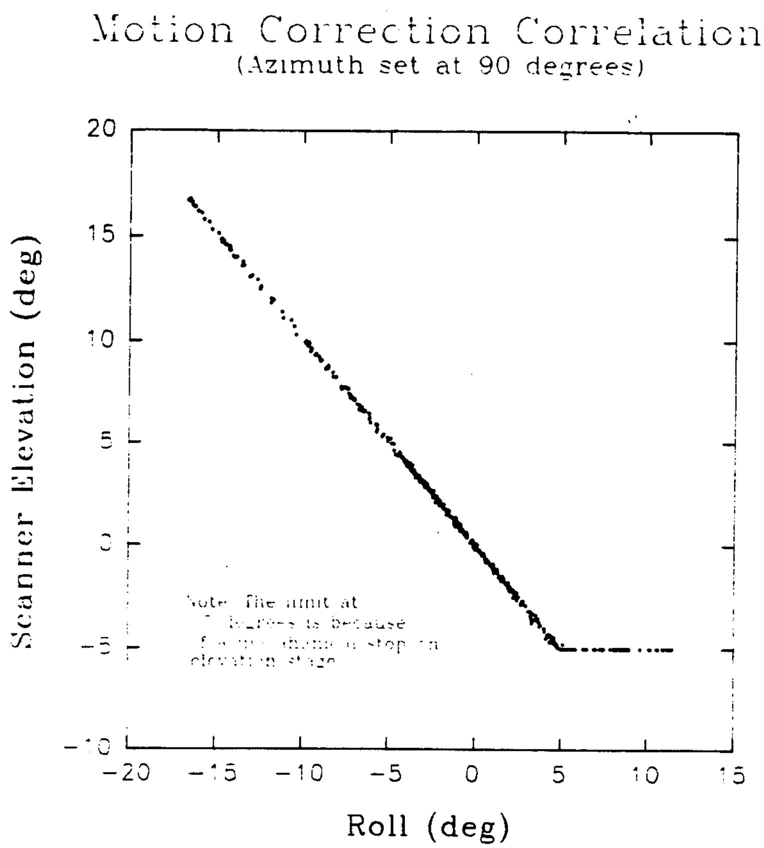

Figure 10. Correlation between corrected elevation and roll.

Conclusions

During MAST, the stabilization hardware and software controlled the scanning mechanism allowing the lidar to detect ship plumes. The pointing accuracy was normally 0.1°. Uncertainties in the "Scanner PC" clock caused the largest pointing errors. The clock also restricted the update rate for the scanner to 10 Hz. In future experiments, a faster PC with a special 'high speed clock' should be used.

The roll, pitch, and yaw test at CBD was critical for testing the gyros and correcting software. Without this test, the shipboard test of the VIL would have almost certainly been a failure. Fortunately, the R/V GLORITA had an auto pilot control that minimized the need for yaw correction. However, the yaw gyro needs to be replaced before any future shipboard experiments.

Acknowledgements

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