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PROGRAMMABLE SCANNER FOR LASER BATHYMETRY

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Abstract

This article describes a programmable scanner for laser bathymetry. Present scanners use a fixed pattern scan. A programmable scanner however offers many advantages regarding system performance and utility in that the sounding pattern and spot density can be chosen by the operator and optimized for the specific charting mission.

INTRODUCTION

Acoustic echo sounding techniques for depth measurement have recently been challenged by faster and more efficient methods such as airborne laser bathymetry. While restricted to shallow coastal waters only, laser bathymetry still offers a great potential with its high surface coverage rate, high mobility and cost effectiveness.

Laser bathymetry has been developed in Australia [1], Canada [2], [3] and the U.S.A. [4]. Tests have also been performed in Sweden [5] and recently a test system has been developed to study various applications of laser depth sounding. The system can be borne by a helicopter which is quite useful in the Swedish archipelago with its numerous islands, narrow straits and ship routes. The system contains many advanced features as regards signal handling and presentation. One of the key components is an advanced scanner.

While as far as we know, all other scanners for laser bathymetry use a fixed pattern, the scanner described in this article is fully programmable which offers many advantages in efficiency, spot density choice, choice of nadir angle etc., all of which will have a strong impact on system performance and utility.

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This article will discuss some of the design considerations relating to a laser bathymetry system in general and how these will impact on scanner design. Factors of prime importance as regards the accuracy will be discussed in greater detail. A technical description of the scanner will be given along with some examples of obtained results.

DESIGN CONSIDERATIONS

In the design of a laser bathymeter several considerations must be taken into account. First of all the system must give accurate data in x, y, z at a minimum sounding density. Moreover the system must fulfill safety requirements concerning eye and flight safety. Besides these absolute requirements, the system must be cost effective in terms of manpower involved in each mission, the aircraft cost, the coverage rate, depth penetration and the system utility.

In addition to the above factors, the scanner design is influenced by the choice of platform, sounding pattern, spot density, accuracy, utility and efficiency.

The platform choice is dependent on the operating scenario. A helicopter offers many advantages compared to a fixed wing aircraft in archipelago areas where its more favourable turn geometry and low speed enable it to use more of its flight time above the area of interest. While the speed of a fixed wing aircraft can exceed that of a helicopter at present the area coverage rate will be limited by laser repetition frequency (for a given swath width) rather than aircraft speed. Another aspect which favours a helicopter, especially in Sweden, is that it can be used to set out transponders for positioning systems and for geodetic work in conjunction with conventional ship surveys. Although it offers a harder vibration environment and involves higher flight time costs it was concluded that a helicopter would be the best choice for a future operational system in Swedish waters.

The ability to select the *sounding pattern and density* offers many advantages. Taking advantage of the maneuverability of a helicopter, the sounding pattern and spot density can be adjusted by the operator according to the area of interest i.e. a rocky area close to a ship route.

The accuracy of the data collected is dependant on several factors connected to the scanner. The beam nadir angle affects the depth bias, which has to be taken into account during the final correction of depth data. It has been shown by Guenther [6] that the beam angle will have a great effect on depth and that a nadir angle of 15-25 degree range will minimize this bias error depending on the signal processing chosen for echo extraction. The accuracy also depends on the ability of the system to determine a mean sea surface reference. This is often done by sensing the surface reflection of the IR beam of the Nd:YAG transmitter. However, during calm conditions this reflection may be too weak to be detected. In such a case the possibilty of changing the beam nadir angle from e.g. 20 degrees to 10 degrees will be very useful.

The utility and efficiency of the system will be improved if the scanner can adopt to the specific surveying mission and to the environmental constraints.

The arguments given above lead to a scanner design capable of generating desirable sounding patterns and spot densities. This can be achieved with a scanner using a flat mirror gimballed in two perpendicular directions and driven by torque motors. In principle any scan pattern can be programmed into the system and a vertical sensing gyro can stabilize the scanner in space, i.e. the outgoing laser beam is independent of the pitch, roll and yaw.

A scanner along the above lines was specified by the Swedish Defence Research Institute for a research program in laser bathymetry and built by the Saab Instruments company.

SCANNER DESCRIPTION

The scanner mirror is circular with a diameter of 280 mm, capable of working with a receiver aperture of 200 mm. The mirror is controlled by torque motors in both axes and the angles are sensed by encoders. Attached to the sensor frame (containing laser, receiver and scanner) is a vertical gyro, being a reference for the roll and pitch angles. A rate gyro can be implemented for the yaw angle. Compensation for yaw is done by simultaneous adjustment in two axes. The total weight of the scanner including vertical gyro is 24.6 kg and of the electronics unit 13.5 kg. The complete scanner system is shown in Figure 1.

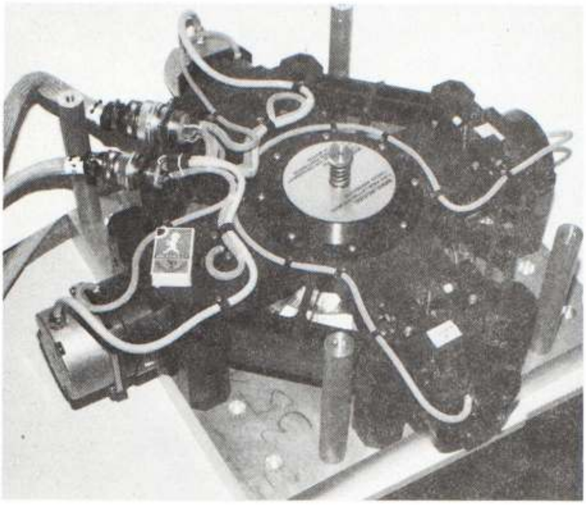
Scanner movement is controlled by a microcomputer system. Scan pattern values are stored in PROM or can be fed into the controller from a host computer. Scanner start up, scanner mode (pattern) and offset values are also given by the host computer.

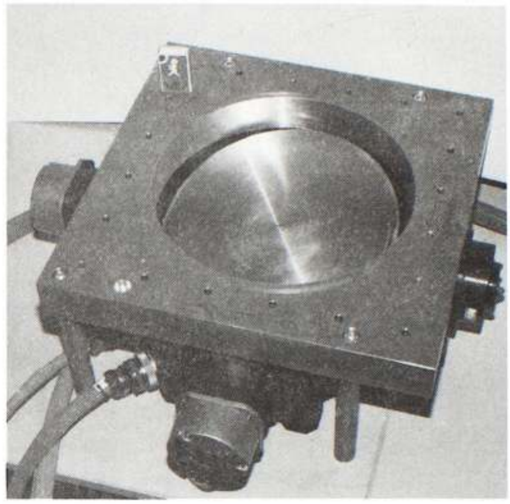
Present scanner design permits a maximum lateral beam angle of ±25 degrees, 15 degrees in the backward direction and 25 degrees in flight direction. Scanner frequency f_{sc} scales approximately as

$$f_{sc} \approx f_p \times a/2 \times S$$

where f_p is the laser repetition frequency, a the distance between laser spots on the surface and S the swath width. Given a swath width of e.g. 200 m, a spot distance a of 5 meters and a pulse repetition frequency of e.g. 100 Hz, the scanner frequency is approximately 2.5 Hz. A laser repetition frequency of about 1-200 Hz is typical of today's technology using flash-lamp pumped Nd:YAG lasers [1].

The area coverage rate Y can be estimated by $Y \approx f_p \times a^2$ assuming a uniform spot density. In the example above this implies $Y \approx 9$ km²/h. Cu-vapor lasers and future diode-pumped solid state lasers may offer still higher repetition frequencies due to substantially better efficiency. Assuming $f_p = 1$ kHz and $S = 200$ m gives $Y \approx 90$ km²/h and a scanner frequency of 25 Hz maintaining a spot distance of 5 m. Such a high frequency is difficult to realize with such a large mirror diameter as 28 cm. If the higher laser frequency is used it can increase both coverage rate and/or sounding density; choosing e.g. $a + 5$ m and $S = 250$ m will lead to $Y \approx 90$ km²/h with a scanner frequency of about 10hz.





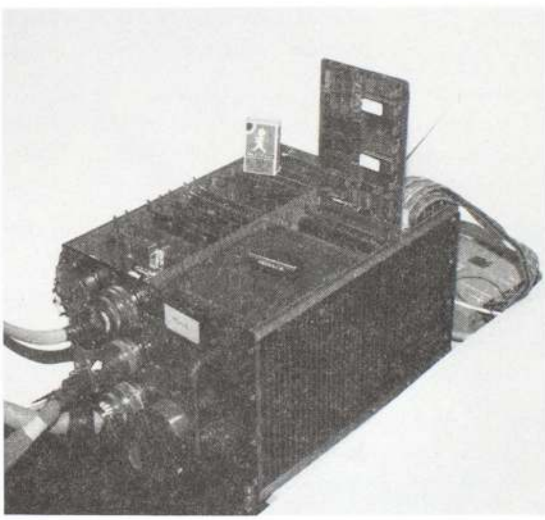


FIG.1.— Scanner unit seen from above and below (upper left and right) together with electronics control (below) unit. Size is indicated by matchbox.

The present design is, however, capable of scanner frequencies up to 10 Hz at full angular range and up to 15 Hz at half range (Fig. 2).

During a survey the operator can choose scanner mode (using pre-programmed scanner patterns) and sounding density. Using the current altitude (by operator or from an altimeter), the scanner controller calculates and sends back a recommended speed. The controller also signals status to the scanner system.

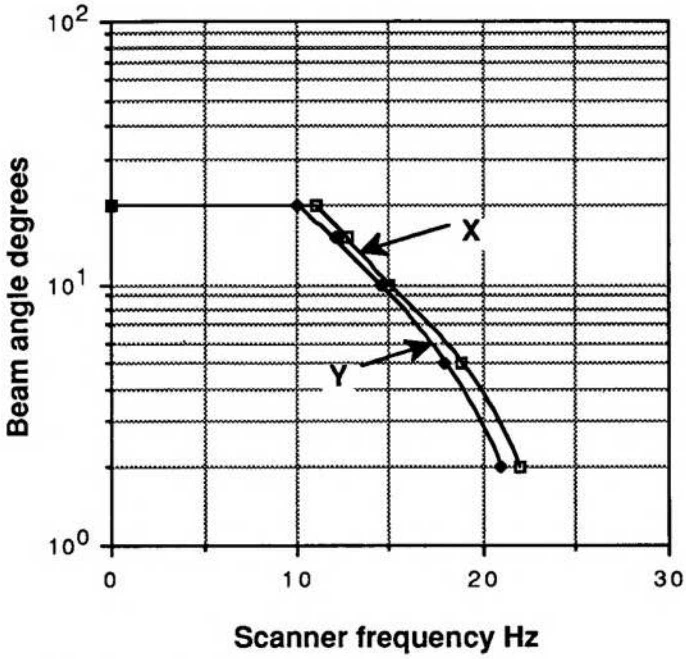


FIG. 2.— Scanner angle (= beam angle) as a function of scanner frequency. X and Y refer to the perpendicular directions with X in flight direction.

Table 1 lists some of the more important technical parameters.

Table 1

Scanner characteristics

Mirror		**Sensors**	
Diameter	280 mm	Angle encoders	
		Resolution	0.005 deg.
Beam nadir			
Lateral	±25 deg.	Vertical gyro	
Backward	–15″	Vert. accuracy	±0.3 deg.
Forward	+25″		
(Flight dir.)		Rate gyro	
		Resolution	0.025 deg./s
Mechanical		**Interface**	
Digital servoloops		1 serial E1A RS 232	
Sampling frequency	1kHz	1 parallel 16 bits, E1A RS 422	
Weight/dimensions			
Scanner	24.6 kg/160 × 255 × 255 mm		
Electronics unit	13.5 kg/320 × 200 × 260 mm		

Environmental criteria

The scanner is tested in accordance with airworthiness criteria for a helicopter.

BEAM POSITIONING ACCURACY

The scanner output angles must be available in conjunction with the platform position for determination of the exact laser spot position on the surface. The scanner angles are also useful in determining a wave corrector by evaluating the wave height for each laser shot to correct the measured depth.

If the rms-error of the spot is maximised at 5 meters and we can assume a platform position error of 3 meters, the error associated with the scanner and altitude must be less than 4 meters. The scanner computer sends the angles ϕ_x and ϕ_r relative to nadir with the help of the vertical gyro. Azimuth of the platform is given by a compass or the rate gyro. In figure 3 the angles ϕ_X and ϕ_y are defined as well as the coordinate system on the water surface to determine the laser spot position P. From the figure it is concluded that the laser spot position vector $r = (x,y) = H^*[\tan(\phi_x), \tan(\phi_y)]$ and that

$$r^2 = H^{2*}\tan^2(\theta) = H^{2*}[\tan^2(\phi_x) + \tan^2(\phi_y)] \quad (1)$$

where θ is the beam nadir angle defined in figure 3. We can now perform conventional error analysis to determine the error in position at P as a function of angle and altitude (H) errors. If we choose a scanner pattern close to an arc (cf. fig. 6 below) but limited to $\phi_y = \pm$ 20 degrees we will keep a constant beam nadir angle $\theta = 20$ degrees.

Assuming that the errors in ϕ_x and ϕ_y are equal and $= \sigma_\phi$, and that the altitude error is 1m, we can plot the beam position error for a given altitude H, σ_ϕ and σ_H to see that the error depends somewhat on the value of ϕ_y and has a maximum around $\phi_y = 15$ degrees (fig. 4). If we choose this value for ϕ_y we can plot the spot error as a function of σ_ϕ for different altitudes (fig. 5).

From figure 5 we can conclude that scan angle errors up to 0.5 degrees can be tolerated for an altitude of 300 m or less if we demand an absolute beam spot error of 5 m and can position the platform within 3 m accuracy.

The present scanner meets the angle error demand due to high accuracy vertical gyro and angle encoders. Great care has also been taken to correct the raw gyro and angular encoder signals for geometry (transformation of angles defined in different coordinate systems) and use them to calculate the wanted angles ϕ_x and ϕ_y. This calculation is done in real time in the scanner processor.

EXAMPLES OF SCANNER PATTERN.

As pointed out in the introduction the depth accuracy depends on such factors as beam nadir angle and the ability to determine a mean sea surface reference. As a constant beam nadir angle around 20 degrees would minimize the depth error, a conical scan would seem to be ideal. However, a full conical scan

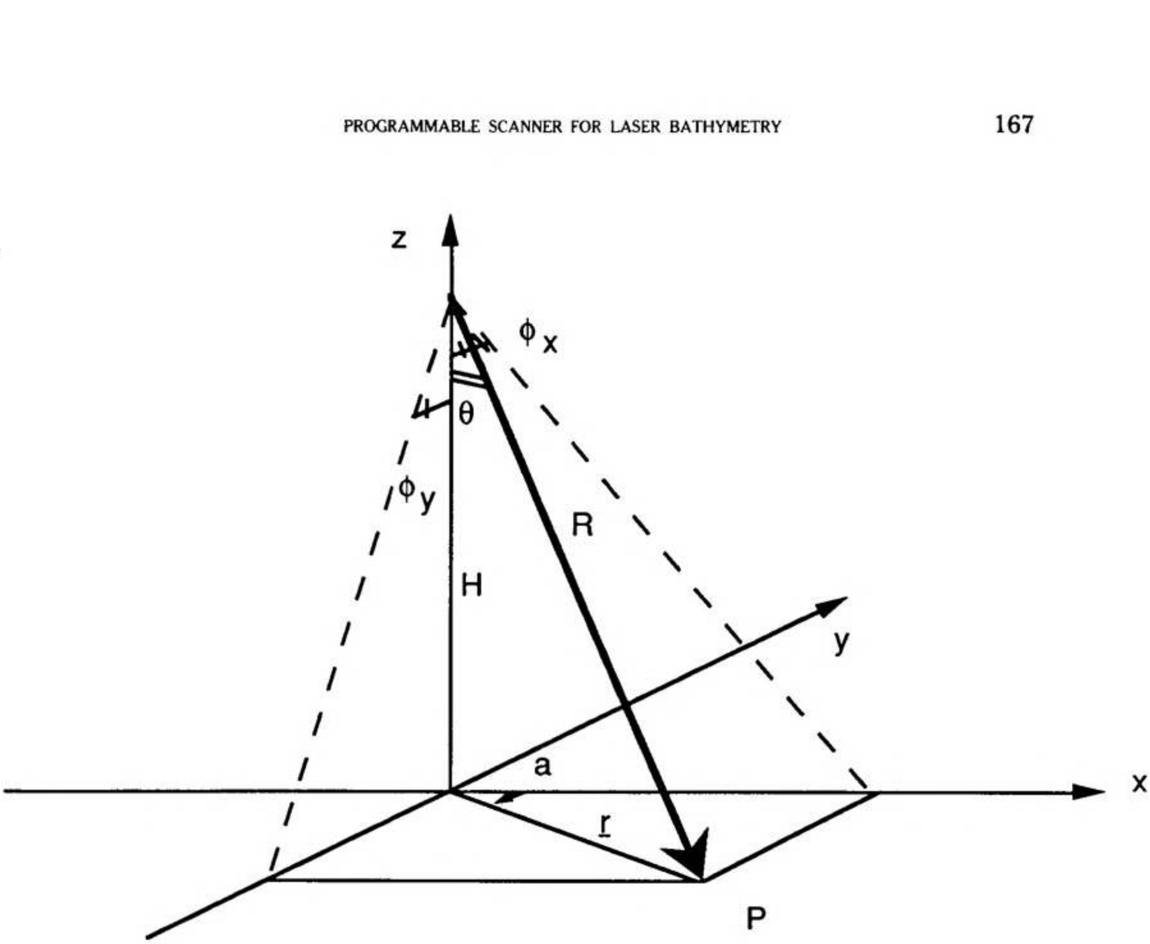


FIG. 3.— Definition of coordinates and scanner angles to determine the error of laser spot position P.

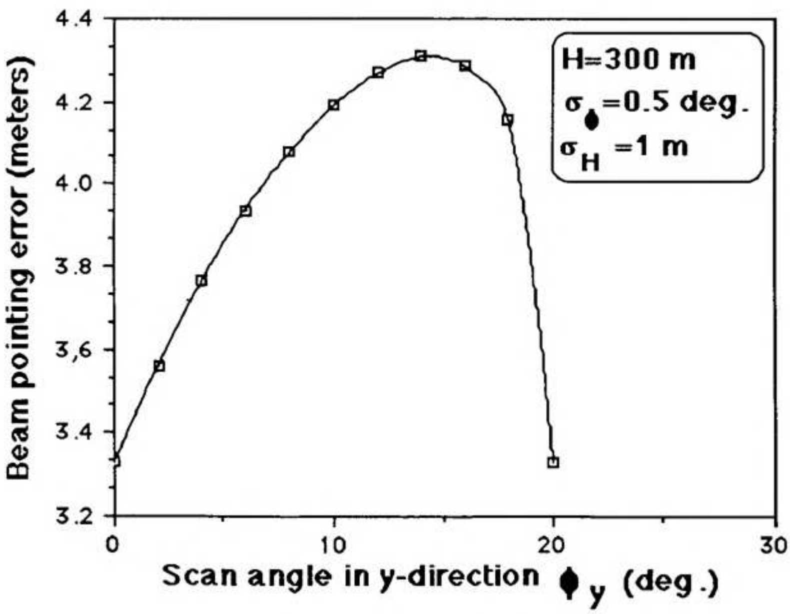


FIG. 4.— Beam pointing error as a function of scan angle ϕ_y for an altitude $H = 300$m, altitude error $\sigma_H = 1$ m and scan angle errors σ_ϕ=0.5 degrees.

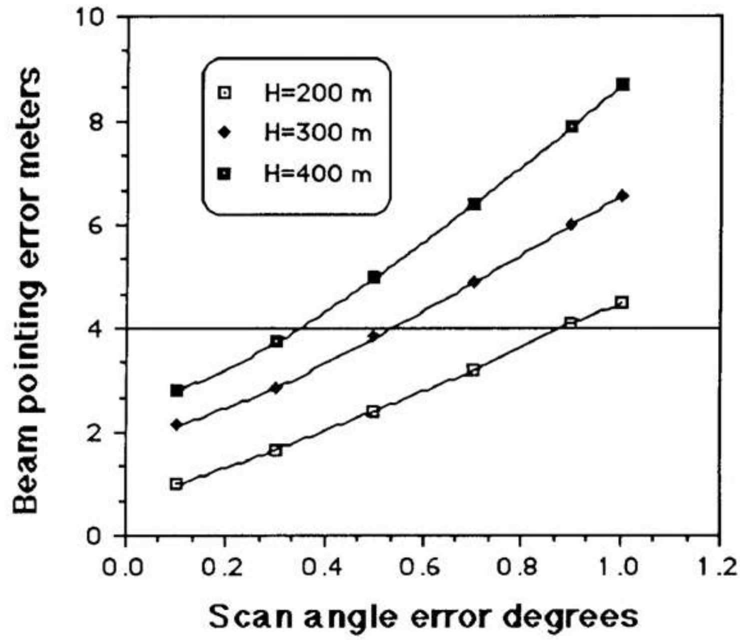


FIG. 5.— Maximum beam pointing error as a function of scan angle errors σ_ϕ. Horizontal line indicates maximum permitted beam pointing error for a platform error of 3 m and an absolute beam position within 5m.

has the disadvantage of oversample close to the edges of the swath (Fig. 6) giving poor efficiency of the system. One way to circumvent this problem is to trigger the laser at certain fixed azimuth angles to distribute the laser spots more uniformly but this is rather complicated. However, for a programmable scanner one can choose a semiarc pattern according to Figure 7. This combines the advantage of a constant beam nadir angle, constant slant range and uniform spot density.

CONCLUSIONS

A scanner capable of generating selectable scan patterns and spot densities offers many advantages for laser bathymetry. Such advantages include uniform spot density maintaining a constant beam nadir angle. Sounding pattern and spot density can be chosen by the operator according to the area of interest. Altogether this increased flexibility compared to a fixed pattern scanner will increase the system accuracy, utility and efficiency.

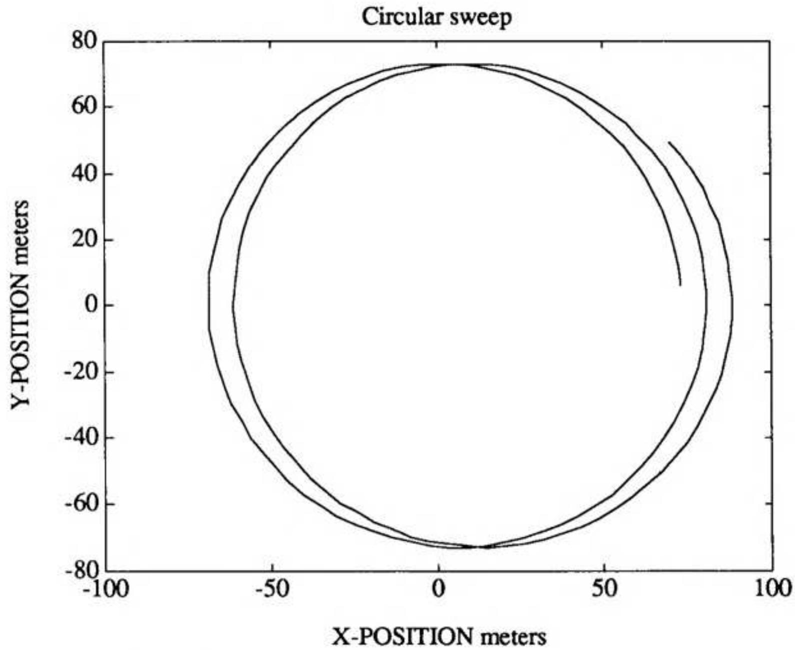


FIG. 6.— Projection of a conical scan pattern on the water surface. Note the oversampling along the edges of the swath.

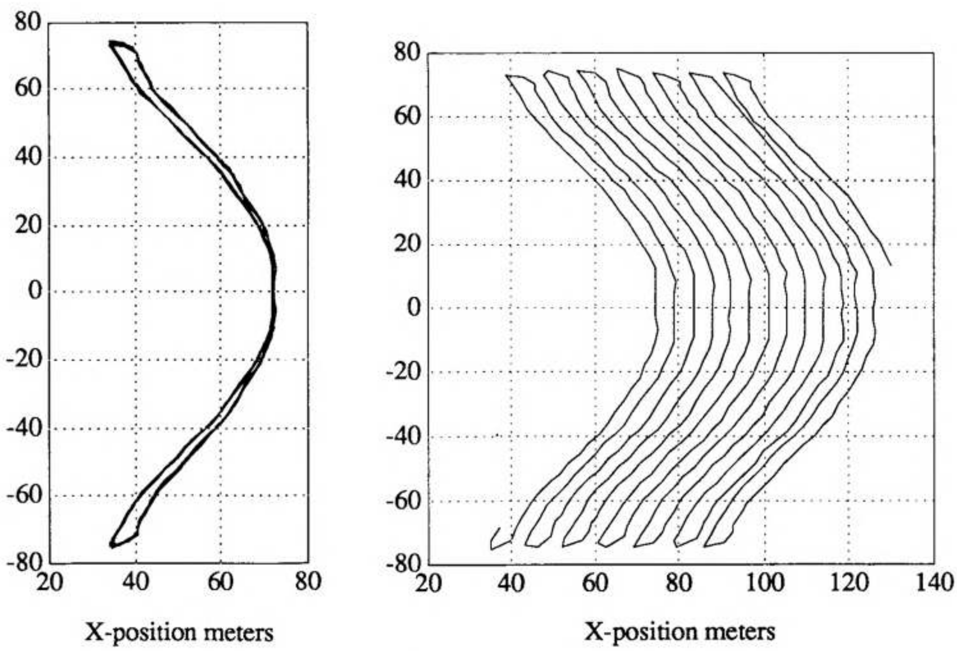


FIG. 7.— Example of scanner pattern generated during field trials. Altitude was 206 meters and swath width was 150 meters. Left, the scanner pattern in the helicopter coordinate system and, right, the pattern generated on the water surface.

References

[1] PENNY et al., (1986): Airborne laser hydrography in Australia. *Applied Optics 25: 2046-2058.* See also other articles by the same group in this issue.

[2] CASEY M.J. and J. VORSBERGH (1986): Chartmaking with Larsen. *The Canadian Surveyor 40:251-260.*

[3] BANIC J., S. SIZGORIC and R. O'NEIL (1986): Scanning lidar bathymeter for water depth measurement. *Proc. of the SPIE meeting on Laser Radar technology and Applications, Quebec City 3-5 June 1986.*

[4] HARRIS M.M., G.D. HICKMAN and R. BOOKER (1986): Development of the Airborne Bathymetric Survey System. *Proc. of the National Ocean Service International Hydrographic Conference, 'Hydro U.S.A.-86', Norfolk, Va., March 25-27* 1986: 50-55.

[5] STEINVALL O., H. KLEVEBRANT, J. LEXANDER and A. WIDEN (1981): Laser Depth Sounding in the Baltic Sea. *Appl. Optics* 20: 3284:85.

[6] GUENTHERG.C. (1984): Effects of propagation induced pulse stretching in airborne laser hydrography. *Proc. of the SPIE meeting on Ocean Optics VII, Monterey June 1984.*