International Journal of Advances in Engineering, 2015, 1(1), 1-6
ISSN: 2394-9260 (printed version); ISSN: 2394-9279 (online version)
url:http://www.venuspublications.com/ijae.html

RESEARCH ARTICLE

High Resolution 3D Imaging Using Innovative Techniques

J.S.PRASATH
Assistant Professor, Electronics and Instrumentation Engineering, Hindustan University, India
jsprasath@gmail.com

Received 05 December 2014 / Accepted 09 January 2015

Abstract: This paper describes the basic principles behind interferometric height estimation and discusses the application of interferometry to synthetic aperture sonar (InSAS). Mapping of the seafloor using traditional sonar is limited to a 2D surface. To provide the third dimension (height), InSAS is formed. We start with a review of bathymetric image reconstruction and looks at sources of phase errors. The problems of echo registration and phase unwrapping are discussed. Synthetic aperture processing provides fine resolution mapping of a target area. Two identical synthetic apertures, from different elevation angles, image the area and the differential phase information contained within these images can be used to map the height. Further we investigate the interferometric imaging problem and various processing such as registration, phase unwrapping, error sensitivity, fringe separation, and image correlation. The image processing algorithms can be outlined in Matlab and the equations to describe the effect of motion errors on interferometry are conversed.

Key words: sonar, image, bathymetry, synthetic aperture

I. INTRODUCTION

The bathymetry of an area is very informative to understand the environment of the observed scene. But the resolution of the illuminated cell depends on the altitude of the surface bottom because the size of the cell is connected to the aperture of the beam [1]. The bathymetry is estimated by a temporal analysis, which measure the go and back time travel of the sound between the sensor and the sea floor. Interferometric processing systems rely on images formed from two separate apertures and is called as one-pass system [2]. It enables small changes in target height to be measured using the phase difference between the echo returns from the target received at two vertically separated receivers. Interferometric synthetic aperture sonar (InSAS) system is capable of making high-resolution 3D images of the seabed. A novel approach to combining the image coregistration and height estimation processes is required. Synthetic aperture (SA) technique provides high along-track resolution imagery, with range independent resolution [3]. Each of the receiver datasets is processed using standard algorithms, with motion compensation and corrective processing, preserving the underlying interferometric time delays. By then estimating the time delay of the incoming wave fronts across the interferometric receiver array, the height of the seafloor can be inferred. The coherence of an InSAS system can be decomposed into five components: additive acoustic noise, footprint misalignment, baseline decorrelation, temporal decorrelation, and processing noise. The importance of maintaining high coherence between the receiver channels is well known; small losses in coherence from the ideal of unity will have a significant impact of the accuracy of the resulting height estimate. To reduce the sensitivity of the height accuracy losses, multiple estimates of the height can be formed from independent looks of the scene. SAS principle is based on increasing the sonar image azimuth resolution by coherent combination of data from successive pings as illustrated in Fig.1. This technique has potential to improve the azimuth resolution by one order of magnitude or more, compared to conventional sonar [4]. To avoid defocus in the sonar images, SAS processing requires a stable slow-moving platform and a highly accurate navigation. The basic principle of interferometry is to use the phase-difference between an incident wave received at two vertically spaced receivers, to estimate a time lag [5]. This time lag can then be related to a path-difference. The specific equations are depended on the type of beamforming. SA to bathymetry measurement uses a standard sonar transducer with a narrow beam width. So the azimuth focusing area is limited inside the main-lobe with a narrow beam width and it is sure that the limited SA could give an effective improvement [6].

II. PULSE COMPRESSION

The SA deals with the acoustic signals of the transducer movements in a few seconds. It follows the inertial navigation system that provides accurate motion measurement sufficient to the process. The SA has advantages of using the standard system as it is and improving the bathymetry resolution [7]. Let $p(t)$ be the waveform used in the system and the band pass signal is

$$p(t) = \Re\{p_e(t)\exp[\ j2\pi f_0 t]\} \tag{1}$$

where $p_e(t)$ is a low-pass complex envelope signal and f_0 designates the carrier frequency.

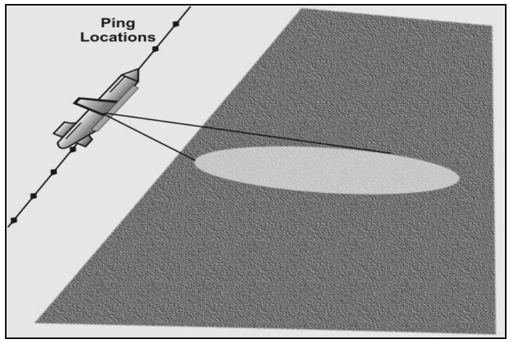

Figure.1 Principle Illustration of SAS

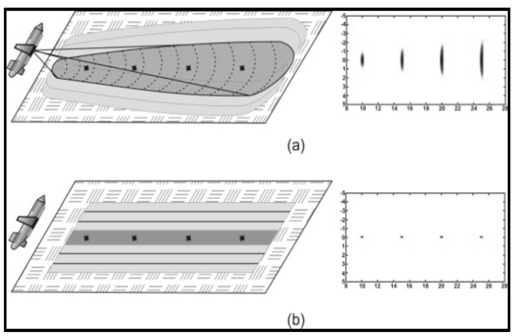

Figure.2 SAS Image a) Raw b) Azimuth compression

Let $S(t, y)$ be the pulse-compressed echo signal, we have

$$S(t, y) = r(t, y) * p_e(t) \tag{2}$$

where $r(t, y)$ is the raw echo signal and * denotes the correlation in time axis. The received band-pass signal is

$$p_r(t) = \Re(p_e(t) exp\{[\ j2\pi v_0 t + \phi]\} \tag{3}$$

where v_0 and ϕ are random variables. We can assume that v_0 is normally distributed with f_0 as mean value and ϕ uniformly distributed in $[-\pi;\pi]$. Bathymetry sonar with interferometry and SA technique proves to be able to make a measurement with a resolution of decimeters. The system assumed here are uses a two simultaneous pulsed, linearly chirped FM signals each of 20 kHz bandwidth, each with center frequencies of 30 kHz and 100 kHz. The returned echoes are received using the hydrophones and stored in baseband form for post-processing. Using standard reconstruction techniques the 2D imaging resolution is approximately 5×15 cm. There are a number of approaches used for estimating seafloor bathymetry with a SAS. In most cases an image is formed using standard phase preserving reconstruction algorithms for each hydrophone. Vertical beamforming can be used to synthesize independent beams with hydrophones, but the angular resolution is poor. The resolution improves with a greater vertical baseline but grating lobe ambiguities occur if the hydrophones are more than half a wavelength apart. In practice, the maximum vertical baseline and the number of hydrophones are limited by the size of the towfish. A better angular precision can be achieved using an interferometer configuration. This assumes that only a single echo wave is incident upon the hydrophones in any given range gate. The time difference of the echoes received by the hydrophones, or equivalently the carrier phase of the complex baseband signals, can be measured and used to estimate the incoming direction of arrival [8]. Provided there is only a single dominant echo signal in each range gate, the accuracy of this method depends on the coherence between the two-hydrophone signals. The coherence between echoes measured by interferometric sonar is limited by noise, baseline decorrelation, and the footprint shift effect. Baseline decorrelation is due to coherent interference between multiple scatterers within the sonar footprint while the footprint shift results in an interferogram formed from different sections of the seafloor. While baseline decorrelation and the footprint shift effect are both geometry dependent, the footprint shift effect dominates for broadband sonars in a shallow water environment. The greater the bandwidth, the smaller the range resolution, the greater the misregistration, and thus the poorer the coherence. The baseline decorrelation is smaller for an InSAS due to the use of small vertical baselines and broadband signals. Filtering the non-overlapping parts of the two echo spectra provided the seafloor height can be estimated can compensate it [9]. The azimuth resolution of a sonar can be computed as the ratio between the acoustic wavelength and the length of the array. For typical sonar, this ratio is of the order 1:60-1:400 (meaning a resolution of 1 m at 60 and 400 m range, respectively). A longer array will increase this ratio, but fitting such a long array is not always possible or practical on most underwater vehicles. Operation at a higher frequency will increase the ratio, but will at the same time limit the achievable range due to higher absorption. The SAS principle overcomes these limitations by utilizing data from several consecutive pings to synthesize a longer sonar array. A fundamental limitation of SAS systems is that the platform cannot travel further than half the length of the receive array per ping interval [10]. For SAS systems, the maximum range is proportional to the receive array length, and inversely proportional to the platform speed. The theoretical azimuth resolution in SAS is half the length of each element in the receive array, at all ranges. In general, this resolution is not practically achievable, and the practical resolution will be 1.5 – 2 times lower. The range resolution is, as in regular sonars, a function of the bandwidth and Fig.2 shows the compression technique. InSAS provides a means of obtaining high resolution 3D images of targets on the sea floor. The method described combines interferometric height estimation and image coregistration into one iterative process. Two complex images of the target scene are formed, one using the upper and one using the lower receiver array. Assuming the two images are perfectly co-registered, the height of the target scene can be estimated from the phase difference between corresponding pixels in the two sonar images. The phase difference between the two images will initially have ambiguity and is removed using 2D phase unwrapping before height estimation [11]. A number of techniques for 2D phase unwrapping exist. SA images are formed by the appropriate summation of many sonar returns received at different locations using a receiver with a broad beam-width. This process is often referred to as azimuth compression, focusing or inversion. Initially, the scene height is not known, an estimate must be used in the initial image coregistration. Interpolation must be used to perform this co-ordinate transform; Fourier based interpolation is used in this work but other methods may be equally suitable.

Table I Comparison of In SAS and In SAR

Parameter	Symbol	Units	SAS	SAR
Wavelength	λ	m	0.05/0.015	7.5
Centre Frequency	fc	Hz	$30/100 \times 10^3$	40×10^6
Bandwidth	BW	Hz	20×10^3	20×10^6
Propagation Speed	c	m/s	1500	3×10^8
Altitude	-	-	5	1500 - 4500
Imaging Distance	H	m	15-200	7500
Resolution	-	m	0.05 x 0.15	8 x 8
Along Track Speed	v	m	1	100
Critical Baseline	B_c	m	-	-
Quality Factor	Q	.	1.5/5	2

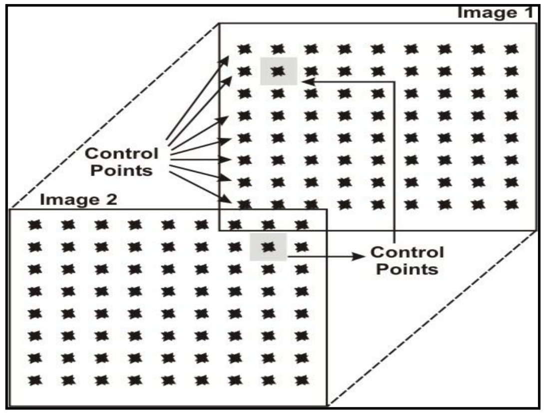

Figure.3 Conceptual view of Image Registration

Detailed seabed mapping plays an important role in a number of different areas such as offshore exploration, environmental surveillance and military applications [12]. This technique requires a strict coregistration of the images. In addition, 2π phase ambiguities have to be resolved. Table I compares the InSAS and its equivalent Radar.

III. IMAGE RECONSTRUCTION

The height of objects is identified from the phase difference between two SA images of the seabed obtained using two arrays separated by a short distance. A central problem is the need to unwrap the phase difference in the presence of noise to obtain an unambiguous height estimate [13]. The susceptibility of this image to reverberation-type noise is evaluated, and the effectiveness of different forms of phase unwrapping algorithms are compared. For a practical InSAS system a large set of parameters need to be chosen for the system design. Many of these parameters are governed either by desired imaging performance, or by practical construction limitations, often in conflict with each other. For the design discussion presented here, the practical considerations of constructing the platform are largely ignored, and an ideal sonar platform considered. The term resolution refers to the resolving power of the system, the minimum distance between two points in the scene able to be separated [14]. The height estimation precision is defined as the error between the estimate and the true value for a single point of the image. The implication of poor vertical resolution is the need for an assumption of only one point of reflection within each resolution cell, allowing only one angle-of-arrival at the receiver array to be estimated. If there is more than one angle-of-arrival from within a single resolution cell, this assumption is violated. Multiple angles-of-arrival can occur in situations of layover, or multipath reflections from the sea-surface. Some attempts to estimate multiple angles-of-arrival have been made using super-resolution techniques. The across-track resolution is independent of frequency, determined solely by the signal bandwidth. However, practical limits exist on the frequency spectrum able to be used since absorption in water increases with frequency. Here it is also assumed the imaging is performed on a plane horizontal to the sonar platform such that the ground plane resolution is equal to the slant plane resolution. This is a reasonable approximation for the angles of imaging typical in a shallow water environment. Often, this is not the case in a real system because of noise in the acoustic channel, and distortion from the sonar transmitter and hydrophone arrays. Also, a spectral window is often applied to reduce the sidelobe height of the matched filtering, with an effect of lowering the effective bandwidth of the system. Therefore, to obtain a desired resolution a greater bandwidth than the theoretical limit is often required. As part of the height estimation process, it is desirable to have several independent looks of the same scene and Fig.3 shows the typical image registration process. One technique to generate these multiple looks is to separate the available bandwidth into smaller subbands. These sub-bands are assumed to be equally sized, non-overlapping functions in the frequency domain, such that each sub-band is independent and the entire original bandwidth is used. The number of along-track samples, combined in the SA processing algorithm, determines the along-track resolution of a strip-map SAS system. As more along-track samples are combined, the resolution is improved. The coherent summation along the SA can only be performed within the extent of the composite along-track beam-pattern of both the transmitter and receiver elements of the sonar. Fig.4 shows the processing flow. Like the across-track resolution, this theoretical limit is never achieved from a real world system, requiring perfect sampling with almost nil platform positional errors for the entire length of the synthetic aperture. Practically, some allowance must be made for resolution loss from a real-world SAS system. Multiple looks can also be generated for the height estimation by considering along track neighboring resolution cells from the reconstructed image. By assuming there is only a small change in the scene for neighboring reconstructed pixels, these may be considered independent looks of the scene. The along-track sampling requirement of a SAS system refers to the along-track distance traveled by each hydrophone between pings. For a single along-track receiver system, this requirement is equivalent to the distance traveled by the entire platform. The along-track sample spacing is normally expressed as a fraction of the largest along track element size. For the present work, we consider a system with a transmitter with an along-track dimension of 0.2 m, and a single along-track receiver with an along-track dimension of 0.1m.

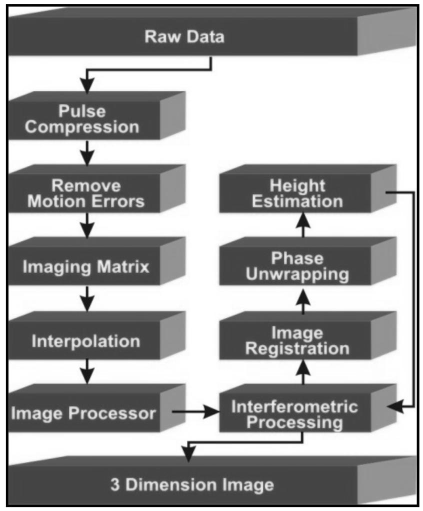

Figure.4 SAS Processing Flow

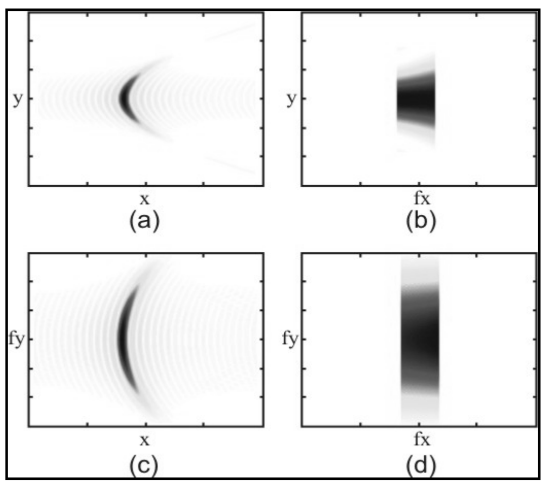

Figure.5 Point Target in a Processing Domain
a) Spatial b) Temporal c) Range Doppler d) Wave Number

For a forward velocity giving a movement of 0.1m between pings, the along-track sampling is referred to as D/2. With a single hydrophone system, the sample spacing can be controlled by altering the pulse repetition frequency (PRF) of the sonar and/or the forward velocity of the platform. For a multiple receiver array based SAS system, the normal mode of operation is for the platform to move forward a distance equal to half the total array length between pings. The resulting receiver positions are therefore fixed in separation, and cannot be controlled by simply altering the speed of the platform. This also implies the along-track sampling ratio is also fixed, determined solely by the size of the transmitter and receiver elements. The along-track sampling ratio for a multiple along-track receiver SAS system is therefore determined solely by the transmitter and receiver element sizes. Fig.5 shows the typical results of various processing domains.

ACKNOWLEDGMENT

We are grateful to Prof.P.Sathyanarayanan, The Vice Chancellor of SRM University for providing the necessary facilities for the stimulating research environment. We received a lot of invaluable guidance and continual encouragement from Dr. T.P.Ganesan, originally Professor of the IIT Madras, India and currently The Pro Vice Chancellor of SRM University, who provided us the initial desire, interest and basic ideas on engineering projects. We extend our thanks to Dr. P.Chandramohan, Former Scientist and Head, National Institute of Oceanography – NIO, India. We thank to Mr.G.Vivek, Scientist of Corporate Research center, ABB Limited, India for his valuable comments on the present work.

REFERENCES

[1] Curlander, J. C. and McDonough, R. N. (1991). Synthetic Aperture Radar: systems and signal processing. John Wiley & Sons, Inc.

[2] Ghiglia, D. C. and Wahl, D. E. (1994). Interferometric synthetic aperture radar terrain elevation mapping from multiple observations. In Digital Signal Processing Workshop, pages 33–36. IEEE

[3] Prati, C., Rocca, F., Guarnieri, A. M., and Damonti, E. (1990). Seismic migration for SAR focusing: Interferometrical applications. IEEE Trans. Geosci. Remote Sensing, 28(4):627–640.

[4] Rolt, K. D. and Schmidt, H. (1992). Azimuthal ambiguities in synthetic aperture sonar and synthetic aperture radar imagery. IEEE J. Oceanic Eng., 17(1):73–79.

[5] Rosen, P. A., Hensley, S., Joughin, I. R., Li, F. K., Madsen, S. N., Rodr´ıguez, E., and Goldstein, R. M. (2000). Synthetic aperture radar interferometry. Proc. IEEE, 88(3):333–382.

[6] Rodriguez, E. and Martin, J. M. (1992). Theory and design of interferometric synthetic aperture radars. Radar and Signal Processing, IEE Proceedings of, 139(2):147–159.

[7] Bellettini, A. and Pinto, M. A. (2002). Theoretical accuracy of synthetic aperture sonar micronavigation using a displaced phase-center antenna. IEEE J. Oceanic Eng., 27(4):780–789.

[8] Runge, H. and Bamler, R. (1992). A novel high precision SAR focussing algorithm based on chirp scaling. In Geoscience and Remote Sensing Symposium, pages 372–375.

[9] Reed, S., Petillot, Y., and Bell, J. (2004). Automated approach to classification of mine-like objects in sidescan sonar using highlight and shadow information. IEE Proc.-Radar Sonar Navig., 151(1):48–56.

[10] Lurton, X. (2000). Swath bathymetry using phase difference: Theoretical analysis of acoustical measurement precision. IEEE J. Oceanic Engineering, 25(3):351–363.

[11] Barber, B. C. (1985). Theory of digital imaging from orbital synthetic aperture data. International Journal of Remote Sensing, 6(7):1009–1057.

[12] Jin, G. and Tang, D. (1996). Uncertainties of differential phase estimation associated with interferometric sonars. IEEE J. Oceanic Engineering, 21(1):53–63.

[13] Massonnet, D., Vadon, H., and Rossi, M. (1996). Reduction of the need for phase unwrapping in radar interferometry. IEEE Trans. Geosci. Remote Sensing, 34(2):489–497.

[14] Migliaccio, M. and Bruno, F. (2003). A new interpolation kernel for SAR interferometric registration. IEEE Trans. Geoscience and Remote Sensing, 41(5):1105–1110.