



NURC

a NATO Research Centre
un Centre de Recherche de l'OTAN



PARTNERING
FOR MARITIME
INNOVATION

Reprint Series

NURC-PR-2010-001

High resolution sonar (tutorial slides)

Marc Pinto

July 2010

Originally presented as a tutorial at:

OCEANS'10 IEEE Sidney, Australia, 24-27 May, 2010

About NURC

Our vision

- To conduct maritime research and develop products in support of NATO's maritime operational and transformational requirements.
- To be the first port of call for NATO's maritime research needs through our own expertise, particularly in the undersea domain, and that of our many partners in research and technology.

One of three research and technology organisations in NATO, NURC conducts maritime research in support of NATO's operational and transformation requirements. Reporting to the Supreme Allied Commander, Transformation and under the guidance of the NATO Conference of National Armaments Directors and the NATO Military Committee, our focus is on the undersea domain and on solutions to maritime security problems.

The Scientific Committee of National Representatives, membership of which is open to all NATO nations, provides scientific guidance to NURC and the Supreme Allied Commander Transformation.

NURC is funded through NATO common funds and respond explicitly to NATO's common requirements. Our plans and operations are extensively and regularly reviewed by outside bodies including peer review of the science and technology, independent national expert oversight, review of proposed deliverables by military user authorities, and independent business process certification.



Copyright © NURC 2010. NATO member nations have unlimited rights to use, modify, reproduce, release, perform, display or disclose these materials, and to authorize others to do so for government purposes. Any reproductions marked with this legend must also reproduce these markings. All other rights and uses except those permitted by copyright law are reserved by the copyright owner.

NOTE: The NURC Reprint series reprints papers and articles published by NURC authors in the open literature as an effort to widely disseminate NURC products. Users should cite the original article where possible.

Special Topic on Advances in Underwater Imaging and Mapping Dr Marc Pinto

Editorial Note:

This reprint is a compilation of the slides presented at the OCEANS'10 tutorial of the same title above.

Summary of the tutorial

The OCEANS '10 IEEE Sydney Conference and Exhibition theme is 'Showcasing advances in marine science and engineering'. Consistent with this theme is the Special Topic on 'Advances in Underwater Imaging and Mapping', which is led by Dr Marc Pinto of the NATO research laboratory NURC located in La Spezia, Italy.

Marc is an international expert in active synthetic aperture sonar, which is a powerful acoustic imaging technique that coherently combines echoes from multiple pings along the sonar trajectory of a survey vehicle that effectively synthesizes a long virtual sonar aperture for the formation of range-independent high resolution sonar images. The image formation requires aligning the echoes to within one millimetre, which is possible through recent advances in sonar transducer technology, precise navigation sensors, spatial filtering and autofocusing algorithms, and stable underwater vehicles. The practical realization of synthetic aperture sonar is a most significant advance in ocean systems engineering in recent times. Synthetic aperture sonar images provide enhanced shadow contrast of objects and multiple aspect views of the same object which, in turn, enhances classification performance. Modern wideband synthetic aperture sonar systems can provide centimetric resolution with an area coverage rate of over a square kilometre per hour.

At OCEANS '10 Sydney on Monday 24th May 2010, Marc will be presenting a half-day tutorial in the morning on the principles and practice of high resolution sonar imaging using real and synthetic apertures.

About the presenter

Marc Pinto was born in Wellington, India in 1960. He graduated from the Ecole Nationale des Ponts et Chaussées, Paris (France) in 1983. From 1985 to 1989 and 1989 to 1993 he worked as a research engineer for Thomson-CSF, specializing in the development of finite element techniques for solving non-linear magnetostatics to support the modeling of the magnetic recording process. In 1991, he received the Ph.D. degree in Solid State Physics from the University of Paris, Orsay. In 1993 he joined Thomson-Sintra ASM (now Thales Underwater Systems) as Head of the Signal Processing Group, specializing in research into advanced MCM and airborne ASW sonar.

Dr Pinto joined the NATO Undersea Research Centre, La Spezia, Italy in 1997 as principal scientist. He was appointed Head of the Mine Countermeasures Group, in the Signal and Systems Division in 1998 and held this position until the Group was dissolved in 2000. From 2000 to 2004, as project leader, he conducted research into synthetic aperture sonar systems for hunting proud and buried mines. In 2004 he was appointed Head of the Expeditionary MCM and Port Protection Department where he presently oversees the research into AUV-based minehunting, electronic mine countermeasures and harbour defence.



NATO
+
OTAN

NURC - Partnering for Maritime Innovation



NURC

High resolution Sonar

Marc Pinto
NATO UNDERSEA RESEARCH CENTRE



Overview



NURC

- I. Basic principles of aperture and array design
- II. Pulse compression in seafloor imaging sonar
- III. Bathymetric sonar
- IV. Impact of the shallow water environment on sonar
- V. Future trends

Tutorial presented at Oceans'10 © NURC



Basic principles of aperture



➤ Today's technology offers very high range resolution using wideband pulses:

$$RR = \frac{c}{2B}$$

➤ High cross-range resolution (CRR) is always difficult to obtain:

$$CRR = \frac{\lambda}{L} \rho$$

- Sound absorption set the limit on minimum λ .
- Platform size sets the limit on maximum L.
- CRR degrades with range
- Synthetic aperture sonar increases the options for the sonar designer.

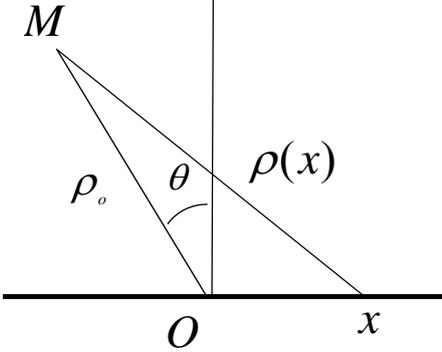
Tutorial presented at Oceans'10 © NURC



Near and far fields



$$\rho(x) = \rho_o + x \sin \theta + \frac{x^2}{2 \rho_o \cos^2 \theta} + \dots$$

$$u = \sin \theta$$


Tutorial presented at Oceans'10 © NURC



Near and far fields (II)



$$\rho(x) = \rho_o + x \sin \theta + \frac{x^2}{2 \rho_o \cos^2 \theta} + o\left(\frac{x^2}{\rho_o}\right) \dots$$

- Quadratic term \ll wavelength defines far field (or Fraunhofer zone)

$$\rho_o \geq \rho_f = \frac{L^2}{\lambda}$$

- Defines Fresnel distance which separates Fraunhofer and Fresnel zones.
- Planar wavefront in far field, curved in near-field.

Tutorial presented at Oceans'10 © NURC



Far field resolution



The far field resolution is

$$CRR = \frac{\lambda}{L} \rho$$

- Far field can be understood as

$$\frac{\lambda}{L} \rho \geq L \Leftrightarrow \rho \geq \frac{L^2}{\lambda}$$

Tutorial presented at Oceans'10 © NURC



Single transducer sonar



- The highest resolution is obtained at the Fresnel distance and is of the order of $L/4$.
- Correct sampling of the sea bottom requires

$$\nu T = 2\nu \frac{R_{\max}}{c} \leq CRR \approx \frac{L}{4}$$

- Tradeoff between area coverage rate (ACR) and resolution for a single transducer sonar
- For given ACR, better reduce far range than speed as this allows higher frequency and maximum Fresnel distance.
- Multi-pulse techniques can increase speed.

Tutorial presented at Oceans'10 © NURC



Multi-element sonar arrays



- An array is a sampled aperture of N elements spaced at d .
- The array exhibits grating lobes at λ/d which have to be placed outside the transmission sector.
- The ACR is defined by the effective length of the transmitter and the resolution by that of the receiver.
- Digital correction of near field quadratic phase variation (focusing) is possible

$$\rho(x) = \rho_o + x \sin \theta + \frac{x^2}{2 \rho_o \cos^2 \theta} + \dots$$

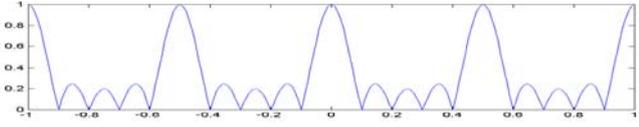
Tutorial presented at Oceans'10 © NURC



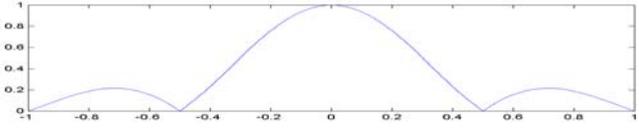
Pattern multiplication



Array factor



Tx Rx (element)



$$\frac{\sin(Nu)}{N \sin(u)} \cdot \frac{\sin(u)}{u} = \frac{\sin(Nu)}{Nu}$$

$$u = \frac{4\pi}{\lambda} D \sin \theta = \frac{2\pi}{\lambda} L \sin \theta$$

Tutorial presented at Oceans'10 © NURC



Multi-element sonar arrays



- The CRR cannot be improved over

$$CRR = \frac{\lambda}{L} \rho$$

- CRR better than L requires near field operation
- Most high resolution sonar arrays operate in near field with focused apertures

Tutorial presented at Oceans'10 © NURC

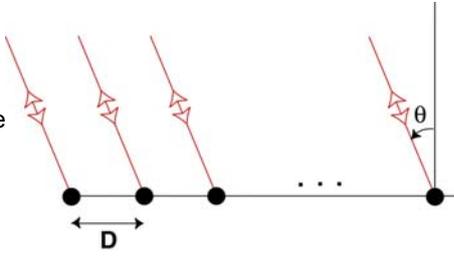


Example of far field array processing



- Virtual array obtained by displacing a single transmit/receive element
- In far field the element-to-element phase shift is

$$\Delta\phi = \frac{4\pi}{\lambda} D \sin \theta$$



The diagram shows a horizontal line representing an array of elements. Four red arrows point downwards from the elements, representing phase shifts. The distance between the first and last element is labeled 'D'. An angle 'θ' is shown between the vertical axis and the direction of the phase shift arrows.

- Beamforming is summation after compensating travel times difference.

$$I(u) = \left| \sum_{m=0}^{M-1} \exp\left(\frac{4\pi}{\lambda} mdu\right) X \right|^2$$

$$u = \sin \theta$$

Tutorial presented at Oceans'10 © NURC



Far field beamforming



$$I(l) = \left| \sum_{m=0}^{M-1} \exp\left(\frac{ml}{K}\right) X(m) \right|^2$$

$$x = m \frac{d}{\lambda}; u = l \frac{\lambda}{Md}$$

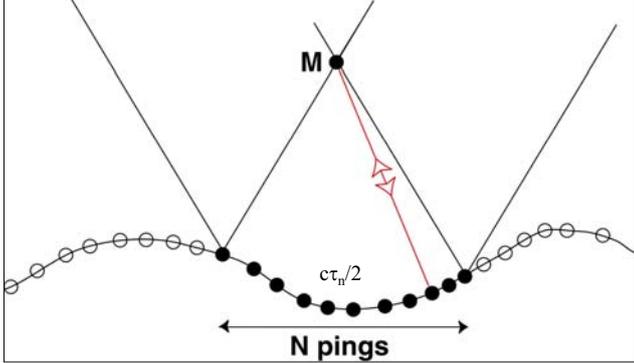
- Efficient far field beamforming can be done by spatial FFT in the narrowband case
- In the wideband case, spatial FFT can be done after a temporal FFT, provided the (frequency-dependent) beam directions are re-interpolated.
- SVP error leads only to image rotation not defocus.

Tutorial presented at Oceans'10 © NURC



Example of near field array processing





- Compute two-way travel times τ_n to M for all N pings in the array
- Temporal interpolation of the sonar returns and coherent summation:

$$I(M) = \left| \sum_{n=1}^N X_n(\tau_n) \right|^2$$

Tutorial presented at Oceans'10 © NURC



Dynamic focusing



- Focusing is needed only in near-field and consists in advancing the phase by

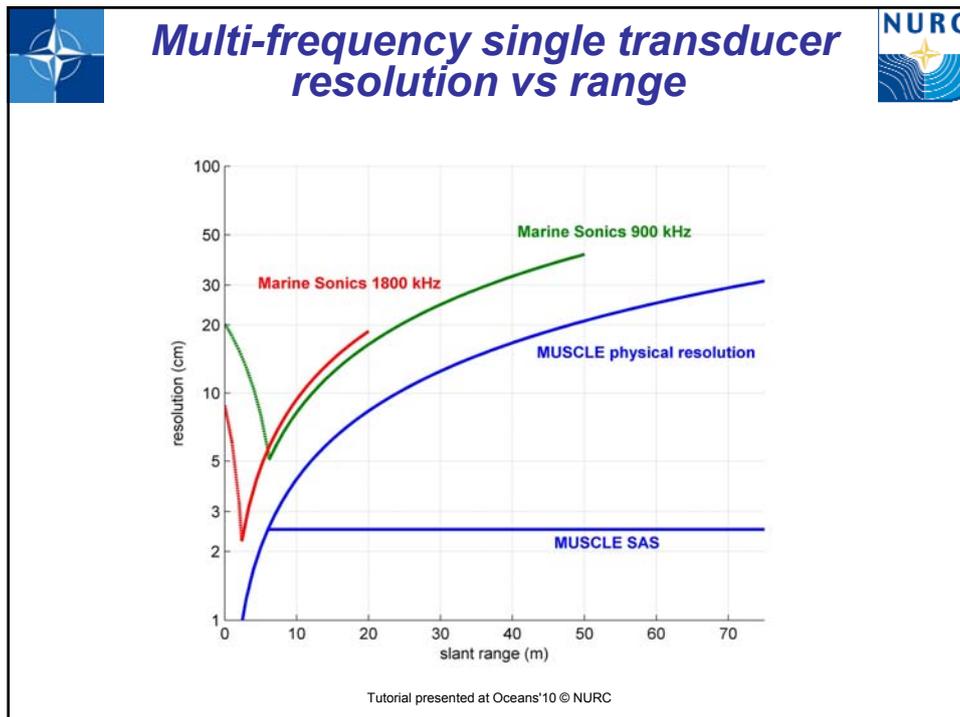
$$\frac{2\pi}{\lambda} \frac{x^2}{2\rho_o \cos^2 \theta} \approx \frac{2\pi}{\lambda} \frac{x^2}{2\rho_o}$$

- This phase correction is range-dependent hence the terminology of dynamic focusing
- Depth of field is the range window for which a constant focus can be used and can be shown to be

$$7\lambda f^2; f = \rho / L$$

- SVP error can lead to defocus.

Tutorial presented at Oceans'10 © NURC



Pulse compression

- For a short CW pulse one has to compromise between transmitted energy PT and range resolution $cT/2$.
 - High resolution \rightarrow short T
 - High energy \rightarrow long T
$$BT \approx 1$$
- Modulated pulses (e.g. chirp) allows decoupling of energy PT and range resolution.
 - High resolution \rightarrow Wideband B
 - High energy \rightarrow long T
$$BT \gg 1$$

Tutorial presented at Oceans'10 © NURC



Understanding pulse compression



- Propagation and scattering are linear (*time-invariant*) filters thus, before matched filtering the echo spectrum is

$$Y(f) = P(f)X(f)$$

- After matched filtering

$$X^*(f)P(f)X(f) = |X(f)|^2 P(f)$$

- Effective short pulse of length 1/B and power increased by BT.
- Sidelobes, temporal coherence can be an issue for large BT.

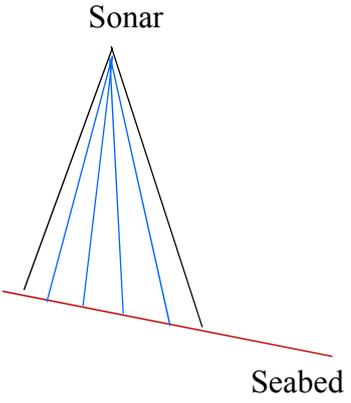
Tutorial presented at Oceans'10 © NURC



II. Bathymetric sonar



- Single-beam echo sounder = “acoustic plumb line”
- A narrow beam is projected towards the seabed and the *average* time of arrival of the seabed echo is measured.
- Down-looking geometry most common (vertical incidence).
- From this average TOA the altitude of the sonar is computed, correcting for SVP.



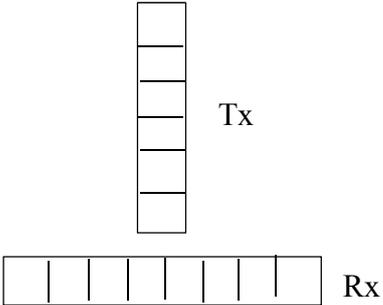
Tutorial presented at Oceans'10 © NURC



Multi-beam bathymetry



- Historically, only the extension to the case of multiple independent single-beam echo sounders steered away from vertical incidence.
- Mills cross design
 - Across-track down-looking receiver array
 - Along-track transmitter
- However split-beam interferometric techniques provide greater accuracy off-nadir!

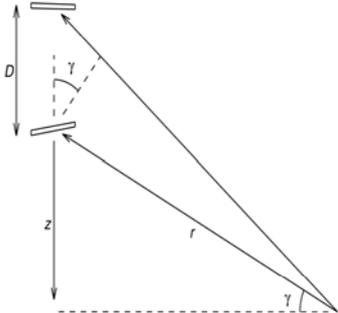


Tutorial presented at Oceans'10 © NURC



Interferometric sonar





- Two vertically superposed linear arrays separated by a baseline d .
- High accuracy bathymetry based on angle of arrival estimation
- Time delay estimation using wideband signals and long baselines d .
- Baseline decorrelation is the key physical effect.

Tutorial presented at Oceans'10 © NURC



Van-Cittert Zernicke theorem



➤ Fundamental theorem of statistical optics which relates correlation of seabed echoes at at interferometric bases A and B

$$\langle I_A I_B^* \rangle$$

to scatterer density within corresponding seabed resolution cell.

➤ The resolution cell acts like a secondary antenna re-radiating correlation.

Tutorial presented at Oceans'10 © NURC



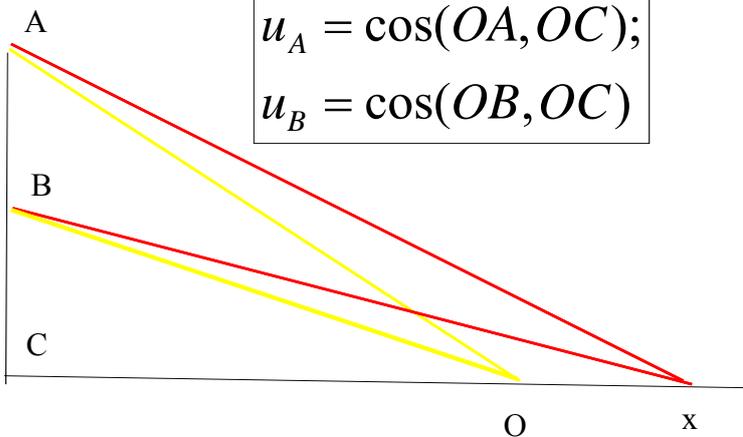
Geometry



$$\rho_A = OA; \rho_B = OB$$

$$u_A = \cos(OA, OC);$$

$$u_B = \cos(OB, OC)$$



Tutorial presented at Oceans'10 © NURC




$$I_A = \int_{-\Delta x/2}^{\Delta x/2} \exp(jk(\rho_A + xu_A)) \zeta(x) dx$$

$$\langle I_A I_B^* \rangle =$$

$$\exp(jk(\Delta\rho)) \int_{-\Delta x/2}^{\Delta x/2} \exp(jk\Delta ux) \sigma(x) dx$$

Tutorial presented at Oceans'10 © NURC



Uniform reverberation case



$$\sigma(x) = Cst.$$

$$\mu = \sin c(k\Delta u\Delta x);$$

$$\Delta\rho \approx D \sin \gamma; \Delta u = O\left(\frac{D}{\rho}\right)$$

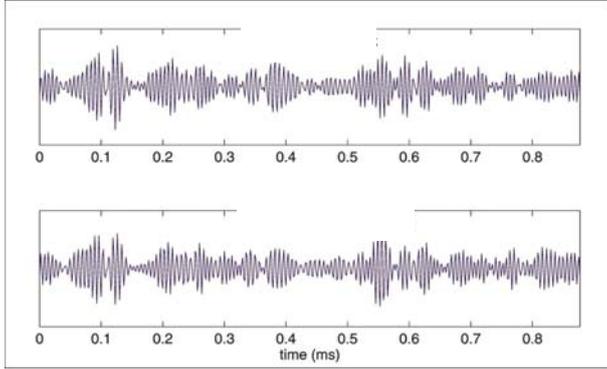
Tutorial presented at Oceans'10 © NURC



Waveform invariance



- Example of short-term top and bottom reverberation signals with low baseline decorrelation



Tutorial presented at Oceans'10 © NURC



Time delay estimation (baseband data)

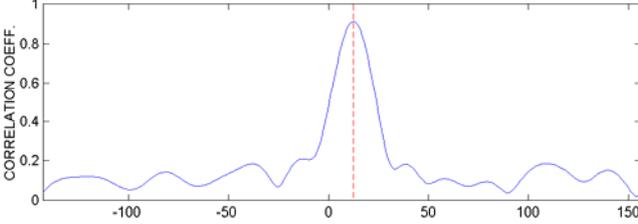


“coarse” TDE for:

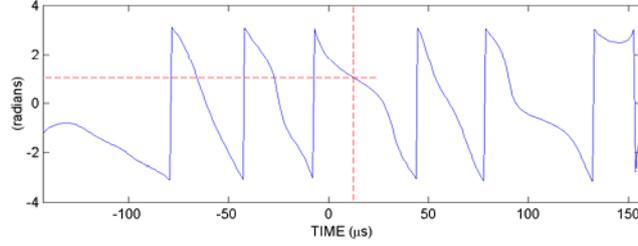
- phase estimation
- phase unwrap

“fine” TDE =
unwrapped phase

COMPLEX CROSS-CORRELATION ENVELOPE



PHASE



Tutorial presented at Oceans'10 © NURC



CRLB on time delay estimate



$$\sigma_{\tau} = \frac{1}{2\pi f_0} \frac{1}{\sqrt{BW}} \sqrt{\frac{1-\mu^2}{2\mu^2}}$$

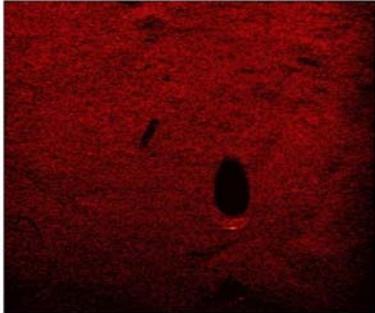
- where B is bandwidth,
- W is correlation window length
- μ is correlation coefficient, which depends on distribution of scatterers in the sonar resolution cell and the baseline d.

Tutorial presented at Oceans'10 © NURC



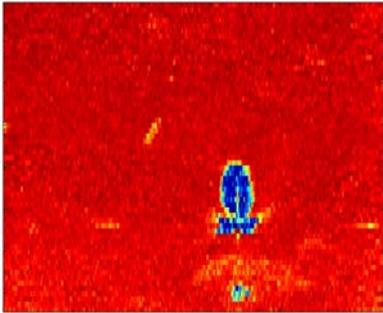
SAS image & coherence map





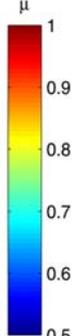
ACROSS TRACK (m)

ALONG TRACK (m)



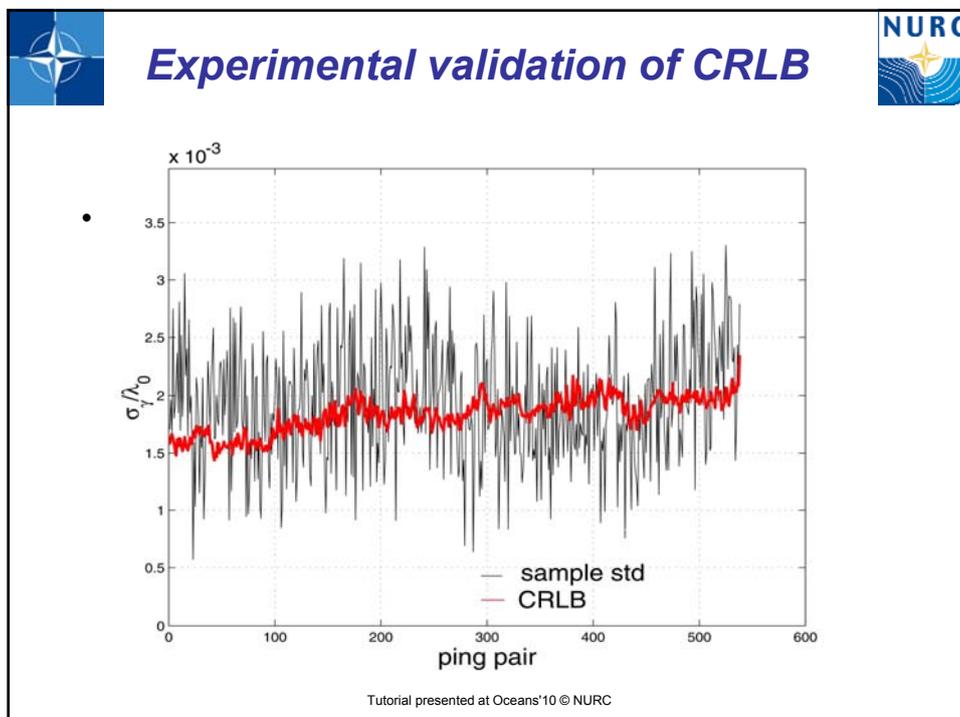
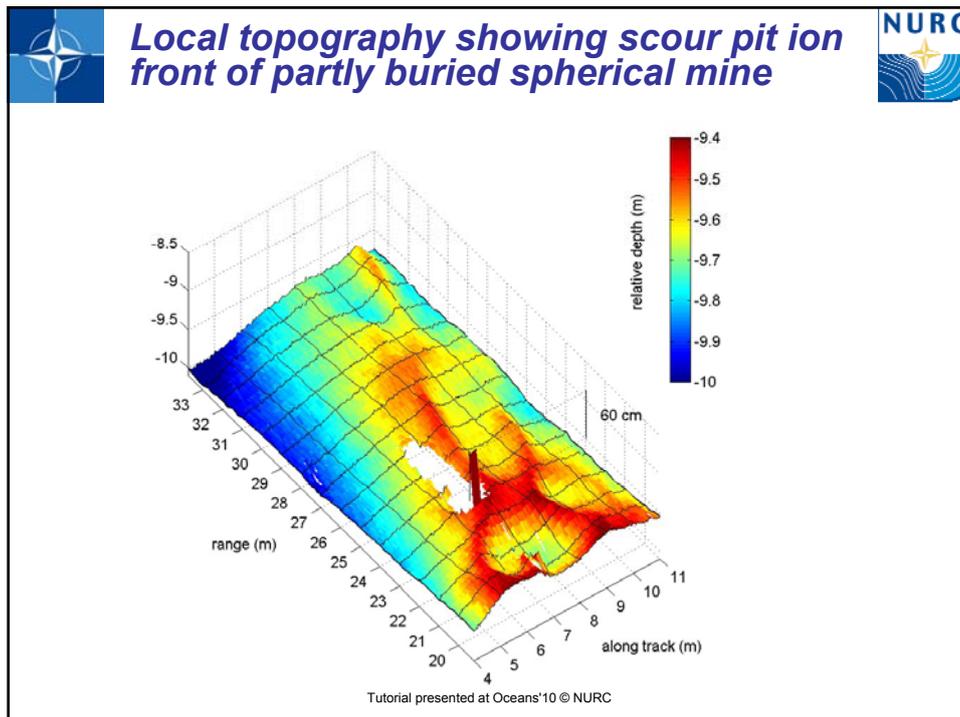
ACROSS TRACK (m)

ALONG TRACK (m)



μ

Tutorial presented at Oceans'10 © NURC





Effect of multipath



- Multipath has been found experimentally to be a major factor degrading seafloor imaging in shallow water.
- Multipath has negative impact on
 - Image contrast (shadow filling)
 - Interferometry performance
 - Target structure (ghosts)

Tutorial presented at Oceans'10 © NURC



Multipath experiment





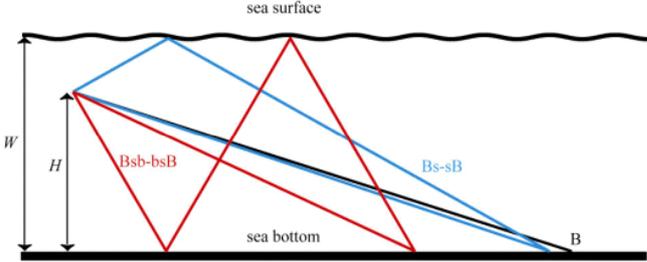
- 100 kHz array mounted vertically at 10.7 m depth in 20 m water depth
- 64 channel programmable transmitter array of length 48 cm
- 256 channel receiver array of length 192 cm.
- Bottom type: flat bottom of hard mud (Cinque Terre, Italy)
- Calm sea states

Tutorial presented at Oceans'10 © NURC



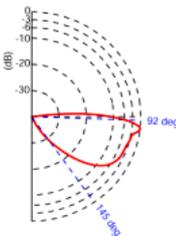
Multipath structure

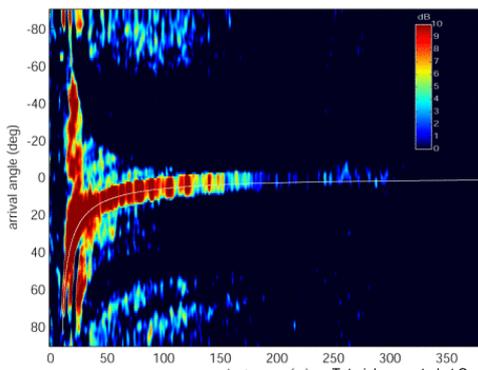




- Figure shows multipath interference of first order (B_s, sB) and second order (B_{sb}, bsB) arriving at the receiver at the same time as the direct path B .
- SW sonar performance can be expressed as a function of a generalised SNR, giving the ratio of the direct path B to multipath and noise.

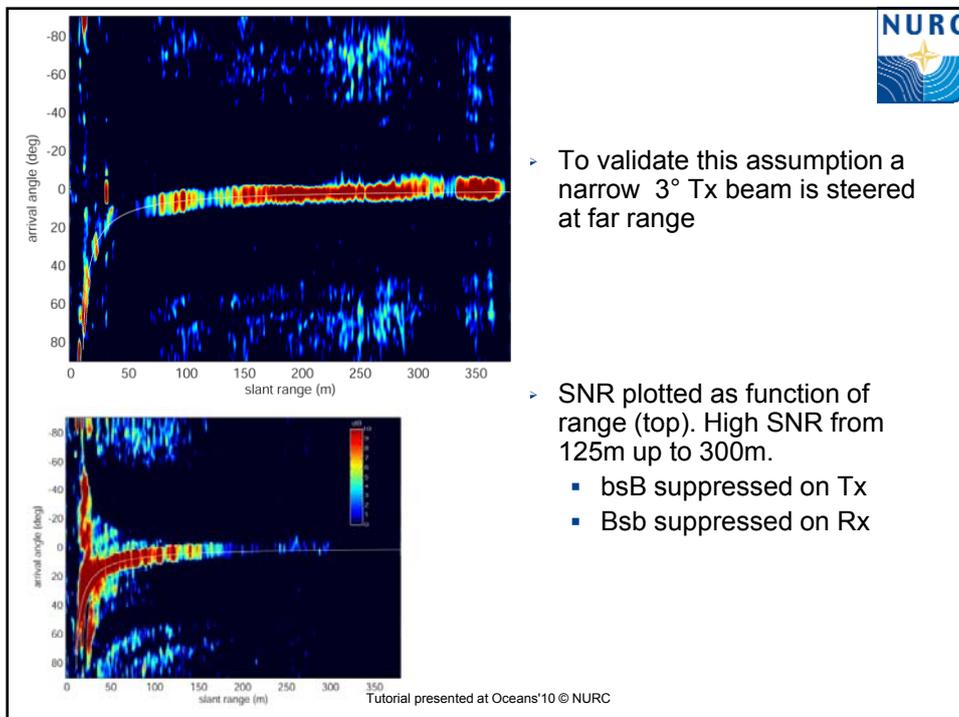
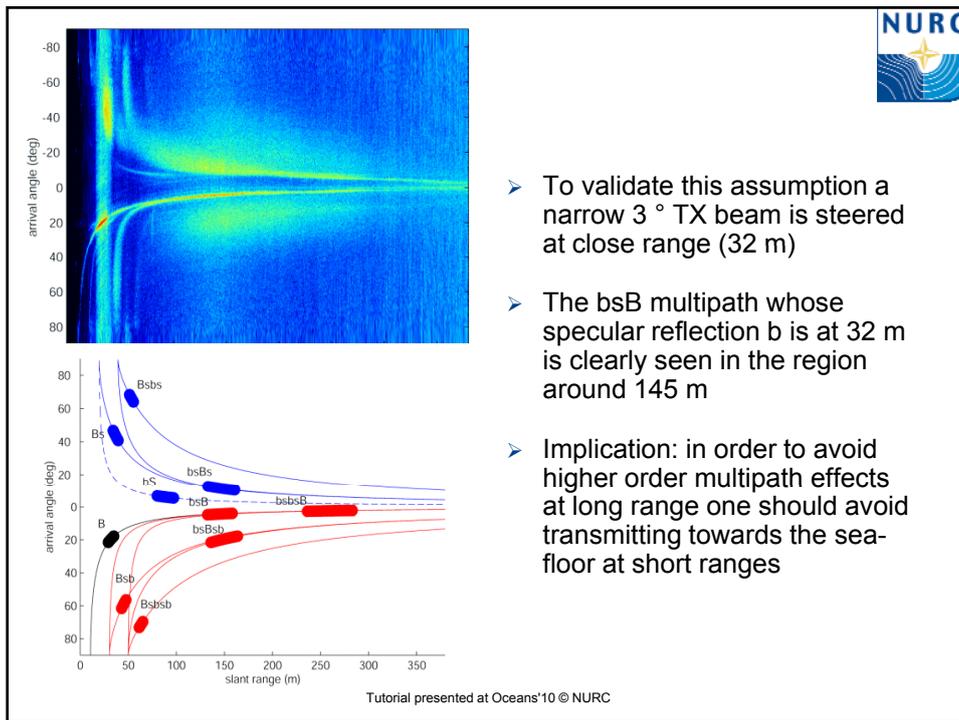
Tutorial presented at Oceans'10 © NURC

- A broad transmission beam shaped to insonify a wide swath of the sea-floor whilst avoiding first order multipaths
- RX a 7° beam with -20 dB side-lobe
- SNR, derived from ping-to-ping correlation, plotted in figure for various depression angles of the receive beam. SNR falls dramatically beyond 125 m
- Conjecture: Drop is caused by $B_{sb}-bsB$ which is not coherent ping-to-ping.

Tutorial presented at Oceans'10 © NURC





Future trends



- SAS has emerged as a strong competitor to traditional SSS.
- This has spurred (overdue?) improvements in these SSS such as
 - Pulse compression
 - Dynamic focusing
 - Wideband
 - Designs suited for lower-speed AUVs rather than towed systems.

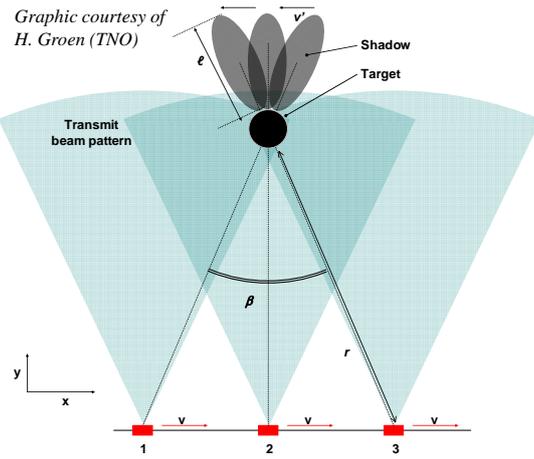
Tutorial presented at Oceans'10 © NURC



Shadow blur



Graphic courtesy of H. Groen (TNO)



- There is a lower limit on the SAS resolution set by viewing angle differences at the extremities of the SAS. This is given by

$$CRR \geq \sqrt{\frac{\lambda l}{2}}$$

where l is the shadow length at the centre of the array.

- Effect is mitigated by increasing both operating frequency and grazing angle, ie, reducing sonar range.
- At 300kHz, limit is 2 cm for a 1 m tall object at 6 deg minimum grazing angle ($l=10$ m).

Tutorial presented at Oceans'10 © NURC



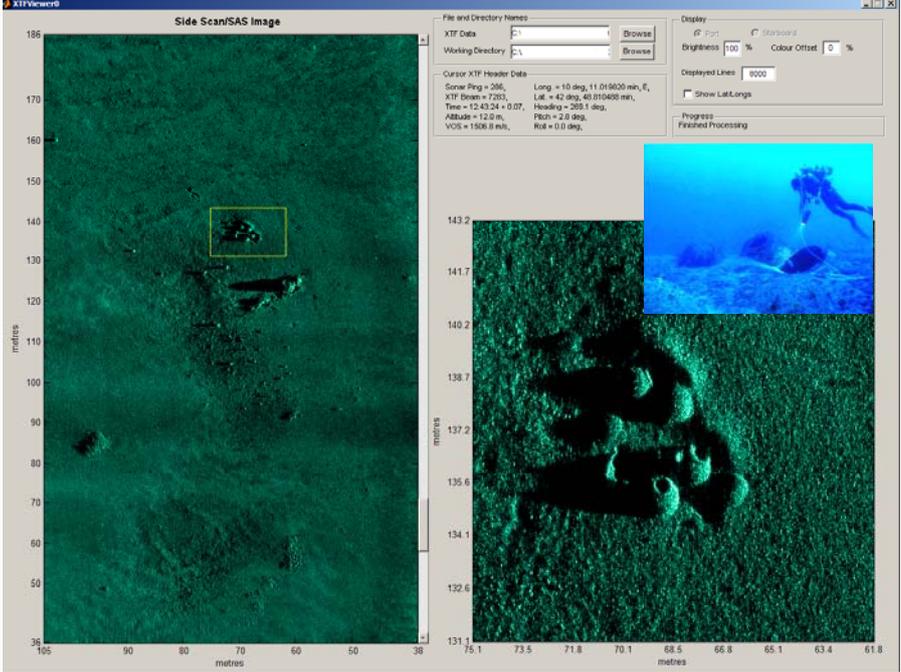
MUSCLE technology testbed





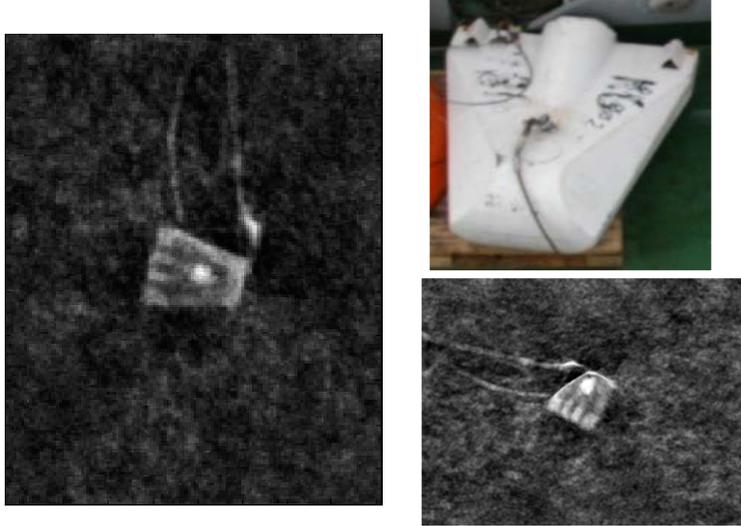

- COTS Bluefin 21 platform.
- High performance 270-330 kHz wideband InSAS optimized for shallow water (Thales)
- High performance aided inertial navigation (IMU 120 IxSea)
- On-board processing capability, pre-programmed & adaptive mission planning

Tutorial presented at Oceans'10 © NURC



Tutorial presented at Oceans'10 © NURC

 **Multi-view/multi-pass SAS image registration** 



Tutorial presented at Oceans'10 © NURC

The figure illustrates the process of multi-view/multi-pass SAS image registration. It consists of three main images: a large, dark, grainy SAS image on the left; a smaller, clear photograph of a white container with handwritten markings in the top right; and a smaller, dark SAS image on the bottom right that has been registered to match the orientation and position of the container in the reference photo.

Document Data Sheet

<i>Security Classification</i> RELEASABLE TO THE PUBLIC		<i>Project No.</i>
<i>Document Serial No.</i> NURC-PR-2010-001	<i>Date of Issue</i> July 2010	<i>Total Pages</i> 23 pp.
<i>Author(s)</i> Pinto, M.		
<i>Title</i> High resolution sonar (tutorial slides)		
<i>Abstract</i>		
<i>Keywords</i>		
<i>Issuing Organization</i> NURC Viale San Bartolomeo 400, 19126 La Spezia, Italy [From N. America: NURC (New York) APO AE 09613-5000]		Tel: +39 0187 527 361 Fax: +39 0187 527 700 E-mail: library@nurc.nato.int