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**Acoustical Society of America**
Portland, Oregon
18 - 22 May 2009
**Session 1aAO: Acoustical Oceanography**


## 1aAO3. Transverse coherence lengths, processing limits and implications


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How does scattering in sound channels(deep and shallow waters) limit coherent array processing or what is the limitation of resolution in terms of the mutual coherence function and its temporal and spatial coherence lengths? The resolution of an array is limited by the mutual coherence function; but estimation in a partially coherent noise background with a multi-path signal is difﬁcult using the normalized cross power spectral density, magnitude squared coherence, because of the properties of both signals and noise. The measurement of magnitude-squared coherence is a poor statistical estimator since it is a function of the signal-to-noise ratio and multipath interference with large conﬁdence bounds. Array gain measurements and a wave-theoretic coherence functional form can provide estimates of temporal and spatial coherence lengths deﬁned as the 1/e value of this function. This paper reviews single path coherence results and those derived from array measurements over the low- to mid-frequency range in deep and shallow water. Representative coherence lengths are discussed in terms of boundary interactions, internal wave scattering, and coastal mesoscale features. The implications for arrays used to estimate geoacoustic properties,mammal locations, and scattering from the boundaries are presented.


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**Spatial Coherence and array signal gain were measured across this front!**


**What is the limit coherent horizontal array processing terms of the mutual coherence function and length in deep and shallow-water-sound channels ?**

**Resolution is limited by the mutual coherence function; but estimation in a partially coherent noise and a multipath signal is difficult since magnitude squared coherence estimator measures the properties of both signals and noise.**

**C. Carter * has determined the magnitude squared coherence is a poor statistical estimator since it is a function of the signal-to-noise ratio with large confidence bounds.**

**However, array signal gain measurements and a wave-theoretic coherence functional form can provide estimates of the horizontal coherence length defined as the 1/e value of this function..**

* G. C. Carter, C. H. Knapp, and A. H. Nuttall, " Estimation of the magnitude squared coherence function via overlapped FFT processing," IEEE Trans. on Audio and Electroacoustics, AU-21(4), pp.337-344,1973.,E. R. H. Scannell and G. C. Carter," Confidence bounds for magnitude-squared coherence estimates," Proc. IEEE Int. Conf. on Acoustics, Speech, and Signal Processing, pp.670-673, 1978.

**Talk Outline**

- **Deep Water Horizontal Coherence**
  - **Coherence Measurement**
  - **Pairwise Coherence Results**
  - **Array Signal Gain results**
- **Shallow Water- Downward Refraction- Sandy-Relative Signal Gain Results**
- **Basic Conclusion:** ***Water borne paths in deep water have coherence lengths on the order of 100 λ at a frequency of 400 Hz at a range of 400 km. While shallow water ( 100m) with sandy bottoms have coherence lengths on the order of 30 λ at a frequency of 400 Hz at a range of 40 km.***

***What do we mean by coherence?***

***How is it estimated from measurements?***

***What bearing does it have on array performance?***

# What do we mean by coherence?

- ***The Mutual Coherence function of a propagating wave is well defined***

$$\Gamma_{12} = \Gamma[R,\ r_1,\ r_2,\ \omega_1,\ \omega_2,\ t_1,\ t_2]$$
$$= \langle p(R,\ r_1,\ \omega_1,\ t_1)\cdot p(R,\ r_2,\ \omega_2,\ t_2)^* \rangle$$

- ***The Spatial Coherence Function***

$$\Gamma_{12} = \langle p(R,r_1)\cdot p(R,r_2)^\bullet \rangle = \langle p(R,r_1)\cdot p(R,r_1 + r_\perp)^\bullet \rangle$$


Born and Wolf, 1959, Principles of Optics, Pergamon Press, Ny,NY, Chapt. 10 pp 401-544.
Beran, M. J., Parrent, G.B., M.J. Beran, Theory of Partial Coherence, Prentice Hall, Englewood,\Cliffs, NJ, pp1-11.
Uscinski, B.J., 1977, The elements of Wave Propagation, , McGraw-Hill ,NY,NY
J. J. McCoy, and B. B. Adams, 1975,“ Effects of a fluctuating temperature field on the spatial coherence of acoustic signals,” NRL, Washington, D.C. 20375, NRL Tech. Rept. 7809, 1975 -(Avail DTIC).
R. F. Dashen, S. M. Flatte, W. H. Munk, and F. Zachariasen, ,1977, “ Limits on Coherent Processing Due to Internal Waves,” Standford Research, Menlo Park, Ca, 94025, Standford Research Rep. Tr-JSR-76-14, 1977-(Avail DTIC).
Flatte, S.M., R. F. Dashen, W. H. Munk, K.E. Watson and F. Zachariasen, 1977, Sound Transmission through a Fluctuating Ocean, Cambridge University press, Cambridge, U.K.pp 126-149.


## Volume scattering relations

**The Beran-McCoy-Adams Formulation:**

**Transverse Coherence Function is**

$$\Gamma(\Delta y) = R_p(R,f,\Delta y,z)/I(z) = \exp\left(-(\Delta y/L_{hc})^{3/2}\right)$$
$$= \exp\left(-E_f f^{5/2} R(\Delta y)^{3/2}\right) = \exp\left(-E_k k^{5/2} R(\Delta y)^{3/2}\right)$$

**where** $E_f = 1.136\cdot 10^{-6}\, E_k = 1.136\cdot 10^{-6}\left(\varepsilon\cdot 10^{-10}\right)$

**and** $L_{hc}^{-1} = f^{5/2}\left(E_f R\right)^{2/3}$.

**The Flatte-Dashen Formulation:**

$$\Gamma(\Delta y) = R_p(R,f,\Delta y,z)/I(z) = \exp\left(-D_{1,2}/2\right) = \exp\left(-(\Phi\Delta y/L_{hc}\sqrt{2})^2\right)$$

**Generally we write:** $\Gamma(\Delta y) = \exp\left(-(\Delta y/L_{hc})^n\right)$.


M.J. Beran, J. J. McCoy, and B. B. Adams, “ Effects of a fluctuating temperature field on the spatial coherence of acoustic signals,” NRL, Washington, D.C. 20375, NRL Tech. Rept. 7809, 1975 -(Avail DTIC).

R. F. Dashen, S. M. Flatte, W. H. Munk, and F. Zachariasen, “ Limits on Coherent Processing Due to Internal Waves,” Standford Research, Menlo Park, Ca, 94025, Standford Research Rep. Tr-JSR-76-14, 1977-(Avail DTIC).

W. M. Carey and W. B. Moseley, “ Space-time processing, environmental-acoustic effects,” in Progress in Underwater Acoustics, ed. H. M. Merklinger, Plenum Pub., pp. 743-758, 1987(IEEE J. Ocean. Eng. 16(3), pp. 285-301, 1991.

## SCATTERING REGIONS (Dashen, Flatte)

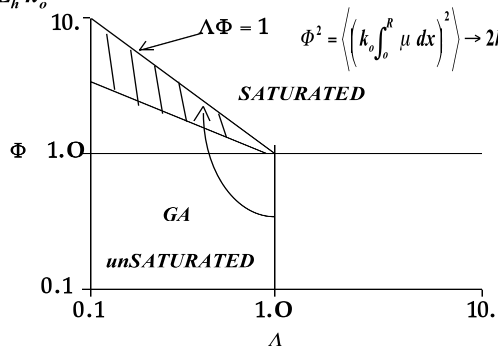
**Weak Scattering**

**Correlation Function:** $\rho\,(\Delta X) = \langle \mu^2 \rangle EXP\left[-(\Delta X / L_h)^{p-1}\right]$

$\Lambda \cong R / 6 L_h\, k_o$

**Scattering Strength**

$$\Phi^2 = \left\langle \left( k_o \int_o^R \mu\, dx \right)^2 \right\rangle \rightarrow 2k_o \int_o^R (R-\xi)\rho(\xi)d\xi \cong k_o^2 \langle \mu^2 \rangle R\, L_h$$




**The regions of interest for sonar are the unsaturated and partially saturated regions because good sonar imaging is possible.**

### *Basic Approach-Measurement, Theory and Analysis*

***Measurement of the signal's space time correlation function or its Fourier transform***

+

***Physical-Acoustic Space time Propagation Theory such as Flatte et al or Beran et al***

Coherence Times

Spatial Coherence
Vertical and Horizontal

Frequency, Range, and
Environmental variations

***No Theory—No Hope!***

## *How is it estimated from measurements?*

## Measurement options

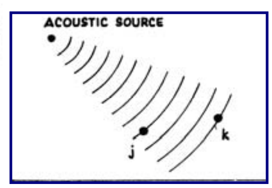
- **Pair-wise coherence: narrowband/broadband signals**
- **Direct measurement of signal gain with a filled aperture with arrivals in the broadside direction.**
- **Steered beam response with a filled or sparse aperture with arrivals near broadside.**
- **Coded Signals ( M Sequence) and Replica Correlation: Multi-Path and Modal separation with high signal to noise ratio.**

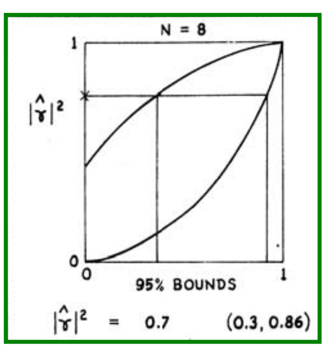
- *What is coherence?*
- *How and how accurately do you estimate it?*

$$\gamma_{ab}(f) = \frac{G_{ab}(f)}{[G_a(f)\,G_b(f)]^{1/2}}$$

$$0 \le |\gamma_{ab}(f)|^2 \le 1, \ \forall f$$

a,b either source, receiver pair or receiver, receiver pair

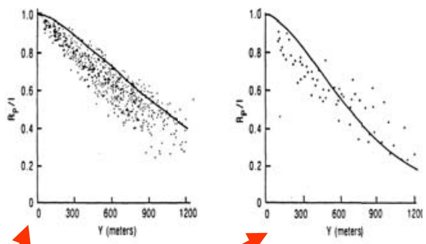


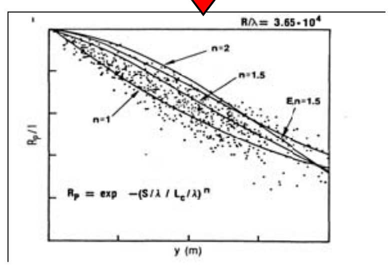

CONCLUSIONS

- COHERENCE
  - NORMALIZED CROSS SPECTRUM
  - SIGNAL TO NOISE MEASURE
  - LINEARITY MEASURE
- ESTIMATION
  - DIFFICULT
  - BOUNDS LARGE

G. C. Carter, C. H. Knapp, and A. H. Nuttall, " Estimation of the magnitude squared coherence function via overlapped FFT processing," IEEE Trans. on Audio and Electroacoustics, AU-21(4), pp.337-344,1973.,E. R. H. Scannell and G. C. Carter," Confidence bounds for magnitude-squared coherence estimates," Proc. IEEE Int. Conf. on Acoustics, Speech, and Signal Processing, pp.670-673, 1978.




*A comparison of exp(-(y/L$_c$)$^n$) with acoustic correlation versus separation distance at 400 Hz.*

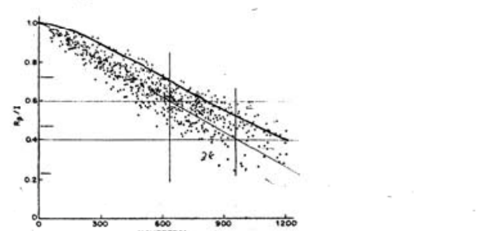



**Acoustic correlation versus transverse receiver separation, range is 259 Km and frequency of 400 Hz.**

**Acoustic correlation versus transverse receiver separation, range is 137 Km and frequency of 400 Hz.**

D.C. Stickler, R.D.Worley, S.S.Jaskot, Bell Telephone Laboratories, unpublished. Summarized by G.H.Robertson, "Model for Spatial variability effects on single path reception of underwater sound at long ranges," J. Acoust. Soc. Am. 69, pp112-123, 1981.

## Coherence length estimates at 400 Hz.



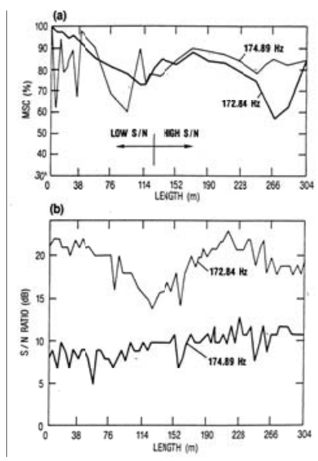
| R(km) | $L_h$ | $L_h / \lambda$ | Efmx10$^{+17}$ |
|---|---|---|---|
| 137 | 1143 | 306 | 5.9 |
| 139 | 1677 | 450 | 3.4 |
| 259 | 1067 | 286 | 3.5 |
| 268 | 1067 | 286 | -- |
| 507 | 381 | 102 | 8.2 |
| 963 | 350 | 94 | 4.96 |

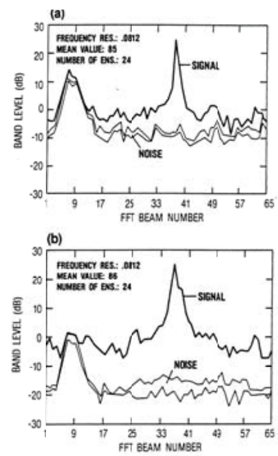
M.J. Beran, J. J. McCoy, and B. B. Adams, " Effects of a fluctuating temperature field on the spatial coherence of acoustic signals," NRL, Washington, D.C. 20375, NRL Tech. Rept. 7809, 1975.

R. F. Dashen, S. M. Flatte, W. H. Munk, and F. Zachariasen, " Limits on Coherent Processing Due to Internal Waves," Standford Research, Menlo Park, Ca, 94025, Standford Research Rep. Tr-JSR-76-14, 1977-(Avail DTIC).

W. M. Carey and W. B. Moseley, " Space-time processing, environmental-acoustic effects," in Progress in Underwater Acoustics, ed. H. M. Merklinger, Plenum Pub., pp. 743-758, 1987( expanded version in IEEE J. Ocean. Eng. 16(3), pp. 285-301, 1991.

## MSC, S/N, and Beam Signal level




**MSC is a function of S/N and Noise Coherency and multi-path effects !**

**Beam signal levels can be separated from noise sources!**

W. M. Carey and W. B. Moseley, " Space-time processing, environmental-acoustic effects," in Progress in Underwater Acoustics, ed. H. M. Merklinger, Plenum Pub., pp. 743-758, 1987( expanded version in IEEE J. Ocean. Eng. 16(3), pp. 285-301, 1991.

## THE EXPECTATION VALUE OF THE MAGNITUDE SQUARED RESPONSE FUNCTION:

$$\left\langle f_{lp}(\psi_s)\cdot f_{lj}^*(\psi_s)\right\rangle = \int \cdot \int_{-L/2}^{+L/2} [4P_p \cdot P_j^* / L^2] \exp\left(-\left[(y_p - y_j)/L_h\right]^2\right) \cdot \exp\left(i2\psi_s (y_p - y_j)/L\right) dy_p dy_j$$

This expression may be written in matrix notation:

$$P(k\sin\theta,\omega) = \left\langle f_{lp}(\psi_s)\cdot f_{lj}^*(\psi_s)\right\rangle = C^T \cdot R_{CPS} \cdot C$$

where:

$$R_{CPS} = \left\| [4P_p \cdot P_j^* / L^2] \exp\left(-\left[(y_p - y_j)/L_h\right]^2\right)\right\| .$$

W. M. Carey, "The determination of signal coherence length based on signal coherence and gain measurements in deep and shallow water", J. Acoust. Soc. Am. 104 (2, pt.1), August 1998, 831-837.

## MATCH THE ENVIRONMENTAL ANGLE SPREAD TO THE BEAMWIDTH OF THE HALF POWER POINTS!

$$S(k\sin\theta) = \int_{-\infty}^{\infty} \exp(-(y/L_h)^n \exp(iky\sin\theta)dy$$

where $\exp(-(y/L_h)^n)$ is the coherence function.

| | n = 1 | n = 1.5 | n = 2 | $\Delta\theta_{hp}$ |
|---|---|---|---|---|
| BW(radian) | 0.318 $\lambda/L$ | 0.457 | 0.530 | 0.886 $\lambda/L$ |
| BW(degrees) | 18.2° | 26.2° | 30.36° | 50.76° $\lambda/L$ |
| $L_a/L_h$ | 2.72 | 1.89 | 1.64 | |

The relative signal gain is:

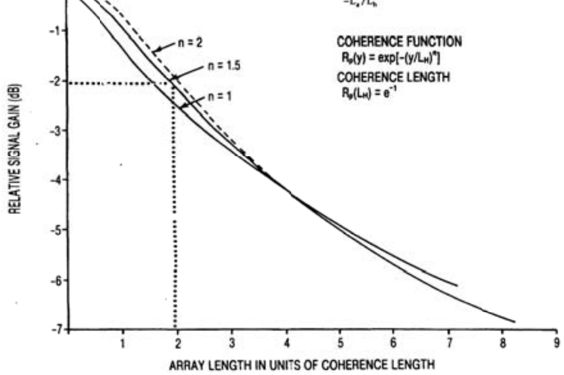
$$rsg = (L_h/L_a)^2 \cdot \int_{-L_a/L_h}^{+L_a/L_h} (L_a/L_h - |x|)\exp(-|x|^n)dx; \qquad RSG = 10Log(rsg)$$

Thus the gain of the array is related to the coherence length – provided we have a criterion and a coherence functional form!

W. M. Carey and W. B. Moseley, " Space-time processing, environmental-acoustic effects," in Progress in Underwater Acoustics, ed. H. M. Merklinger, Plenum Pub., pp. 743-758, 1987( expanded version in IEEE J. Ocean. Eng. 16(3), pp. 285-301, 1991.

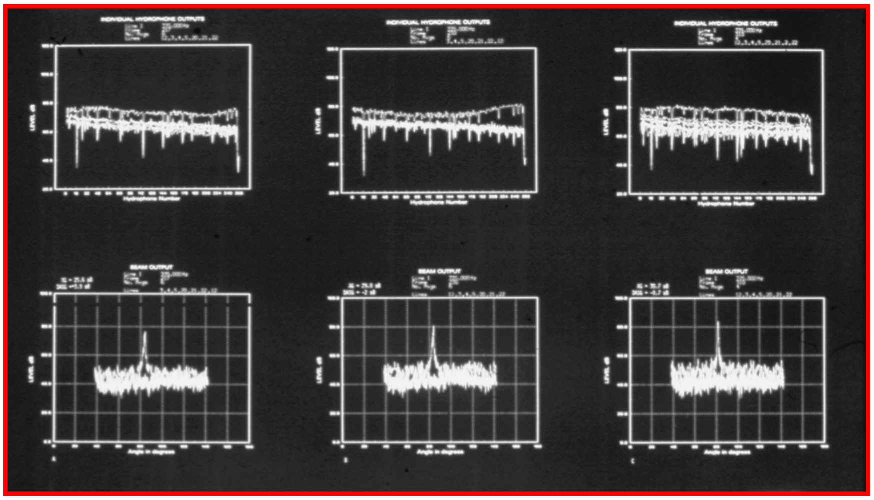
## THE RELATIVE SIGNAL GAIN

$$rsg = (L_h/L_a)^2 \cdot \int_{-L_a/L_h}^{+L_a/L_h} (L_a/L_h - |x|)\exp(-|x|^n)dx; \qquad RSG = 10Log(rsg)$$

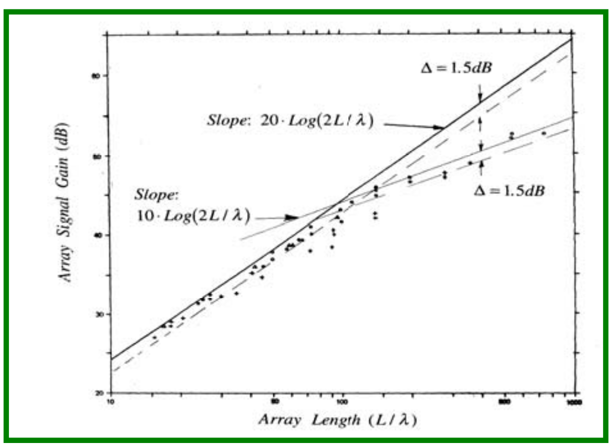



W. M. Carey and W. B. Moseley, " Space-time processing, environmental-acoustic effects," in Progress in Underwater Acoustics, ed. H. M. Merklinger, Plenum Pub., pp. 743-758, 1987( expanded version in IEEE J. Ocean. Eng. 16(3), pp. 285-301, 1991.

***The illumination and beam pattern for a long range source of sound.***

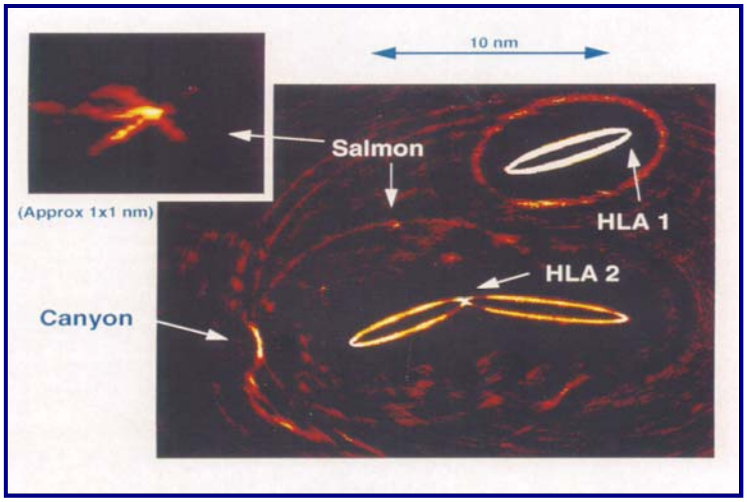


***Signal Gain** is an indicator of coherence and when interpreted with a wave theoretic model yields coherence length estimates*

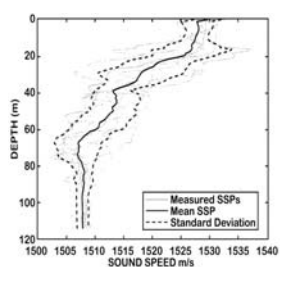


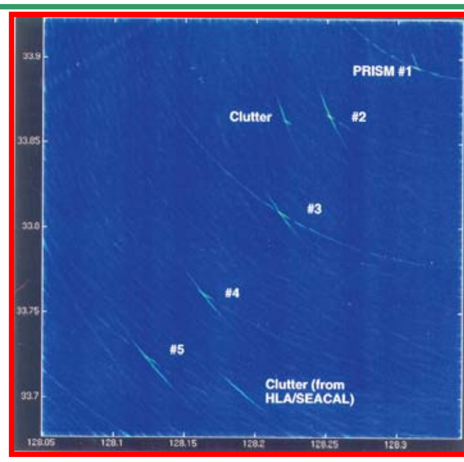

***A summary of experimental array estimates***

## *Shallow water coherent array processing results North of The Hudson Canyon*




***This figure shows a range/cross range plot of echoes received on two experimental arrays ten miles apart. The explosives were detonated midway between the two arrays. The distance to T5 is approximately 20 nmi from the source location. In this 400 nmi square area we observe two target like clutter echoes one of which was cross fixed. However both clutter events had different frequency content than the targets.***




These results are from the ACT series of experiments conducted by W. Carey, P. Cable, and J. O'Connor on the Florida Shelf in the Gulf of Mexico, on the Jersey Continential Shelf, and in the Straits of Korea. Explosive sources were developed and deployed by W. Marshall and the analysis was performed by Mike Steele, T. Kooij, J. Angle from BBN Laboratories. In addition the CW sources were deployed by W. Carey and G. Hunsaker, NRAD. Analysis of the Straits of Korea array data was performed by J. Reese, NRAD.

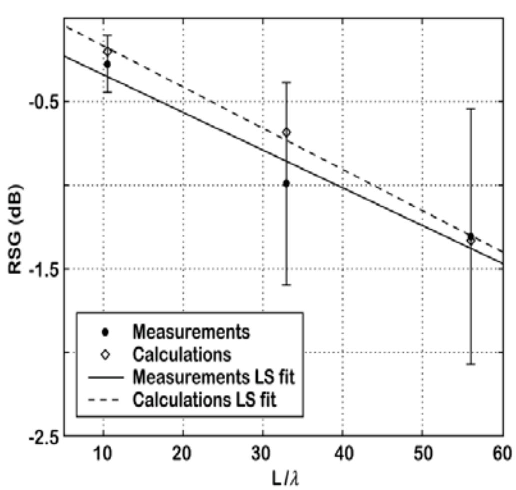
## *Shallow water coherence length results.*

| Ref. | [17] | [18] | [19] | [20] | [20] | [20] | [20] | [20] |
|---|---|---|---|---|---|---|---|---|
| Location | N. Sea | N.W. Atl. | GM/WFE | GM/FS | NWA/JS | SOK-1 | SOK-1 | SOK-2 |
| SVP | ISV | DR | DR | DR | DR | DR | DR | DR |
| WD | 65m | 0.1-1 km | 0.1-1km | 200m | 100m | 100m | 100m | 100m |
| Bottom | S | S-SC | S-SC | S-SC | S-SC | S-SC | S-SC | SC-S |
| **f1(Hz)** | **400** | **135** | **173-175** | **200-400** | **200-400** | **354** | **300** | **354** |
| **f2** | **800** | | | **400-800** | **400-600** | **600** | **500** | **604** |
| **Range km** | **7.4** | **100** | **25** | **9.3** | **4-22** | **7-11** | **5-45** | **14-24** |
| $L_c$ | **18** | **31** | **21** | **30** | **23** | **27** | **29** | **38** |
| $L_c$ | **10** | | | **32** | **25** | **30** | **31** | **54** |
| Source | Exp. | CW | CW | Exp. | Exp. | CW | Exp. | CW |
| SD | 21m | 18m | 100m | 100m | 52m | 30 m | 52m | 33m |
| RD | 15m | 750m | 400m | 200m | 100m | 101m | 101m | 94m |
| COV | 8% | 4% | 6% | 4% | 4% | 4% | 5% | 2-4% |

SVP=Sound Velocity Profile; ISV= Isovelocity; DR=Downward Refracting; WD= Water Depth; S= Sand; S-SC= Sandy- Silty- Clay; SD=Source Depth; RD= Receiver Depth. COV=coefficient of variation in measured results.

W. M. Carey, "The determination of signal coherence length based on signal coherence and gain measurements in deep and shallow water", J. Acoust. Soc. Am. 104 (2, pt.1), August 1998, 831-837.

## Wave Theoretic Numerical Modeling provides for Extrapolation



## *Urick's Coherence Summary*

TABLE 2
TABULAR SUMMARY OF COHERENCE MEASUREMENTS

| COHERENCE LENGTH $r_o$ | FREQUENCY | BAND WIDTH | AVERAGING TIME | PROPAGATION PATH(S) | SOURCE DEPTH | RECEIVER DEPTH | SOURCE RECEIVER RANGE | HYDROPHONE ORIENTATION | REFERENCE REFERENCE |
|---|---|---|---|---|---|---|---|---|---|
| >3 km ($\rho$=0.8, constant to 3 km) | 7.5 kHz cw | Narrow | 0.1 sec | Single, Near Surface | Shallow | — | 0.6-12 km | Horizontal Transverse | 16 |
| 6 meters<br>1 meter | 4, 7, 15 kHz | Pulses | 3 and 30 ms Pulses | Surface Reflection | Shallow Water, Depth 80 m. | | 600 m. | Horizontal<br>Transverse<br>Vertical | 17 |
| >4000 ft.<br>1600 ft. | 400 Hz | Pulses | 0.1 hr. | Single, Refracted | — | Artemis* | 19 mi. | Horizontal<br>Vertical | 19 |
| 1300 ft.<br>700 ft. | 400 Hz | Pulses | — | Single, Refracted | 1200 ft | Artemis* | 270 mi. | Horizontal<br>Vertical | 18 |
| 48 ft.<br>6 wavelengths | 750 Hz cw | Narrow | 106 ms | Surface Reflected | 9500 ft | TVA** | 24 mi. | Vertical | 9 |
| 300 ft. | 800 Hz Pulses | — | 5 ms | Single, Refracted | 9500 ft | TVA** | 24 mi. | Vertical | 20 |
| 8 wavelengths | 50-100 Hz<br>100-200 Hz<br>200-400 Hz | Octave | Shot Duration | Multiple Refracted | 800 ft. | TVA** | 100-600 mi. | Vertical | 21 |
| 300 ft.<br>1000 ft. | 367 Hz | Narrow | 840 sec<br>150 sec | Multiple Refracted (RSR) | — | Artemis* | 700 mi. | — – | 22 |
| 2 wavelengths<br>8 wavelengths<br>10 wavelengths<br>30 wavelengths | 3.1-3.3 kHz<br>1.5-1.7 kHz<br>0.7-0.9 kHz<br>0.3-0.5 kHz | 200 Hz | Shot Duration | Shallow Water Paths | Shallow Water, Depth 65 m. | | 4 mi. | Horizontal Transverse | 23 |
| 500 ft. ± | 44-88 Hz<br>177-354 Hz<br>354-707 Hz | Octave | 2 sec | Surface-Bottom Reflections | 15 ft. | 4000 ft. | 1 ky<br>2 ky<br>3 ky | Vertical | 14 |

*Hydrophone field on bottom 2000 - 4000 feet depth on channel axis near Bermuda.
**Vertical string on bottom at 14,000 feet near Bermuda (TRIDENT Vertical Array).

Work performed before 1978-Darpa 1979-PO,Stefanick 1987

## *Conclusions*

- Deep water ( Sofar Propagation):
  - A summary of single path and array signal gain measurements show that coherence lengths of 100 λ are achievable at a frequency near 400 Hz at ranges of 400 Km.
  - This length should scale with frequency to the five halves power and range to the two thirds power.
- Shallow Water ( Downward Refraction, Coastal, Sandy):
  - RASG estimate show that a coherence length of 30λ at a range of 40 Km is a reasonable number.
  - Theoretical description is lacking.
  - Most likely cause is the combination of volume fluctuations in temperature, salinity and sound speed.*

*W. M. Carey, J.F. Lynch, W.L. Siegmann, Et al ,"Sound Transmission and Spatial Coherence in Selected Shallow Water Areas: Measurements and Theory" , Theoretical and Computational Acoustics 2003, eds. A. Tolstoy et al, World Scientific, New Jersey, 2004, pp 38-71. (in Press, JCA 14 (2) , 2006).

# A Key Sonar Issue :

**How large of a transverse-horizontal aperture will be supported by the deep ocean and shallow water wave guide?**

**OR**

**What is the azimuthal spread of the signal due to long range propagation?**

## Presentation References

[1] W.M. Carey and R.A.Wagstaff, "Low frequency noise fields," J. Acoust. Soc. Amer. 80(5), pp. 1523-1526,1986.

[2] G. C. Carter, C. H. Knapp, and A. H. Nuttall, " Statistics of the estimate of the magnitude coherence function," IEEE Trans. on Audio and Electroacoustics, AU-21(4),pp.388-389,1973.

[3] G. C. Carter, C. H. Knapp, and A. H. Nuttall, " Estimation of the magnitude squared coherence function via overlapped FFT processing," IEEE Trans. on Audio and Electroacoustics, AU-21(4), pp.337-344,1973.

[4] E. R. H. Scannell and G. C. Carter," Confidence bounds for magnitude-squared coherence estimates," Proc. IEEE Int. Conf. on Acoustics, Speech, and Signal Processing, pp.670-673, 1978.

[5] W. M. Carey and W. B. Moseley, " Space-time processing, environmental-acoustic effects," in Progress in Underwater Acoustics, ed. H. M. Merklinger, Plenum Pub., pp. 743-758, 1987( expanded version in IEEE J. Ocean. Eng. 16(3), pp. 285-301, 1991.

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