Professional Development Short Course On:

Underwater Acoustic Modeling and Simulation

Instructor:

Paul C. Etter

ATI Course Schedule: http://www.ATIcourses.com/schedule.htm

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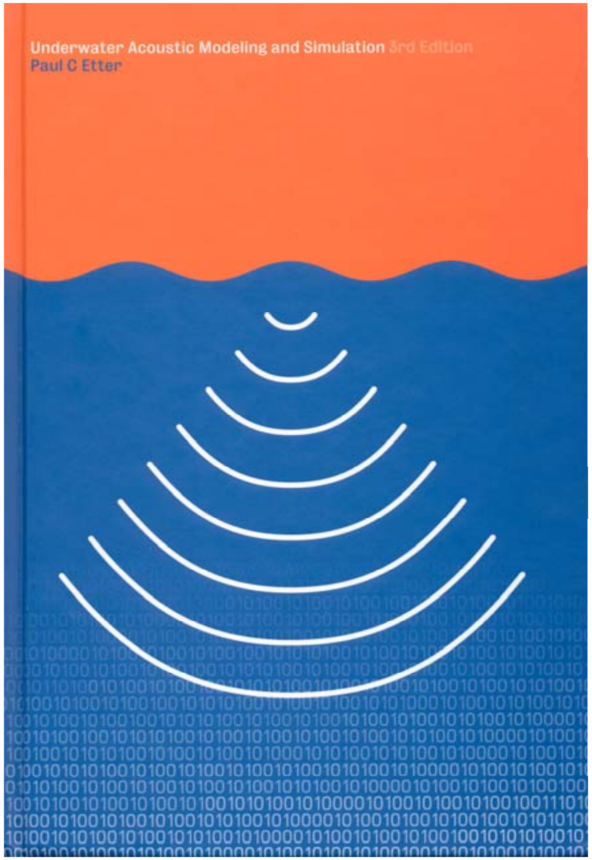
Course Textbook:

Underwater Acoustic Modeling and Simulation,
3rd edition, by Paul C. Etter, Spon Press (2003)



E-STREAMS Vol. 6, No. 11 - November 2003 - Physics
- Book Review -

Underwater Acoustic Modeling and Simulation, 3rd edition by Paul C. Etter. New York, NY, Spon Press/Taylor & Francis, 2003. 424p., illus., bibliog., index. ISBN 0-419-26220-2. LC Call no.: QC242.2.E88 2003.

Reviewer: Robert F. Skinder, Science Reference Librarian, University of South Carolina—Columbia Thomas Cooper Library.

"This book includes several well done appendices including abbreviations and acronyms, a glossary, a list of websites for important acoustic databases and an extraordinary collection of references, many culled from the gray literature.

Underwater Acoustic Modeling and Simulation meets the highest standards of professional writing and scholarship. The book is thorough yet very readable. It belongs in libraries that serve a naval, geophysical or oceanographic clientele or any college or university serving the graduate applied physics or applied mathematics student."

Course Outline

1. Introduction
2. Acoustical Oceanography
3. Propagation I. Observations and Physical Models
4. Propagation II. Mathematical Models (Part 1)
5. Propagation II. Mathematical Models (Part 2)
6. Noise I. Observations and Physical Models
7. Noise II. Mathematical Models
8. Reverberation I. Observations and Physical Models
9. Reverberation II. Mathematical Models
10. Sonar Performance Models
11. Model Evaluation
12. Simulation

Course Schedule

Day 1		Day 2		Day 3		Day 4	
AM	PM	AM	PM	AM	PM	AM	PM
Registration / Opening Remarks Introduction Acoustical Oceanography ↓ Propagation I: Observations and Physical Models	↓ Propagation II: Mathematical Models (Part 1) ↓	↓ Propagation II: Mathematical Models (Part 2) ↓	Lab I : Transmission Loss and Passive Sonars ↓	Propagation II: Mathematical Models (Part 2) Continued Noise I: Observations and Physical Models Audio Tape Noise II: Mathematical Models Reverberation I: Observations and Physical Models	Reverberation II: Mathematical Models Sonar Performance Models ↓	Lab II: Active Monostatic and Bistatic Sonars ↓	Model Evaluation ↓ Simulation ↓ Closing Remarks / Evaluation Forms

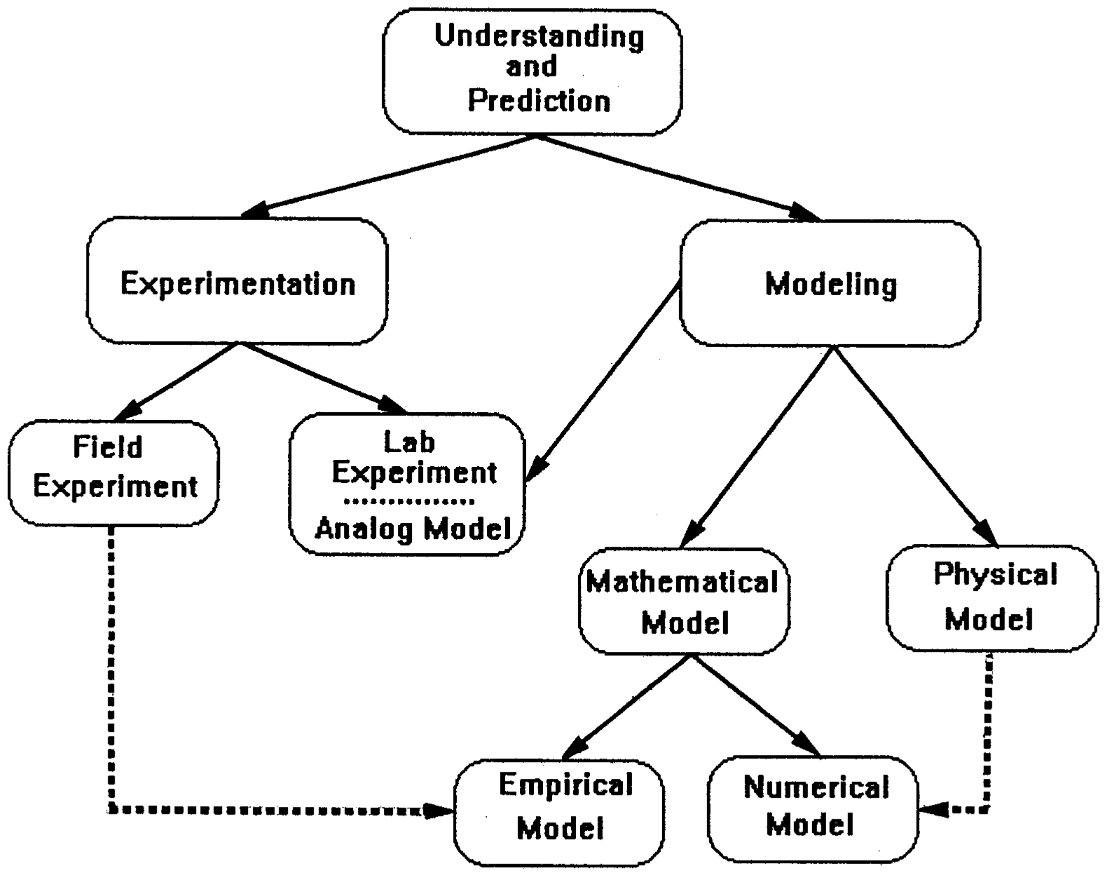
Definitions

- *Underwater acoustics*
  - Development and employment of acoustical methods to
    - Image underwater features
    - Communicate information via the oceanic waveguide
    - Measure oceanic properties
- *Modeling*
  - Method for organizing knowledge accumulated through observation or deduced from underlying principles
- *Simulation*
  - Method for implementing a model over time
- *Computational ocean acoustics*
  - Development and refinement of numerical codes that model the ocean as an acoustic medium

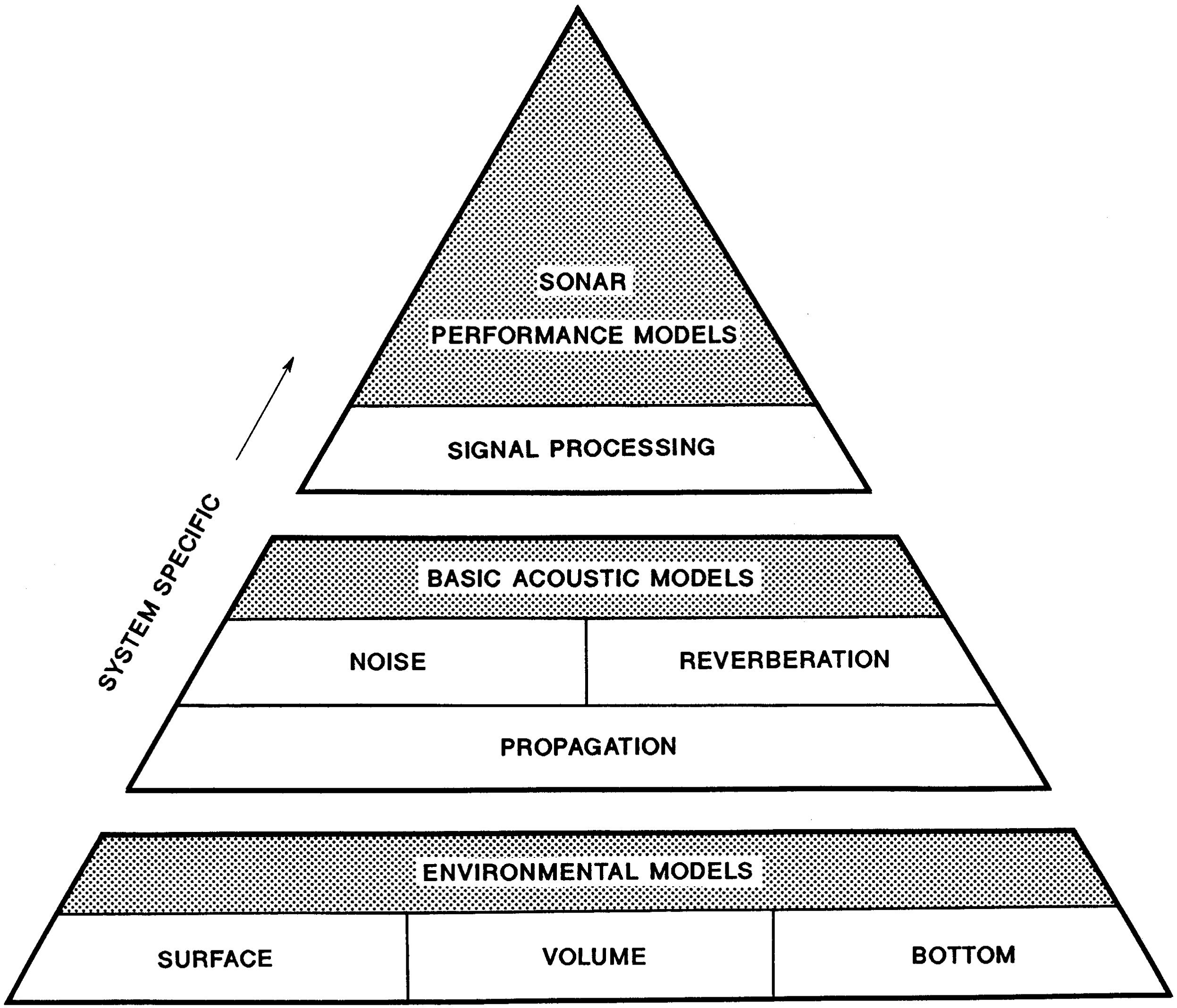
Types of Models

- Physical models
  - Conceptual representation of the physical processes occurring in the ocean
  - Sometimes called analytical models
- Mathematical models
  - Empirical models
    - Based on observations
  - Numerical models
    - Based on mathematical representations of the governing physics
- Analog models
  - Controlled acoustic experimentation in water tanks using appropriate oceanic scaling factors

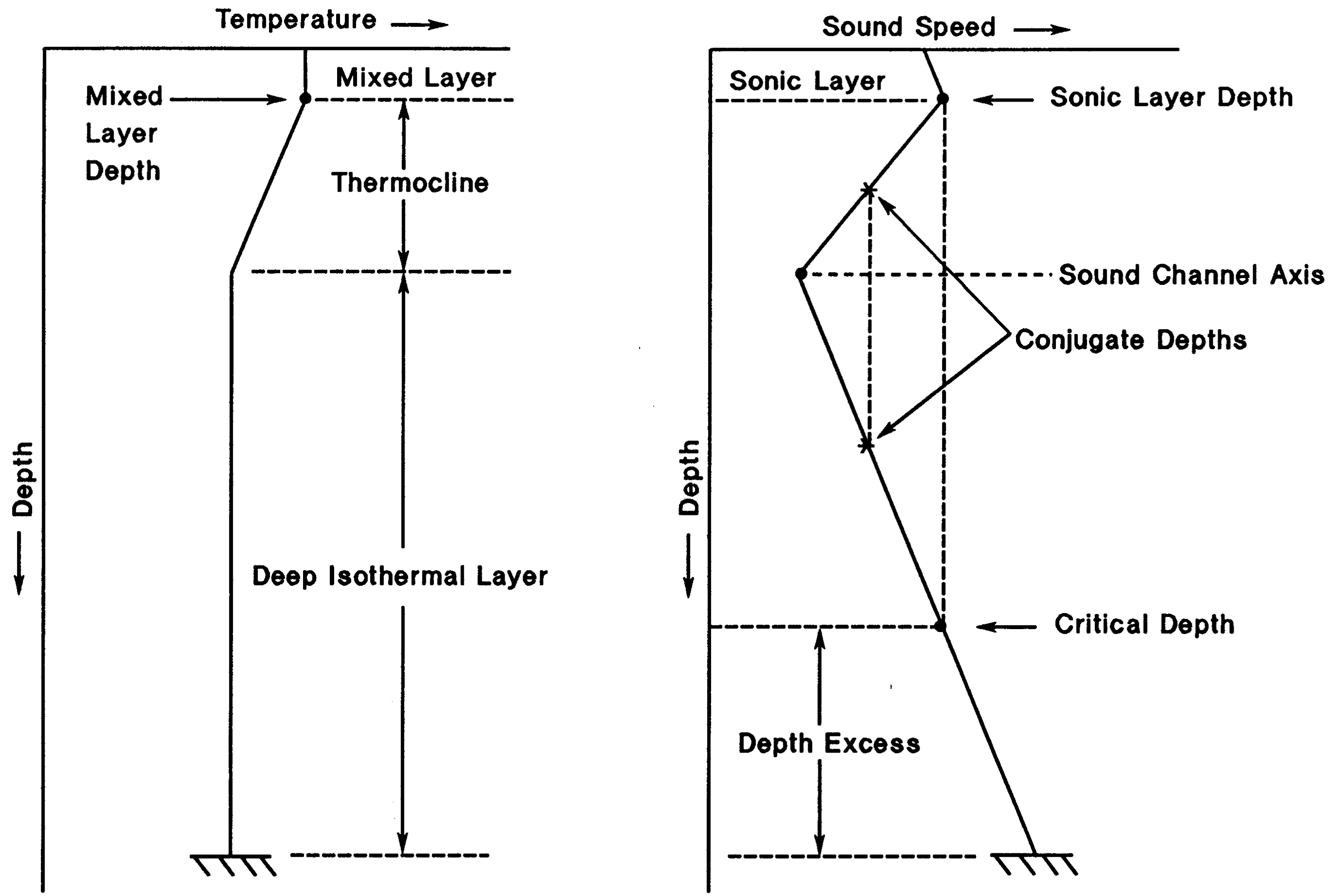
Schematic relationship between experimentation and modeling.



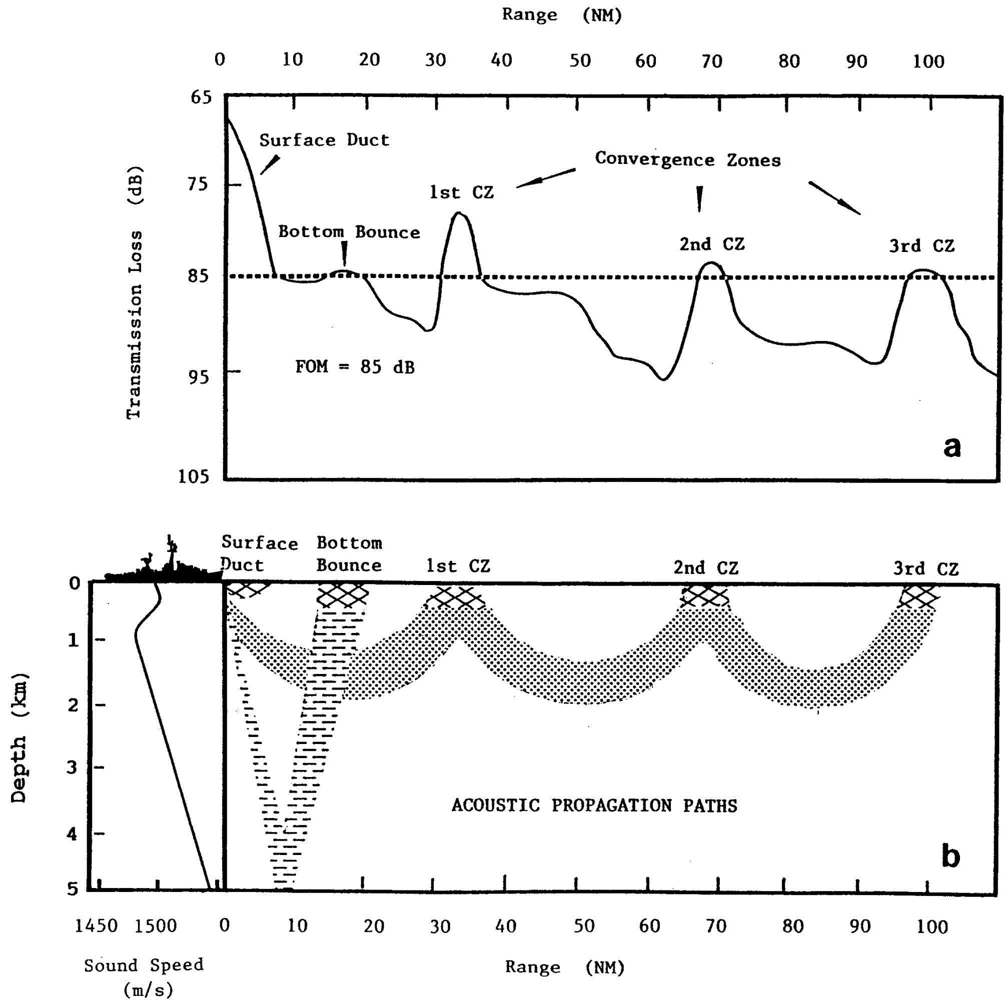
Generalized relationships among environmental models, basic acoustic models and sonar performance models.



Schematic relationship between temperature and sound speed profiles in the deep ocean.



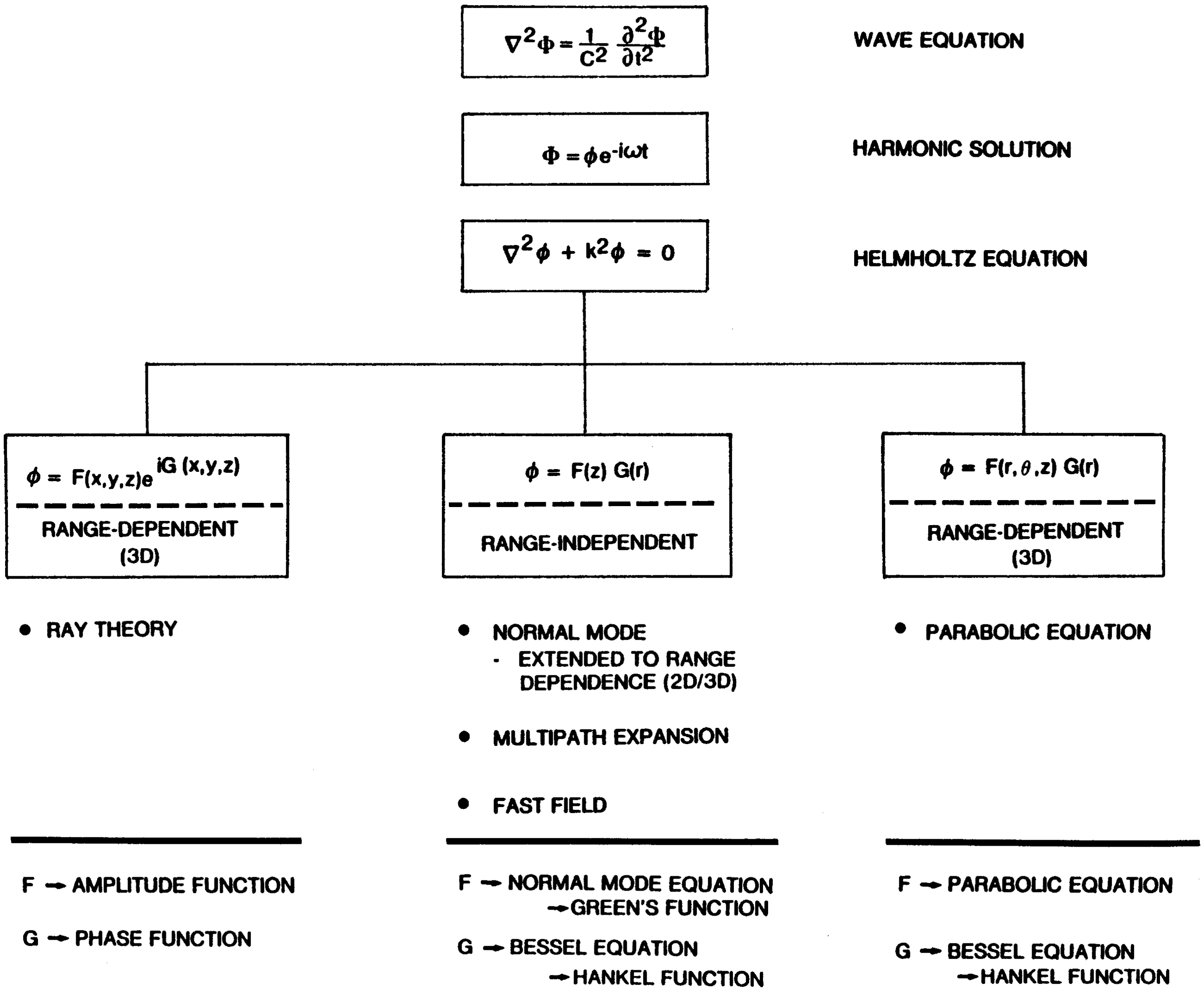
Hypothetical relationship between (a) transmission loss (TL) curve and (b) the corresponding propagation paths and detection zones (cross-hatched areas near the sea surface) associated with a figure of merit (FOM) of 85 dB. A plausible sound speed profile is shown at the left side of panel (b). Both the source (target) and receiver (ship's sonar) are positioned near the surface.



Classification of Propagation Models

- Techniques
  - Ray theory
  - Normal mode
  - Multipath expansion
  - Fast field
  - Parabolic equation
- Hybrid formulations
  - Combinations of two or more techniques to optimize capabilities
- Range dependence
  - Range independent
    - Variables are functions of depth (z) only
  - Range dependent
    - Variables are functions of depth (z), range (r) and azimuth (θ)
      - 2-D f (z, r)
      - 3-D f (z, r, θ)

Summary of relationships among theoretical approaches for propagation modeling. (Adapted from Jensen and Krol, 1975.)



Domains of applicability of underwater acoustic propagation models. (Adapted from Jensen, 1982; Proc. MTS / IEEE Oceans 82 Conf., pp. 147-54; copyright by IEEE.)

MODEL TYPE	APPLICATIONS							
	SHALLOW WATER				DEEP WATER			
	LOW FREQUENCY		HIGH FREQUENCY		LOW FREQUENCY		HIGH FREQUENCY	
	RI	RD	RI	RD	RI	RD	RI	RD
RAY THEORY	○	○	◑	●	◑	◑	●	●
NORMAL MODE	●	◑	●	◑	●	◑	◑	○
MULTIPATH EXPANSION	○	○	◑	○	◑	○	●	○
FAST FIELD	●	○	●	○	●	○	◑	○
PARABOLIC EQUATION	◑	●	○	○	◑	●	◑	◑

LOW FREQUENCY (< 500 HZ) RI: RANGE-INDEPENDENT ENVIRONMENT

HIGH FREQUENCY (> 500 HZ) RD: RANGE-DEPENDENT ENVIRONMENT

● MODELING APPROACH IS BOTH APPLICABLE (PHYSICALLY) AND PRACTICAL (COMPUTATIONALLY)

◑ LIMITATIONS IN ACCURACY OR IN SPEED OF EXECUTION

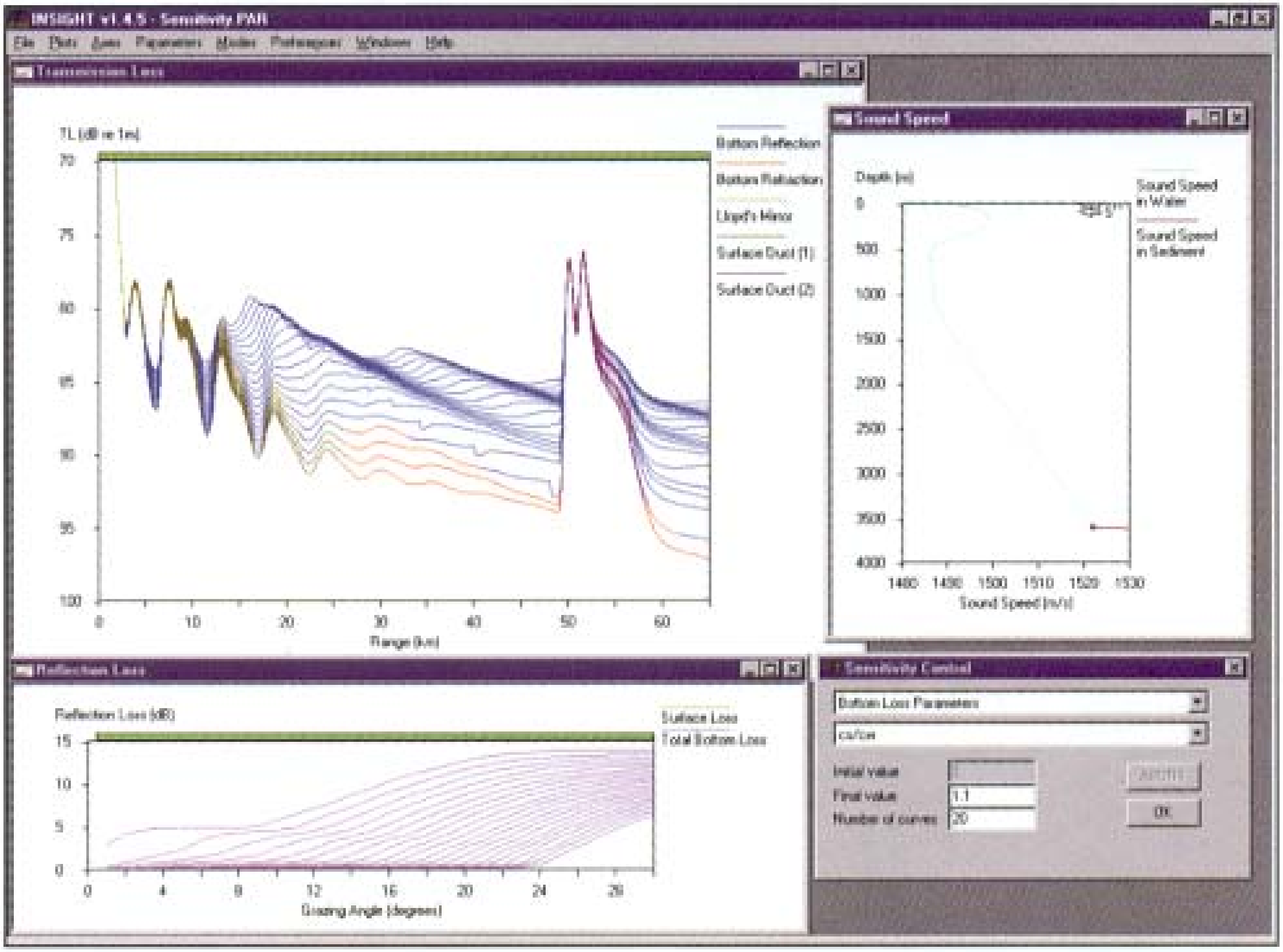
○ NEITHER APPLICABLE NOR PRACTICAL

Summary of underwater acoustic propagation models.

Technique	*Range Independent*		*Range Dependent*	
Ray Theory	CAPARAY [1] FACT [2] FLIRT [3] GAMARAY [4] ICERAY [5] PLRAY [6] RANGER [7]		ACCURAY [8] BELLHOP [9] Coherent DELTA [10] FACTEX [11] GRAB [12] GRASS [13] HARORAY [14] HARPO [15] HARVEST [16] LYCH [17]	MEDUSA [18] MIMIC [19] MPC [20] MPP [21] Pedersen [22] RAYWAVE [23] RP-70 [24] SHALFACT [25] TRIMAIN [26]
Normal Mode	AP-2 / 5 [27] BDRM [28] COMODE [29] DODGE [30] FNMSS [31] MODELAB [32] NEMESIS [33] NLNM [34] NORMOD3 [35] NORM2L [36] ORCA [37]	PROTEUS [38] SHEAR2 [39] Stickler [40]	ADIAB [41] ASERT [42] ASTRAL [43] CENTRO [44] CMM3D [45] COUPLE [46] CPMS [47] FELMODE [48] Kanabis [49] KRAKEN [50] MOATL [51]	MOCTESUMA [52] NAUTILUS [53] PROLOS [54] PROSIM [55] SHAZAM [56] SNAP / C-SNAP [57] WEDGE [58] WKBZ [59] WRAP [60] 3D Ocean [61]
Multipath Expansion	FAME [62] MULE [63] NEPBR [64] RAYMODE [65]		No Existing Solutions	

Summary of underwater acoustic propagation models (continued).

Technique	*Range Independent*		*Range Dependent*	
Fast Field or Wavenumber Integration	FFP [66] Kutschale FFP [67] MSPFFP [68] OASES [69] Pulse FFP [70]	RPRESS [71] SAFARI [72] SCOOTER [73] SPARC [74]	CORE [75] RDFFP [76] RD-OASES [77] RDOASP [78] RDOAST [79]	SAFRAN [80]
Parabolic Equation	Use Single Environmental Specification		AMPE / CMPE [81] CCUB/SPLN/CNP1 [82] Corrected PE [83] DREP [84] FDHB3D [85] FEPE [86] FEPE-CM [87] FEPES [88] FOR3D [89] HAPE [90] HYPER [91] IFD Wide Angle [92] IMP3D [93] LOGPE [94] MaCh1 [95] MOREPE [96] OS2IFD [97]	PAREQ [98] PDPE [99] PE [100] PECan [101] PE-FFRAME [102] PESOGEN [103] PE-SSF (UMPE / MMPE) [104] RAM / RAMS [105] SNUPE [106] Spectral PE [107] TDPE [108] Two-Way PE [109] ULETA [110] UNIMOD [111] 3DPE (NRL-1) [112] 3DPE (NRL-2) [113] 3D TDPA [114]



INSIGHT v1.4.5 - Sensitivity PAR
Transmission Loss
TL (dB re 1m)
Bottom Reflection
Bottom Refraction
Lloyd's Mirror
Surface Duct (1)
Surface Duct (2)
Range (km)
Sound Speed
Depth (m)
Sound Speed in Water
Sound Speed in Sediment
Sound Speed (m/s)
Reflection Loss
Reflection Loss (dB)
Surface Loss
Total Bottom Loss
Grazing Angle (degrees)
Sensitivity Control
Bottom Loss Parameters
Initial value
Final value
Number of curves
OK

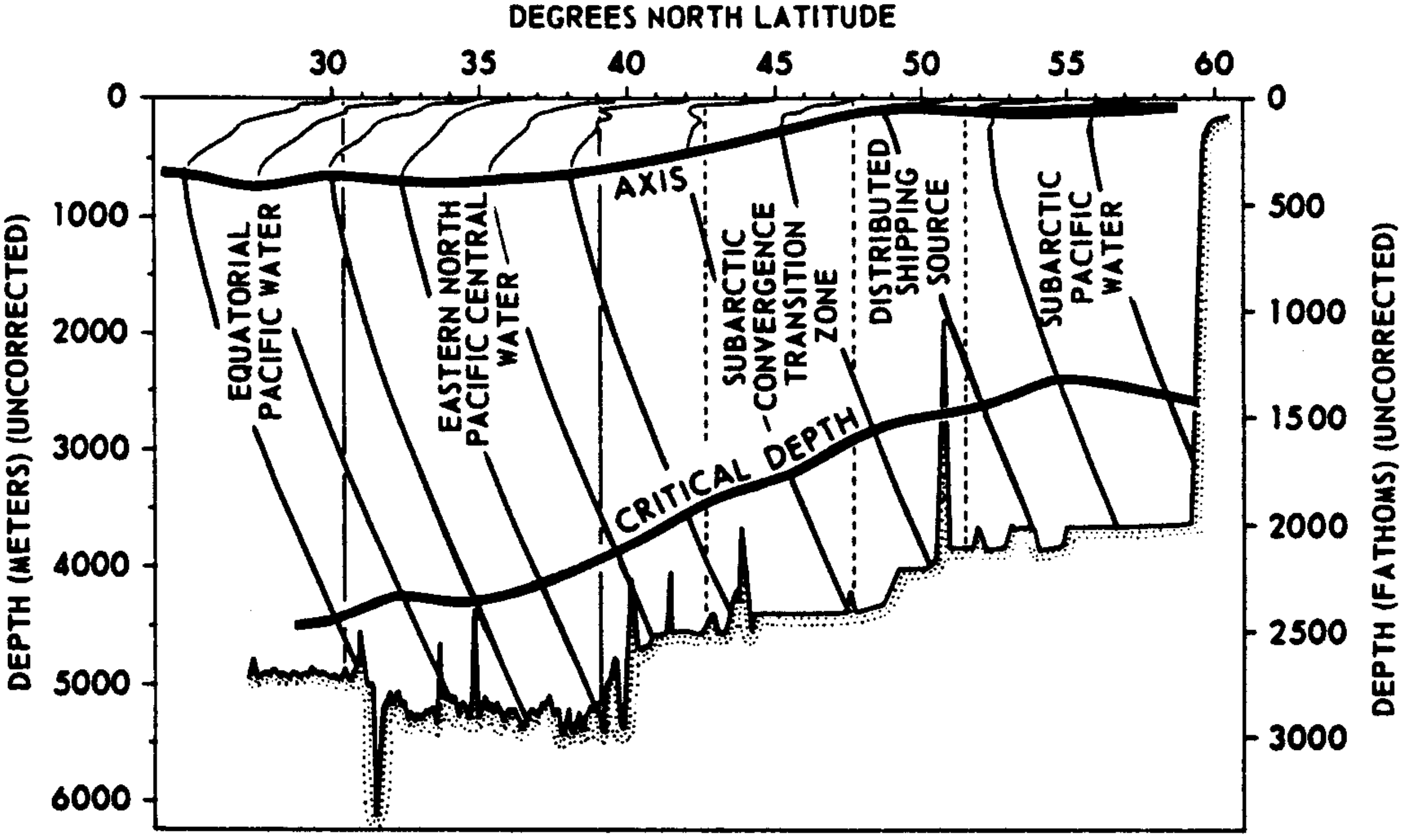
Summary of inverse ocean-acoustic sensing techniques.

Propagation	*Noise*	*Reverberation*
• Matched field processing ✓ source localization ✓ marine environment characterization	• Field inversion ✓ wind speeds ✓ rainfall rates	• Field inversion ✓ sea-floor imaging
• Ocean acoustic tomography ✓ density field (eddies, currents) ✓ temperature (climate monitoring)	• Acoustic daylight ✓ object imaging	
• Deductive geoacoustic inversion ✓ sediment parameters ✓ sea-floor scattering characteristics	• Geoacoustic inversion ✓ seabed acoustics	

Mathematical Models of Noise

- Ambient noise models
  - Mean noise levels due to:
    - Surface weather
    - Biologics
    - Commercial activities (e.g., shipping, oil drilling)
  - Regression formulas
- Beam-noise statistics models
  - Low-frequency shipping noise
    - Application to large-aperture, narrow-beam passive sonars
    - Convolution of receiver beam pattern with noise intensities
  - Two approaches
    - Analytic (deductive)
    - Simulation (inductive)

Bathymetric and sound-speed structure in the North Pacific Ocean. The noise from distributed shipping sources at high latitudes can enter the sound channel and propagate with little attenuation to lower latitudes. Relationships between the sound speed structure and the prevailing water masses are also illustrated. (Kibblewhite et al., 1976.)



Beam-Noise Statistics Models

- Noise power at beamformer output

$$Y = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{A_{ij}} S_{ijk} Z_{ijk} B_{ijk}$$

m = number of routes in the basin

n = number of ship types

A_{ij} = number of ships of type j on route i (a random variable)

S_{ijk} = source intensity of the kth ship of type j on route i (a random variable that is statistically independent of the source intensity of any other ship)

Z_{ijk} = intensity transmission ratio from ship ijk to the receiving point

B_{ijk} = gain for a plane wave arriving at the array from ship ijk

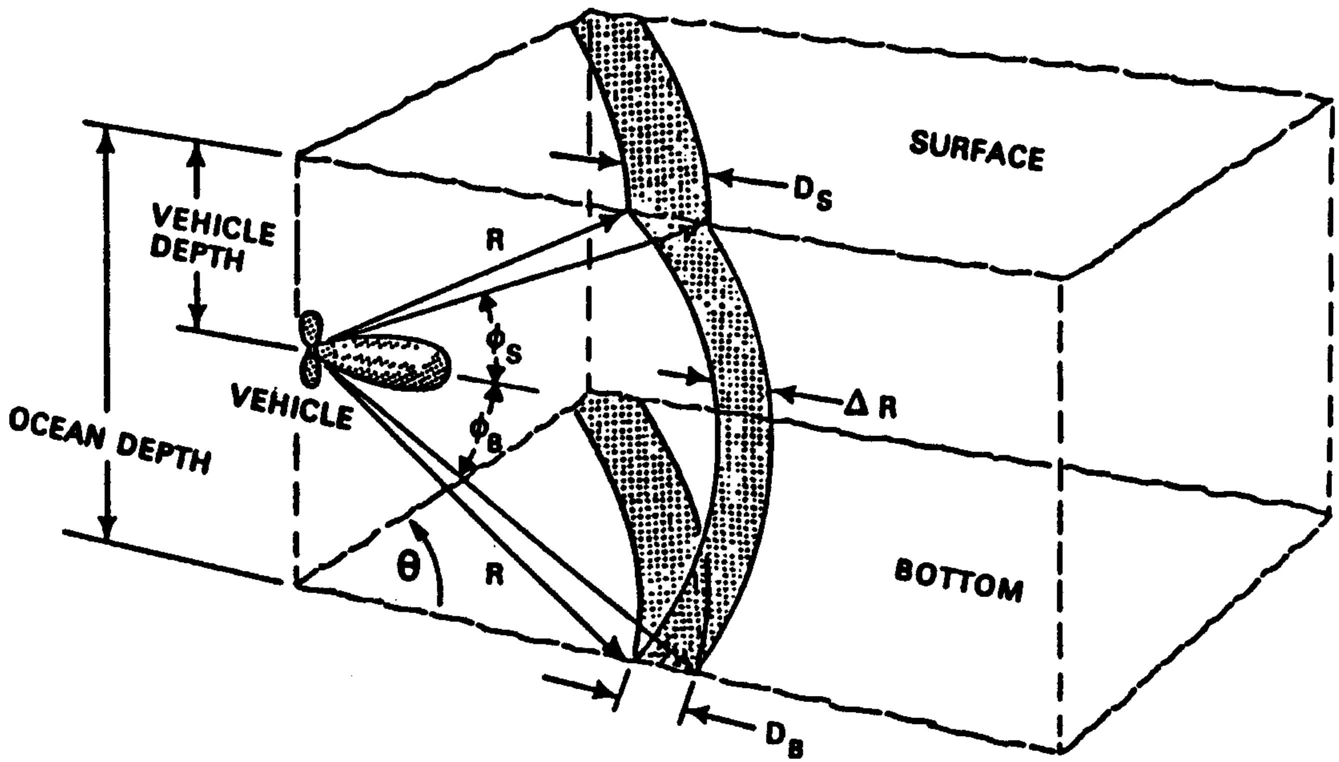
Summary of underwater acoustic noise models.

Ambient Noise	*Beam Noise Statistics*	
	Analytic	*Simulation*
AMBENT [1]	BBN Shipping Noise [11]	BEAMPL [15]
ANDES [2]	BTL [12]	DSBN [16]
CANARY [3]	USI Array Noise [13]	NABTAM [17]
CNOISE [4]	Sonobuoy Noise [14]	
DANES [5]		
DINAMO [6]		
DUNES [7]		
FANM [8]		
Normal Mode Ambient Noise [9]		
RANDI - I / II / III [10]		

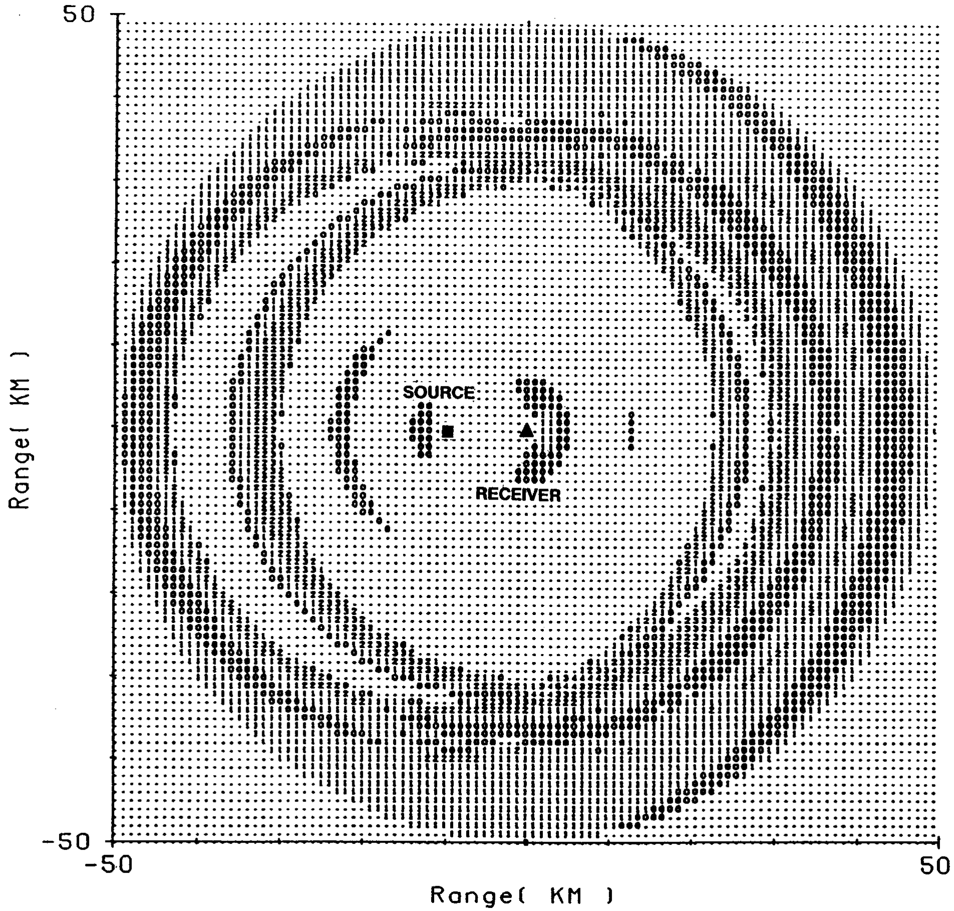
Classification of Reverberation Models

- **Cell Scattering Models**
  - Scatterers are uniformly distributed
  - Ocean is divided into cells, each containing a large number of scatterers
  - Backscattering strengths are used to approximate the target strength per unit area or volume
  - Summing the contributions of each cell yields the total average reverberation level as a function of time after transmission
- **Point Scattering Models**
  - Statistical approach in which the scatterers are randomly distributed
  - Reverberation is computed by summing the echoes from each individual scatterer

REVMOD reverberation model geometry. (Hodgkiss, 1984; *IEEE J. Oceanic Engr.*, **10**, 285-9; copyright by IEEE.)

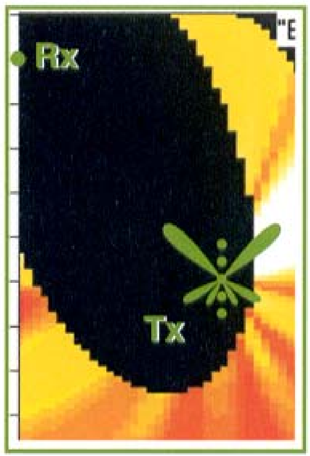


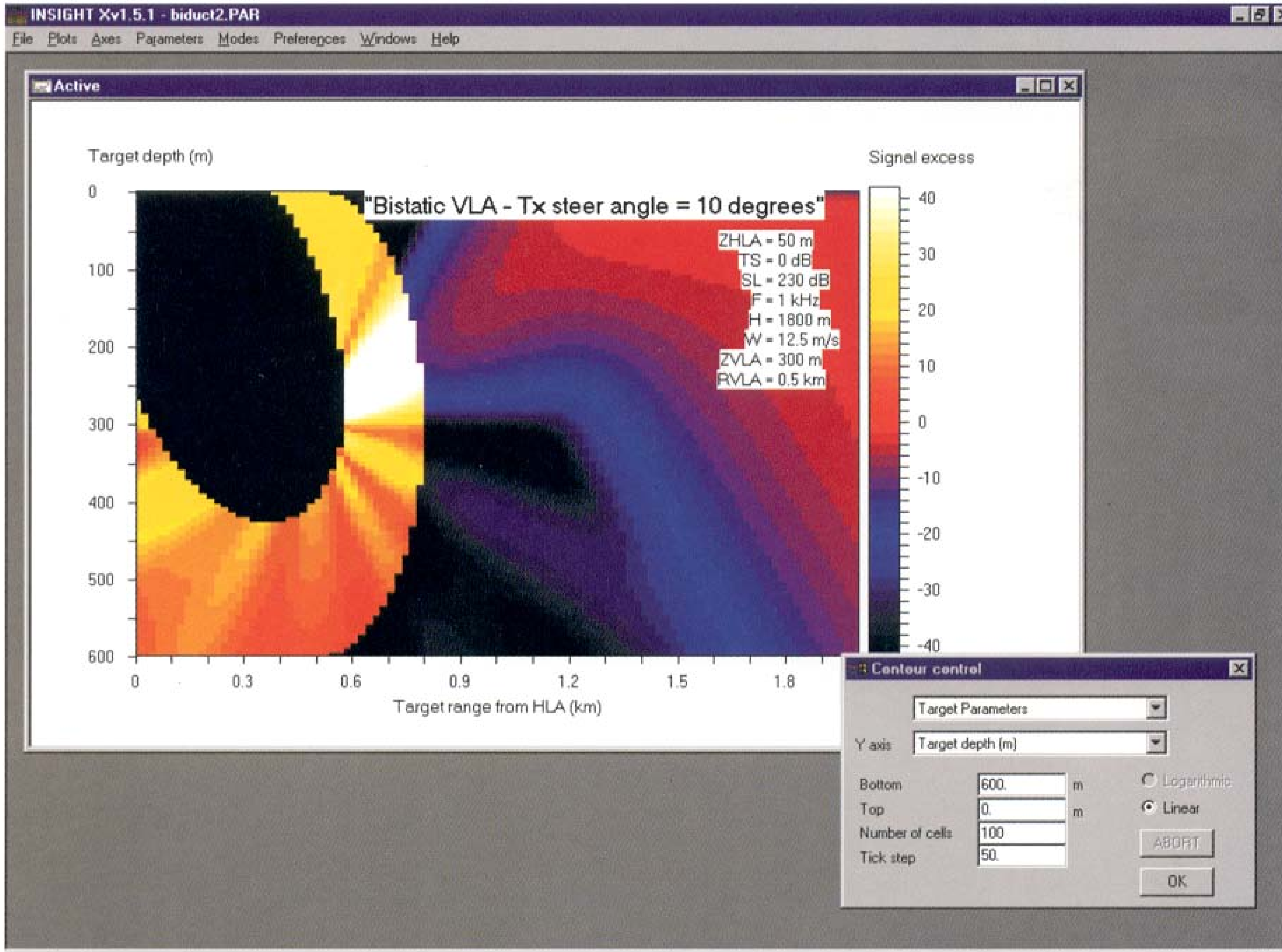
Sample output from the bistatic acoustic model (BAM) showing echo-to-background levels. Also shown is the cumulative area coverage contained within specified contours of echo-to-background level.



Symbol	Echo-to-Background Level
•	< -10 dB
0	-10 to -6
1	-6 to -2
2	-2 to 2
3	2 to 6
4	6 to 10
5	10 to 14
6	14 to 18
7	18 to 22
8	> 22

Contour Level	Cumulative Area
≥ -10 dB	4942 km^2
≥ -6	3427
≥ -2	871
≥ 2	283
≥ 6	45
≥ 10	2
≥ 14	0
≥ 18	0
≥ 22	0





Signal excess plotted as a function of target position for a bistatic sonar geometry. The transmitter is a steered vertical line array at a range of 500 m from the receiver and depth 300 m. Notice the black ellipsoidal region of low signal excess between transmitter and receiver due to direct blast reverberation.

Summary of underwater acoustic reverberation models.

Cell Scattering		*Point Scattering*	
Monostatic	*Bistatic*	*Monostatic*	*Bistatic*
DOP [1]	BAM [8]	REVGEN [16]	Under-Ice Reverberation Simulation [17]
EIGEN / REVERB [2]	BiKR [9]		
MAM [3]	BiRASP [10]		
PEREV [4]	BISAPP [11]		
REVMOD [5]	BISSM [12]		
REVSIM [6]	OGOPOGO [13]		
TENAR [7]	RASP [14]		
	RUMBLE [15]		

Sonar Equations

- Active sonars
  - Noise background

    $$SL - 2TL + TS = NL - DI + RD_N$$

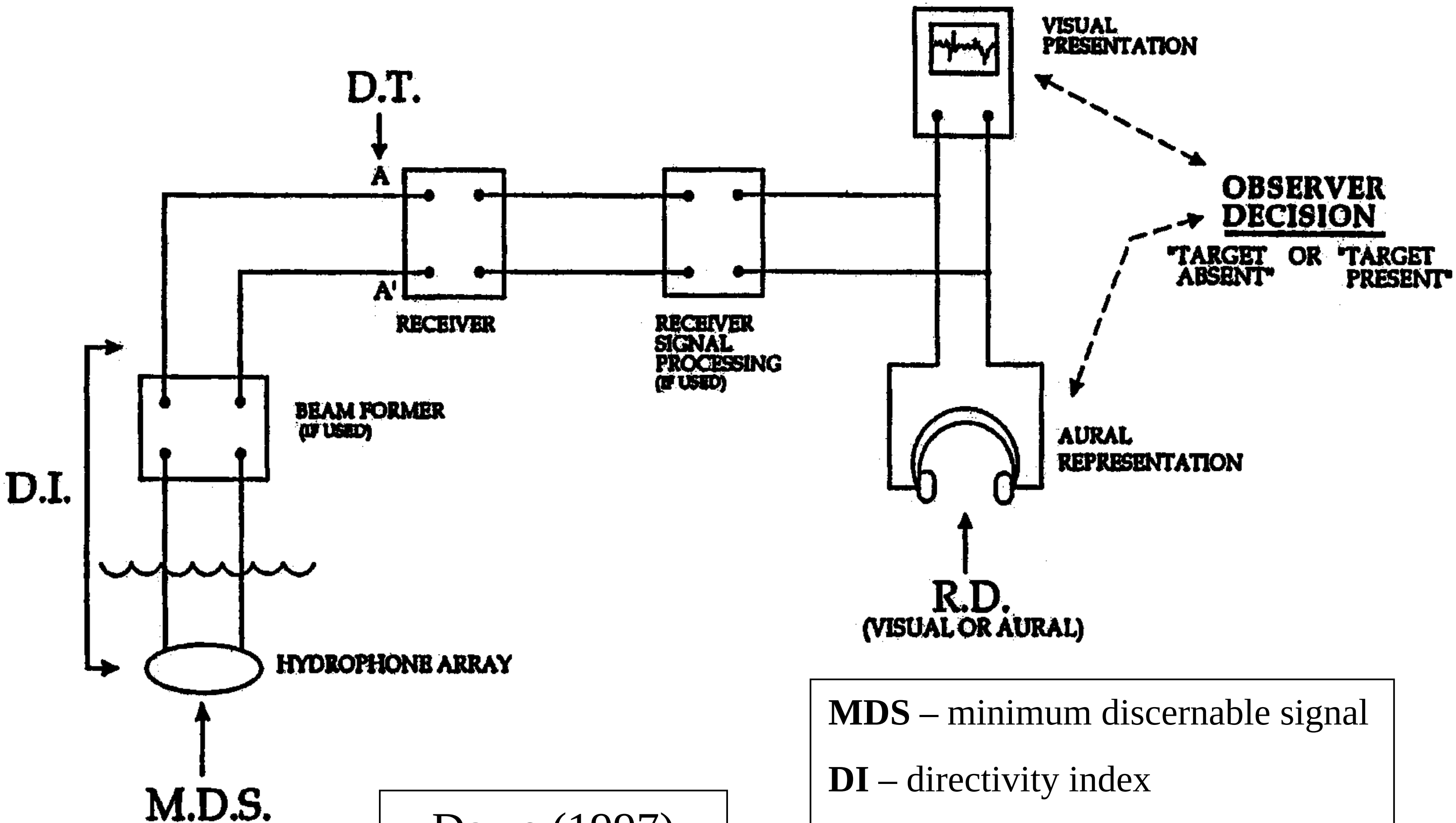
  - Reverberation background

    $$SL - 2TL + TS = RL + RD_R$$

- Passive sonars

  $$SL - TL = NL - DI + RD$$

Components of Detection Process



Dawe (1997)

MDS – minimum discernable signal

DI – directivity index

DT – detection threshold

RD – recognition differential

INSIGHT v1.4.5 - Active.PAR - [Active]
In-beam Spectrum Level (dB re 1 µPa²/Hz)
"Active plot title"
Target Depth = 200 m
Array Depth = 100 m
TS = 30 dB
SL = 220 dB
R = *
F = 4000 Hz
H = 3600 m
W = 10 m/s
Signal
Wind Noise
Shipping Noise
Rain Noise
Surface Reverberation
Bottom Reverberation
Volume Reverberation
Target range (km)

Summary of primary data banks.

Data bank	*Custodian*	*Representative database parameters*
FNMOC Data Files http://www.fnmoc.navy.mil/	FNMOC	*Marine meteorology* ▪ Solar radiation ▪ Clouds ▪ Surface pressure ▪ Precipitation ▪ Surface air temperature ▪ Surface marine winds ▪ Total heat flux ▪ Sensible and evaporative heat fluxes *Oceanography* ▪ Wave direction, period and height ▪ Combined sea height direction and period ▪ Significant wave height ▪ Swell direction, period and height ▪ White caps ▪ Insolation, reflected radiation ▪ Sensible and evaporative heat flux ▪ Total heat flux ▪ Bathymetry ▪ Shipping density ▪ Operational bathy-thermograph observations ▪ MBT, XBT, STD, hydrocasts ▪ Sea-surface temperature ▪ Sea-surface temperature anomaly ▪ Potential mixed layer depth ▪ Primary layer depth ▪ Temperature at the top of the thermocline ▪ Thermocline gradient
DoD Bathymetric Data Library http://www.nima.mil/	NIMA	▪ Ocean floor depth
NAVOCEANO Data Files http://www.navo.navy.mil/	NAVOCEANO	▪ Bathymetry ▪ Climatology ▪ Temperature / salinity / oxygen versus depth ▪ Computed sound speed, sigma-t, specific volume ▪ Conductivity ▪ Transmission loss ▪ Ambient noise ▪ Volume reverberation ▪ Bottom loss ▪ Surface currents ▪ Subsurface currents ▪ Ice type / thickness ▪ Core samples ▪ Sediment samples ▪ Geomagnetics ▪ Seismic profiles ▪ Gravity ▪ Dangerous marine animals ▪ Boring / fouling organisms ▪ Plankton ▪ Bioluminescence

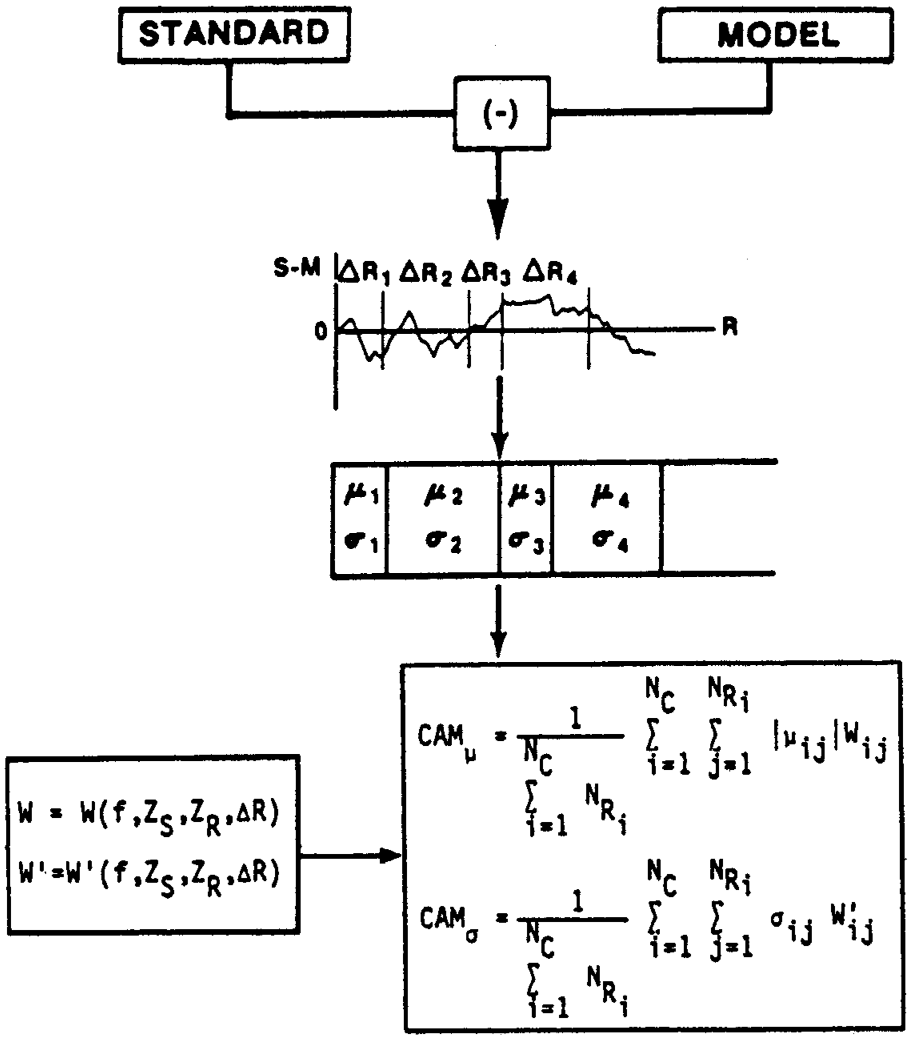
Summary of primary data banks (continued).

NCDC Marine Climatic Data Files http://lwf.ncdc.noaa.gov/oa/ncdc.html	NOAA / NCDC	▪ Air temperature ▪ Pressure ▪ Waves	▪ Dew point temperature ▪ Sea-surface temperature	▪ Low clouds ▪ Total clouds	▪ Wind ▪ Visibility
NGDC Marine Geology and Geophysics Data Files http://www.ngdc.noaa.gov/	NOAA / NGDC	▪ Airborne magnetic survey (elements D,I,F) ▪ Marine magnetic survey (total intensity F only)	▪ Megascopic core description, marine geological sample index, grain size analysis	▪ Digital hydrographic survey ▪ Summary bathymetric and topographic files	▪ Marine bathymetry ▪ Seismic profiles ▪ Marine gravity
NODC Data Files http://www.nodc.noaa.gov/	NOAA / NODC	▪ Temperature ▪ Salinity ▪ Computed sound speed	▪ Marine meteorological parameters	▪ Marine chemical parameters	▪ Surface currents

Summary of sonar performance models including active sonar models, model-operating systems and tactical decision aids.

Active Sonar Models		*Model Operating Systems*	*Tactical Decision Aids*
Active RAYMODE [1]	LORA [11]	CAAM [20]	IMAT [25]
ALMOST [2]	MINERAY [12]	CASS [21]	NECTA [26]
ASPM [3]	MOCASSIN [13]	GSM – Bistatic [22]	
CASTAR [4]	MSASM [14]	HydroCAM [23]	
CONGRATS [5]	NISSM – II [15]	PRISM [24]	
GASS [6]	SEARAY [16]		
HODGSON [7]	SONAR [17]		
INSIGHT [8]	SST [18]		
INSTANT [9]	SWAT [19]		
LIRA [10]			

Summary of the POSSM model evaluation methodology. (Lauer, 1979.)



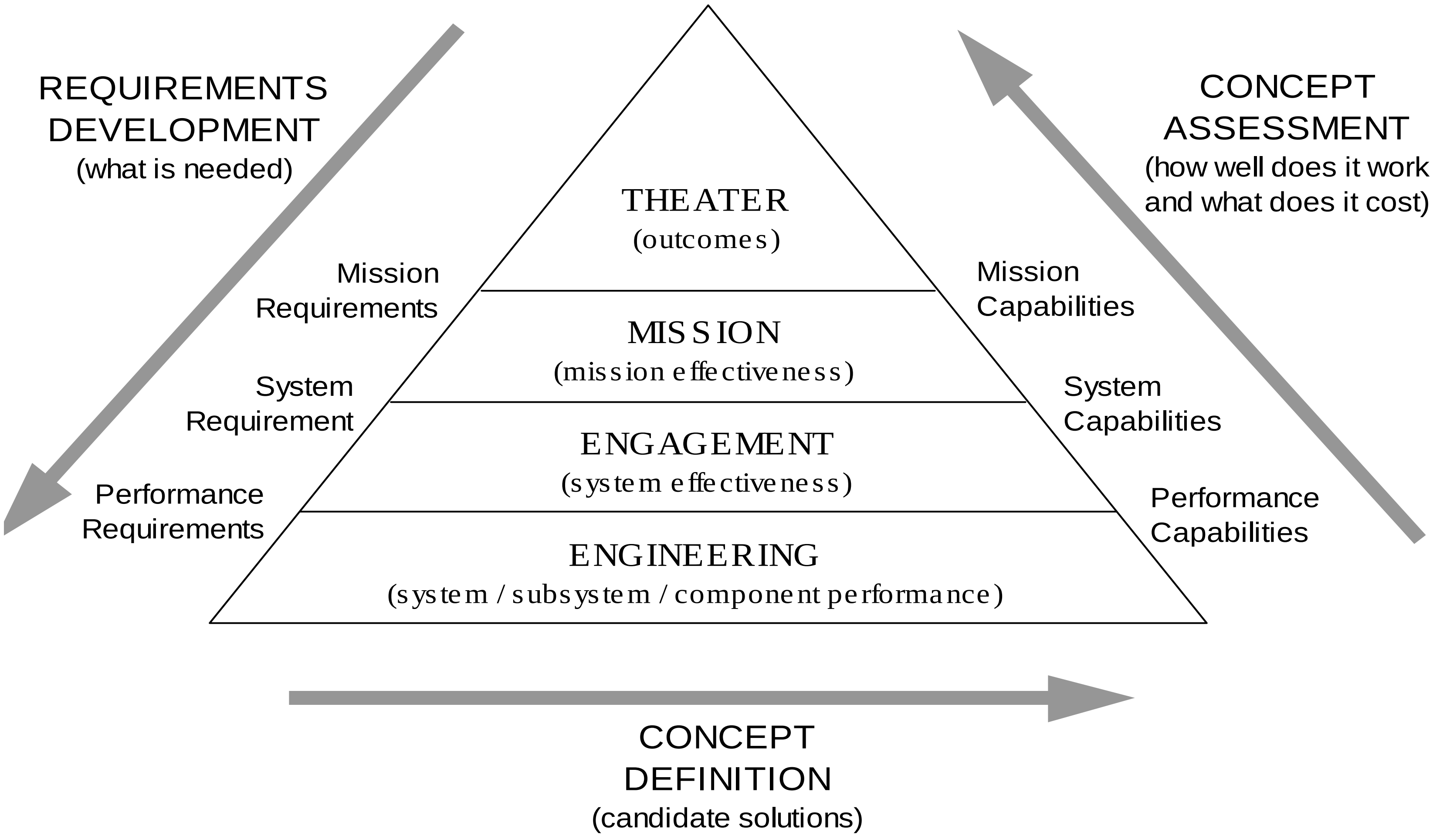
Four categories of simulation based on the degree of human involvement.

	Real systems	*Simulated systems*
Real people	Live Simulation	Virtual Simulation
Simulated people	Smart Systems	Constructive Simulation

Four principal levels of simulation for naval applications.
(National Research Council, 1997.)

Level	*Output*	*General Applications*
Theater	Force dynamics	• Evaluate force structures. • Evaluate strategies.
Mission	Mission effectiveness	• Evaluate force employment concepts.
Engagement	System effectiveness	• Evaluate system alternatives. • Train system operators. • Evaluate tactics.
Engineering	System performance	• Design and evaluate systems/subsystems. • Support system testing.

Modeling and simulation in system design. (US Department of the Navy, 2000a.)



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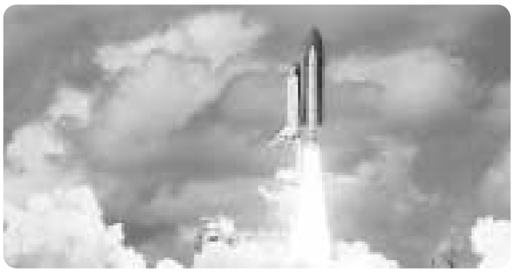

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- Signal Processing & Information Technology
- Sonar & Acoustic Engineering
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