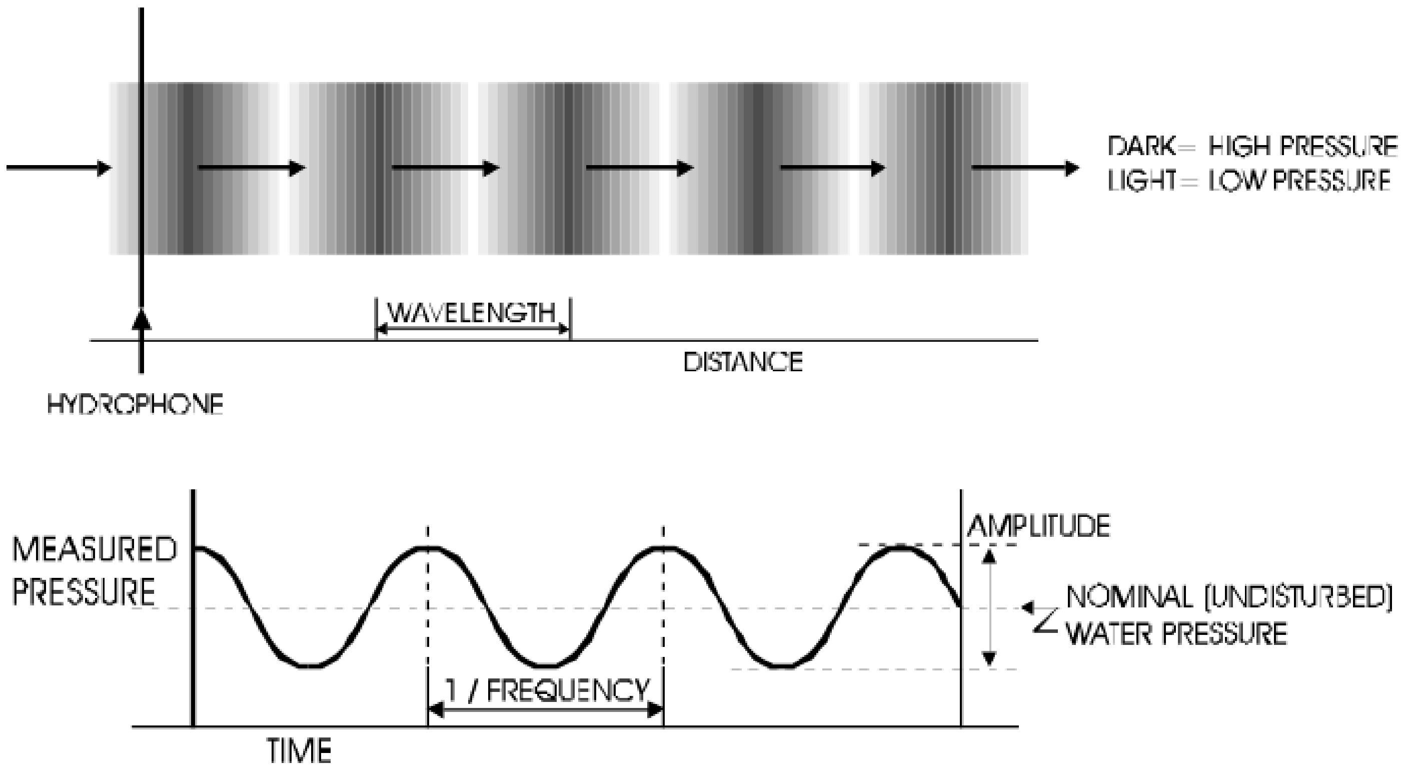
MARINE PHYSICAL LABORATORY

SEAFLOOR MAPPING APPLICATIONS:

- Safety of navigation, underkeel clearance
- Cable route surveys
- Offshore mining + oil & gas exploration
- Fisheries management
- Base maps for ocean circulation modeling
- Understanding tectonic structures and forces (seismicity, hydrothermal venting)

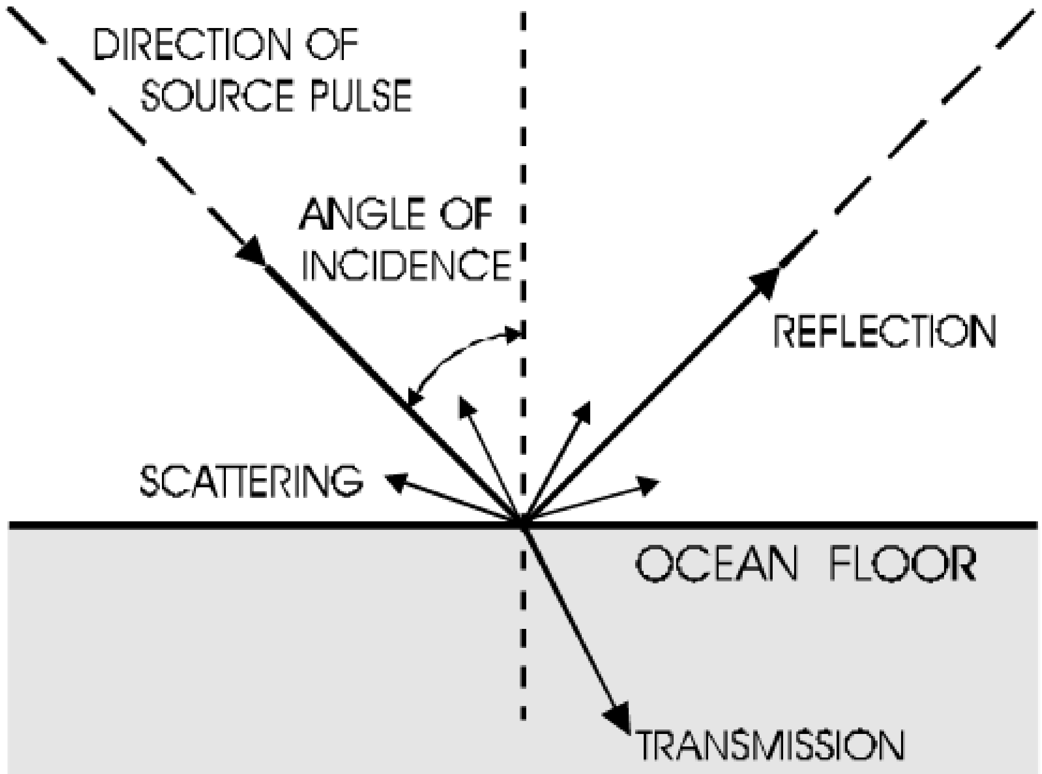
Components of a Sound Wave



Speed of sound = frequency x wavelength

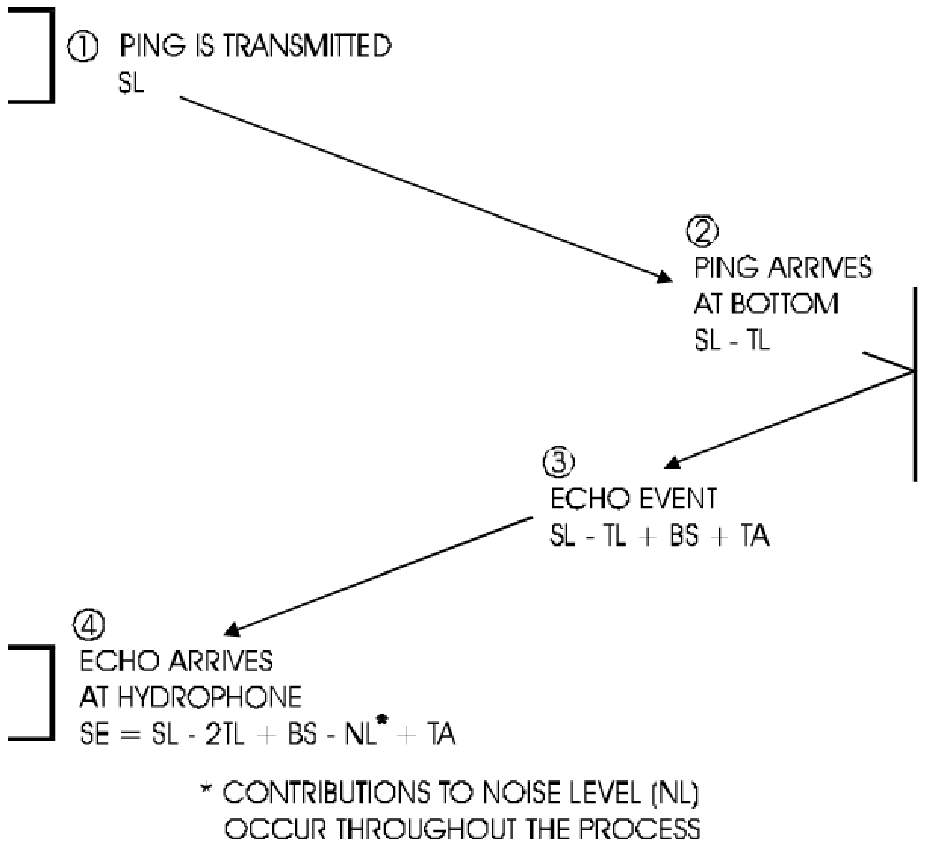
1500 m/s = 12 kHz x 0.125 m

Components of an Echo Event at the Sea Floor



Incident energy is partitioned between transmission into the sea floor and the echo, which is both reflection and scattering back into the water

Ping cycle



SE = signal excess

TL = transmission loss

BS = back scatter

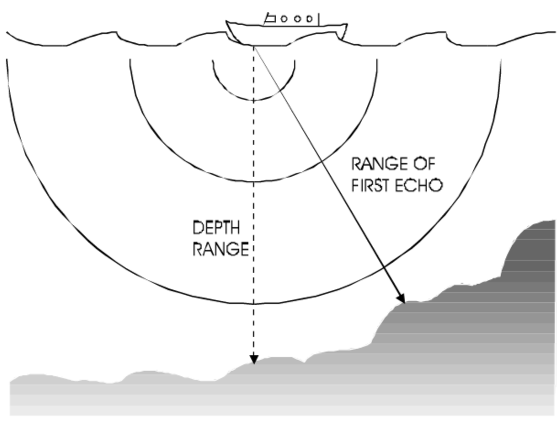
TA = target area

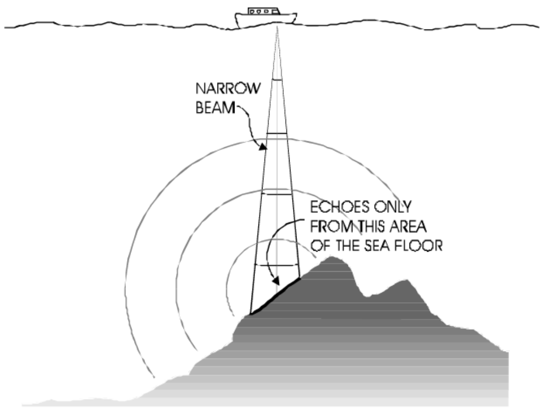
NL = noise level (active throughout cycle)

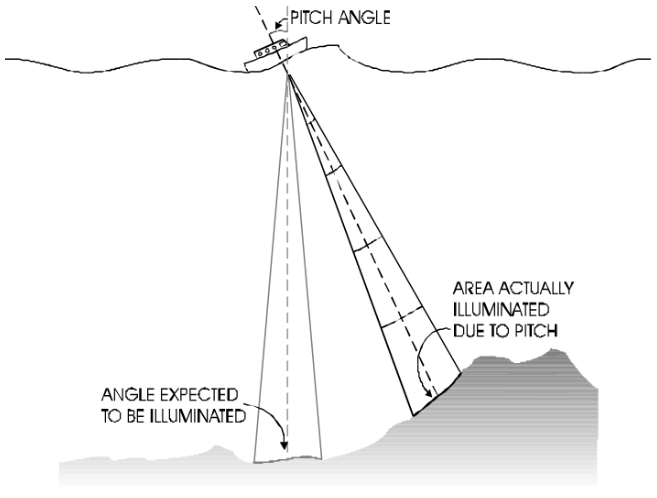
$$SE = SL - 2TL - NL + (BS + TA)$$

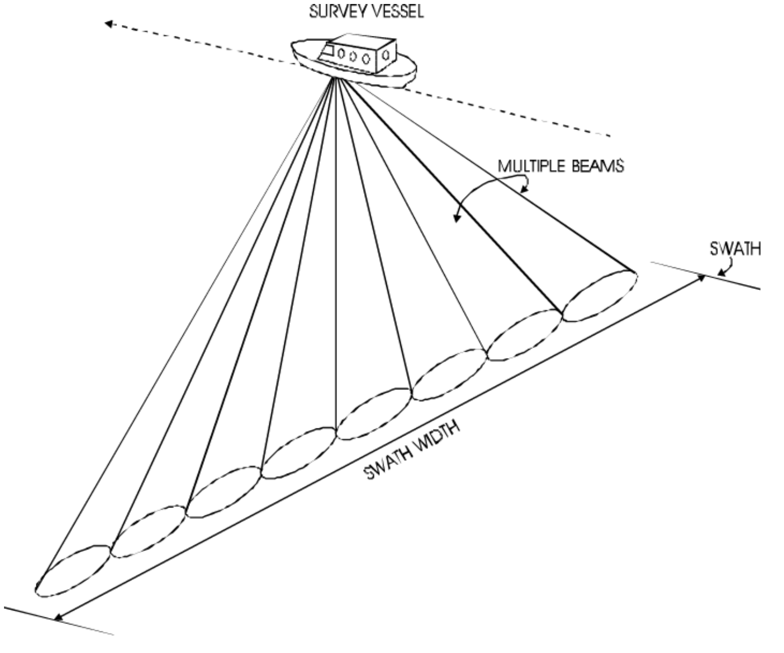
e.g., $SE = 220\ dB - 2x70\ dB - 40\ dB - 20\ dB$

Single-beam versus multi-beam sonars









Two main approaches to swath bathymetry:

1. Multi-beam Sonars

2. Multi-row Sidescan Sonar

Issues:

•Resolution in range and azimuth

•Narrow fore-aft beamwidth on transmit

•Sonar calibration for quantitative studies

Multibeam Bathymetry: “Classic” SEABEAM

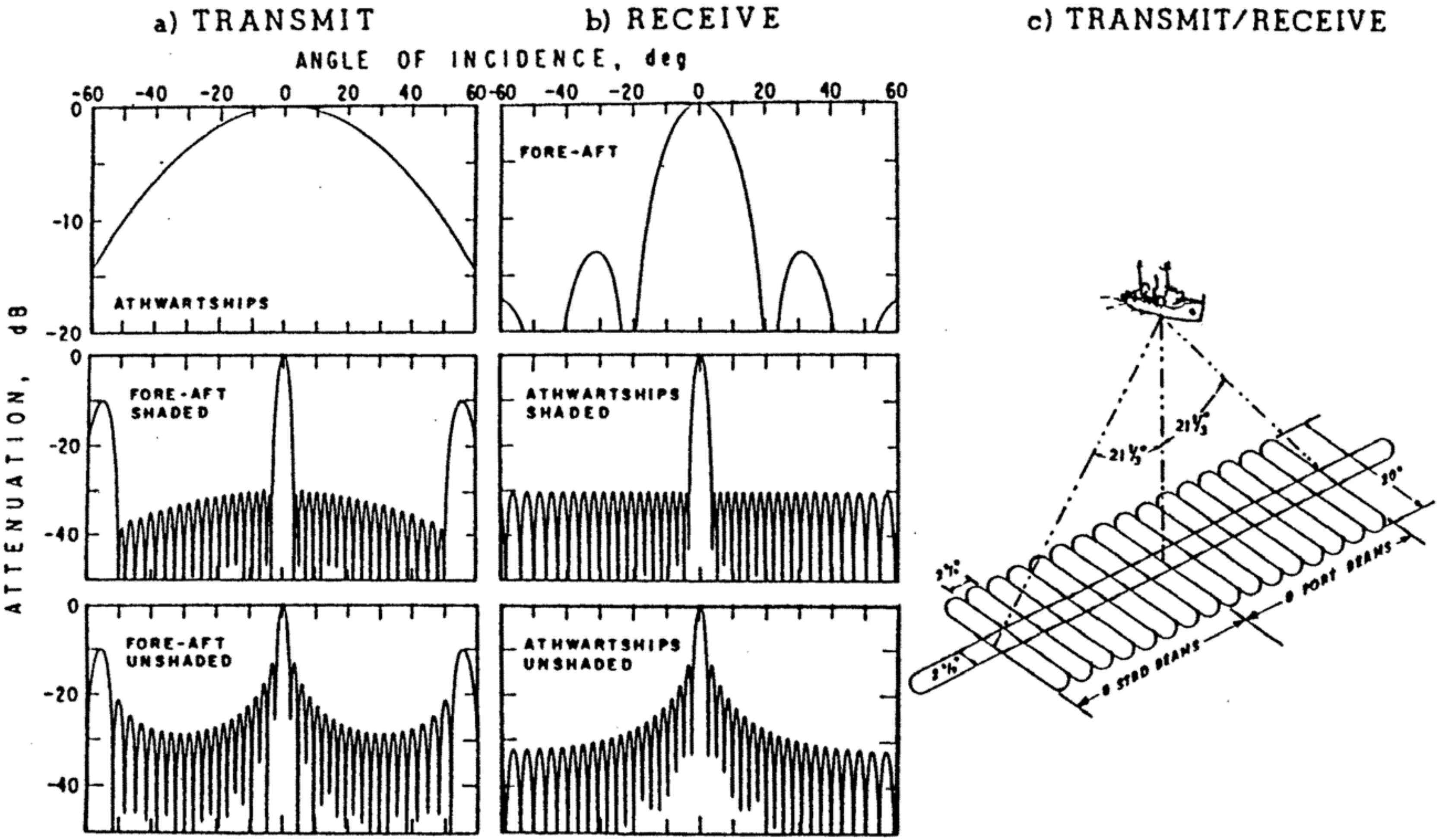
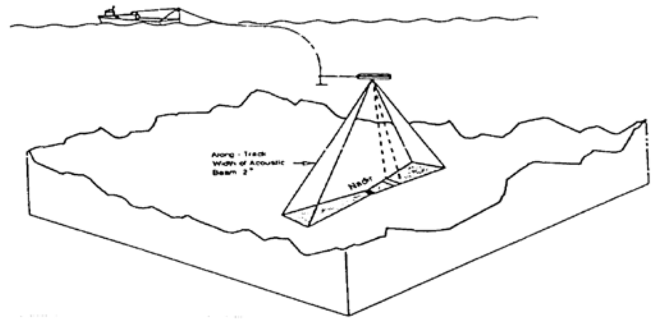
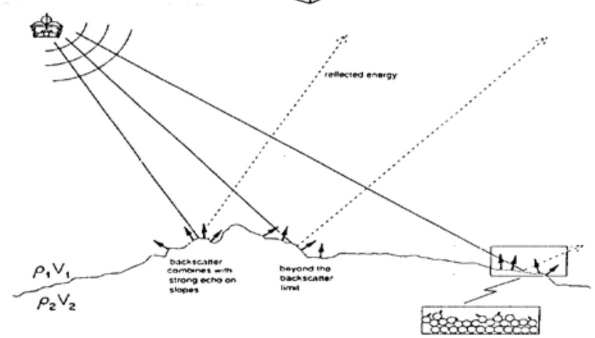
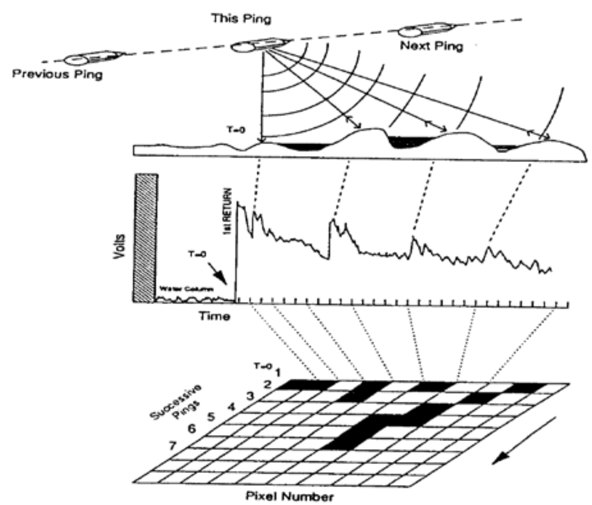


FIG. 1. — Theoretical radiation pattern for the Sea Beam system: (a) Transmit, (b) Receive, (c) Cross fan beam geometry (from de MOUSTIER and KLEINROCK [27]).

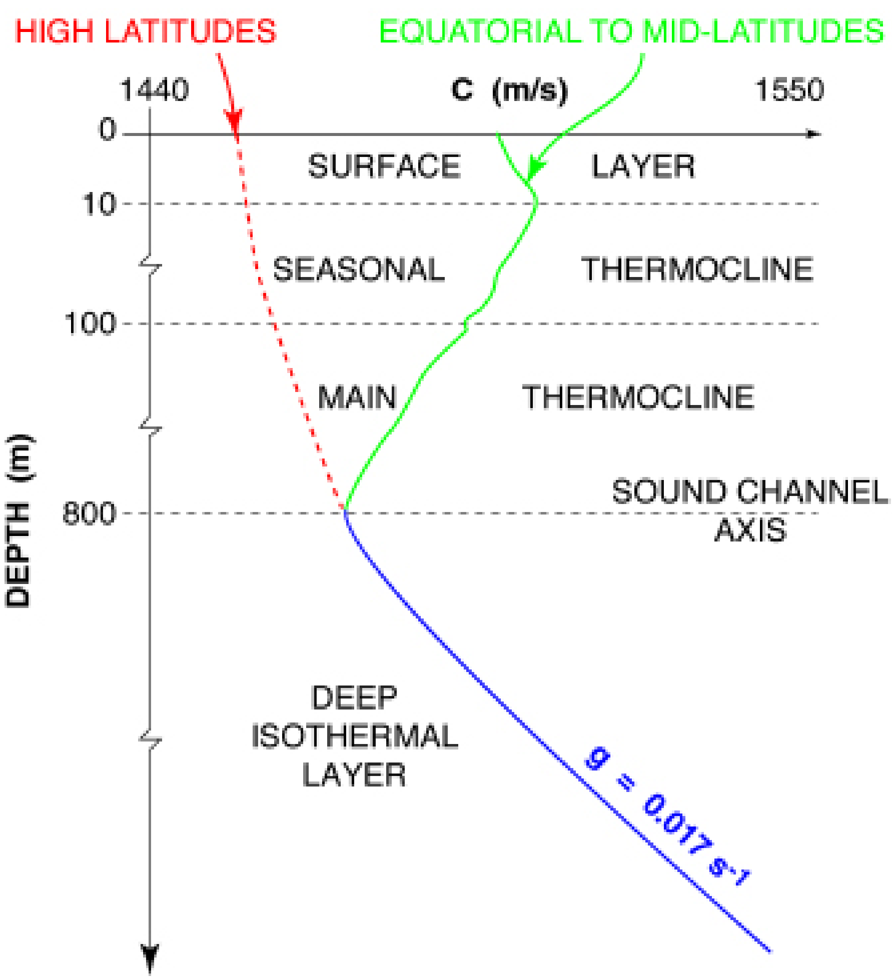
SideScan Sonar

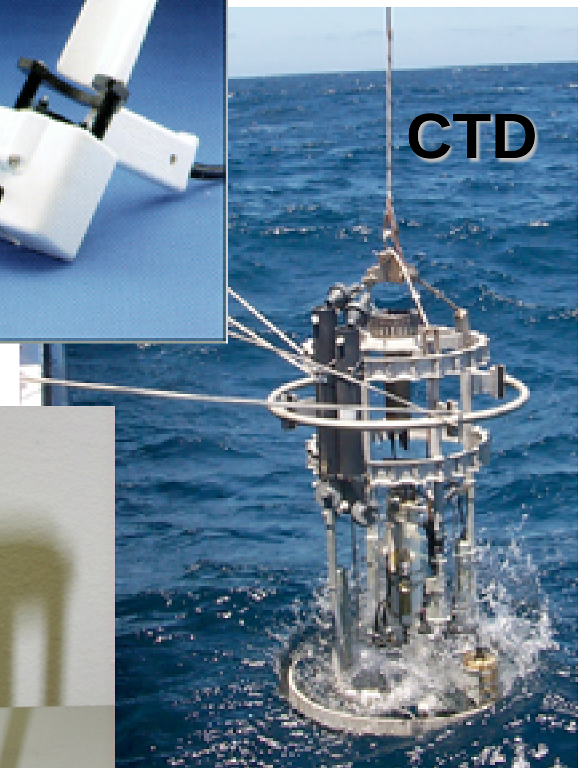




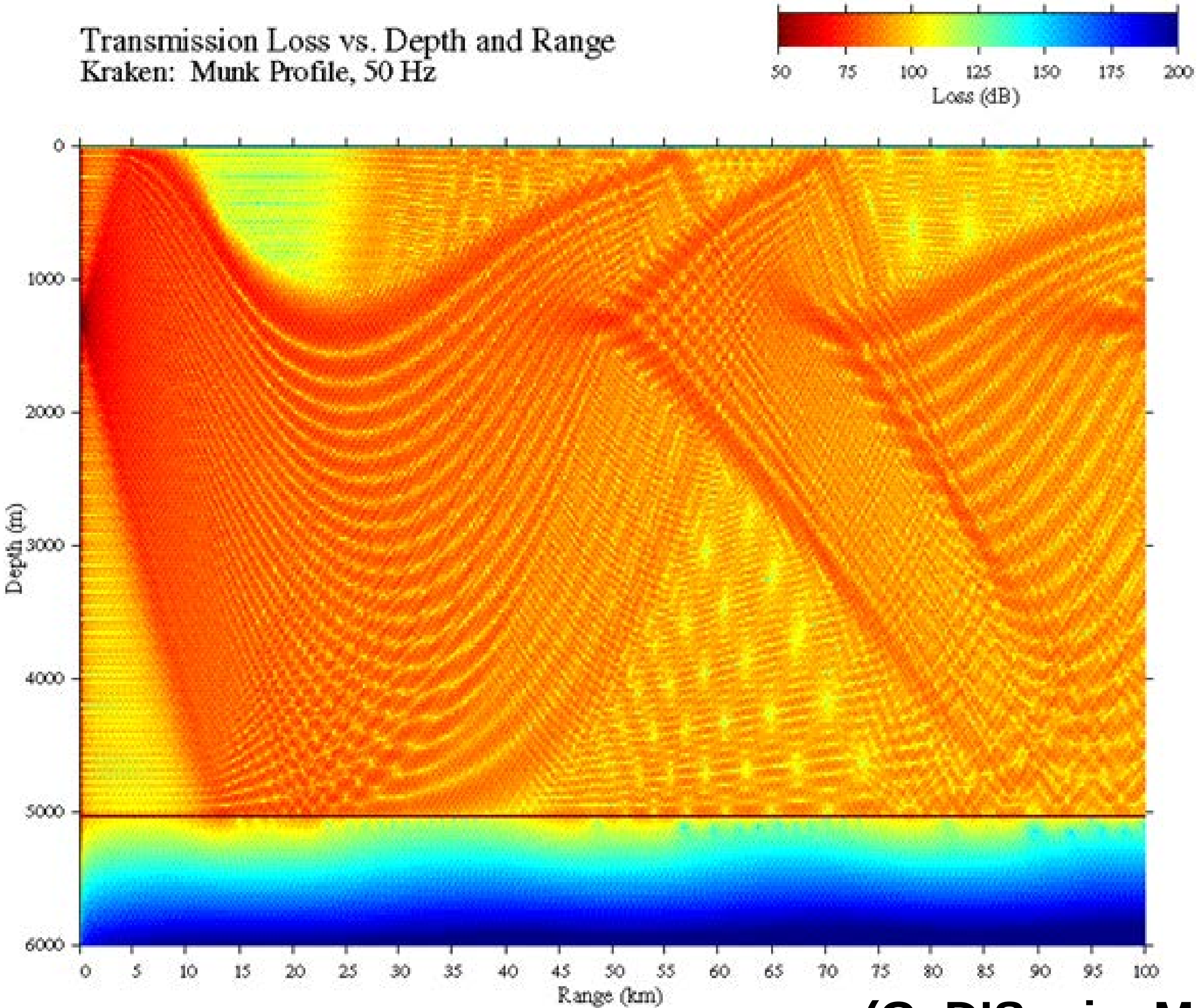


Sound Speed vs. Depth





SOUND SPEED


Transmission Loss vs. Depth and Range
Kraken: Munk Profile, 50 Hz
50 75 100 125 150 175 200
Loss (dB)
0
1000
2000
3000
4000
5000
6000
Depth (m)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Range (km)

(G. D'Spain, MPL)

Nimitz Marine Facilities, Scripps institution of Oceanography

Research Vessels

- Roger Revelle -1996
- Melville-1969
- New Horizon-1978
- R.G. Sproul-1981

Research Platform

- FLIP(Floating Instrument Platform) 1962

R/V ROGER REVELLE

Built 1996

Length: 273' 8"

Beam: 52 '6"

Draft, Full: 17 '

Cruising Speed: 12 kts

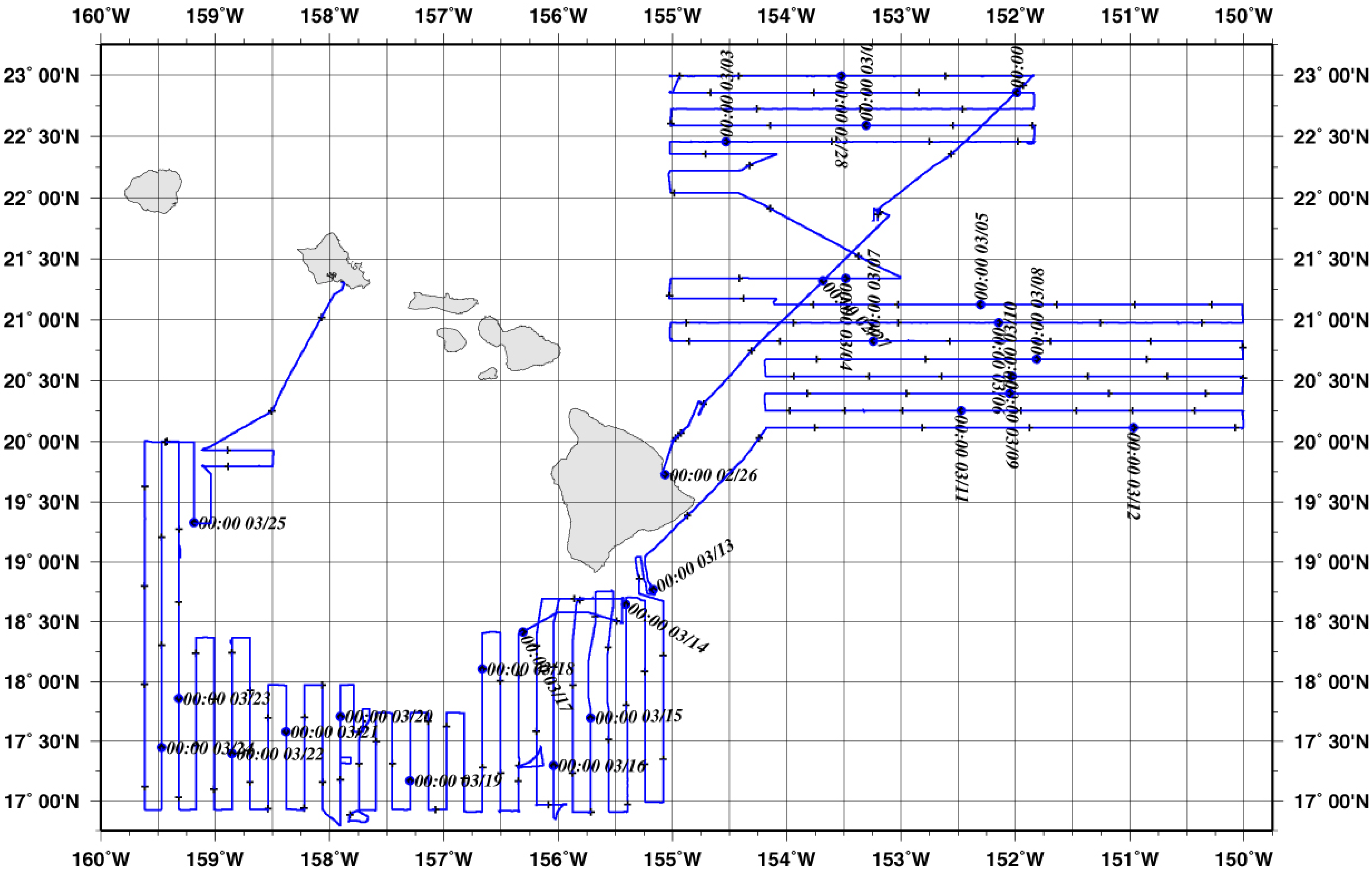
Crew: 22

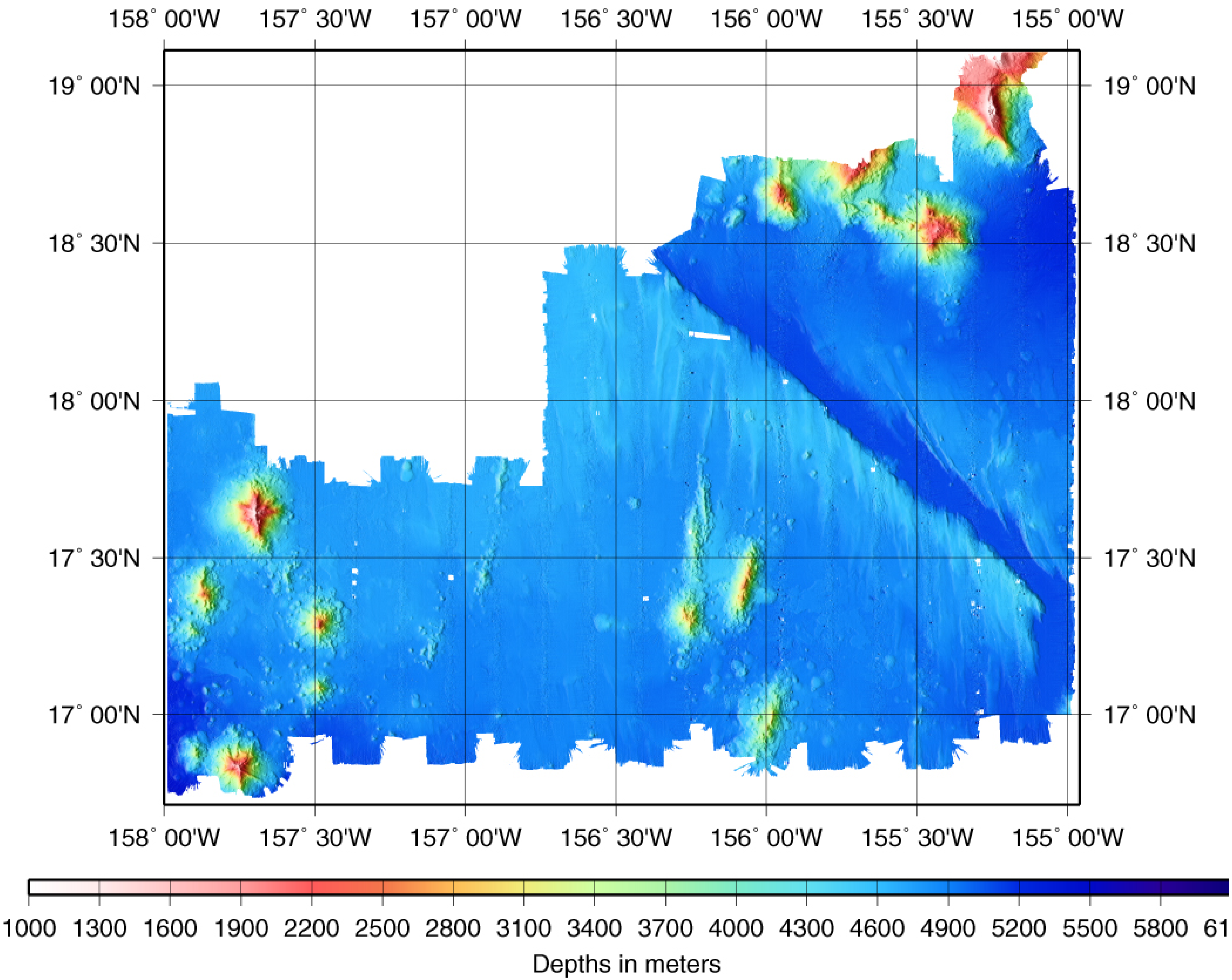
Scientific Party: 37

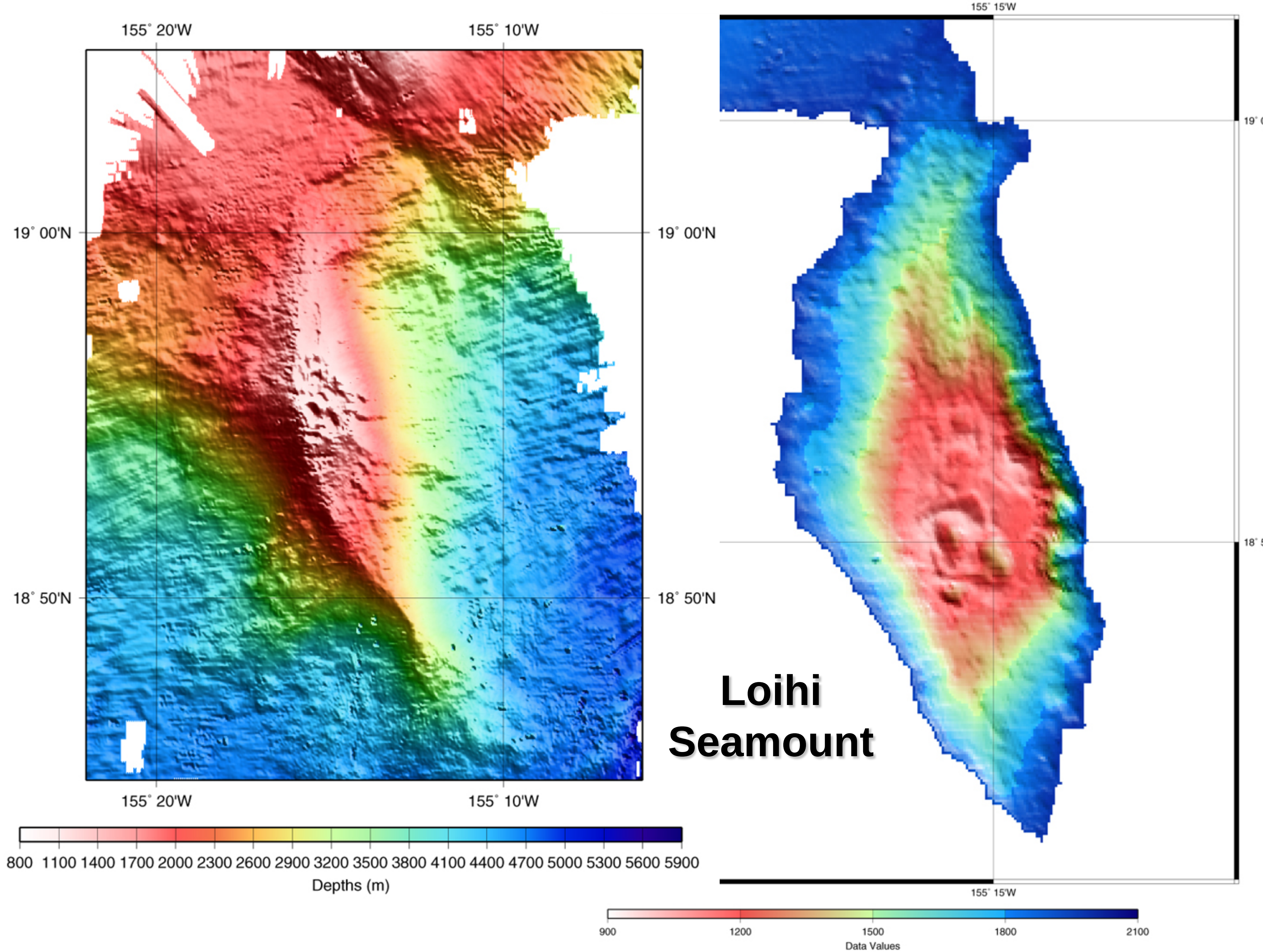
R/V Roger Revelle
Kongsberg-Simrad EM120 Installation 1-2001

Multibeam Sonar

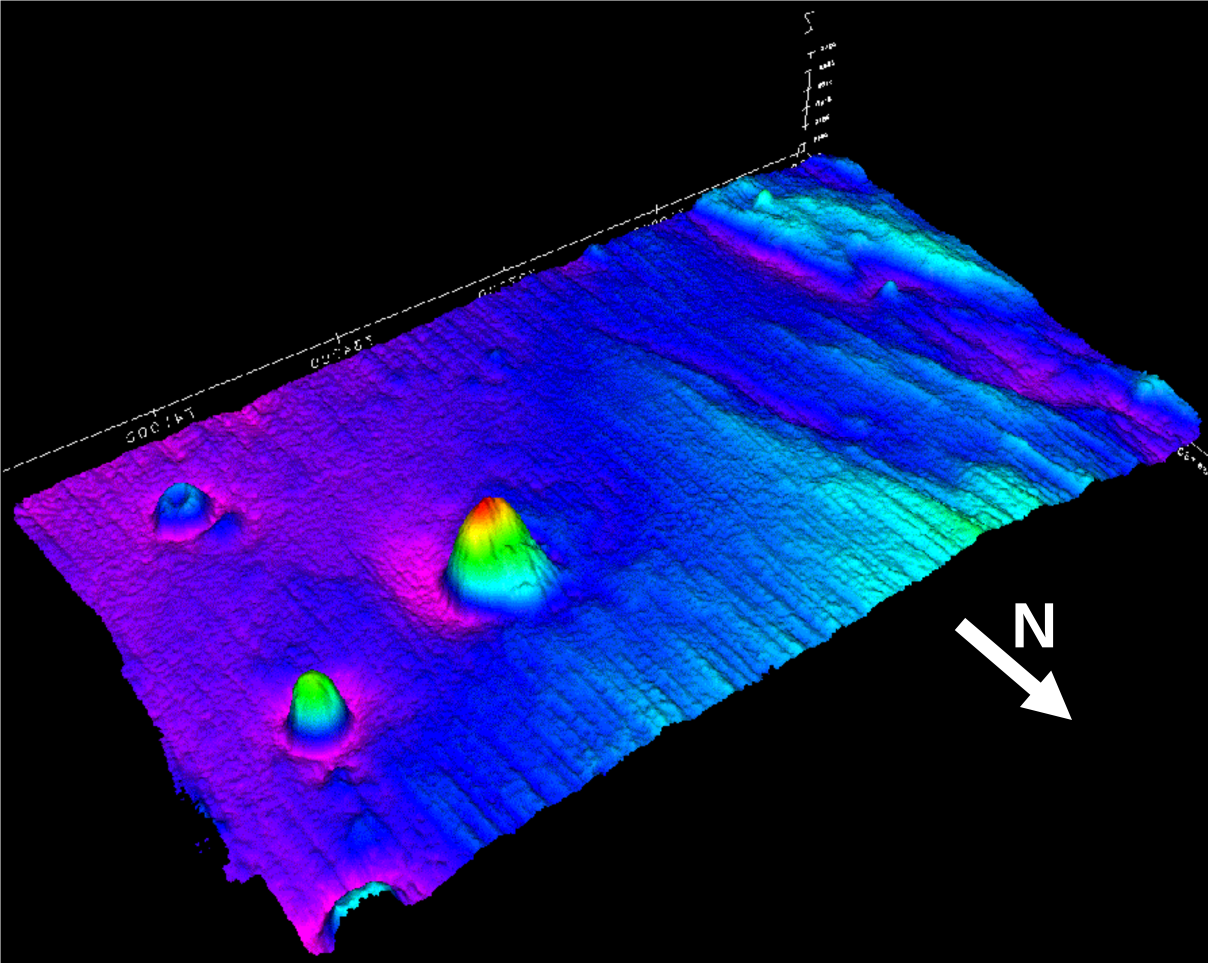
STN-Atlas


160°W
159°W
158°W
157°W
156°W
155°W
154°W
153°W
152°W
151°W
150°W
23° 00'N
22° 30'N
22° 00'N
21° 30'N
21° 00'N
20° 30'N
20° 00'N
19° 30'N
19° 00'N
18° 30'N
18° 00'N
17° 30'N
17° 00'N
00:00 03/03
00:00 02/28
00:00 03/05
00:00 03/08
00:00 03/04
00:00 03/11
00:00 03/09
00:00 03/12
00:00 02/26
00:00 03/25
00:00 03/13
00:00 03/14
00:00 03/18
00:00 03/17
00:00 03/23
00:00 03/20
00:00 03/15
00:00 03/21
00:00 03/22
00:00 03/16
00:00 03/19

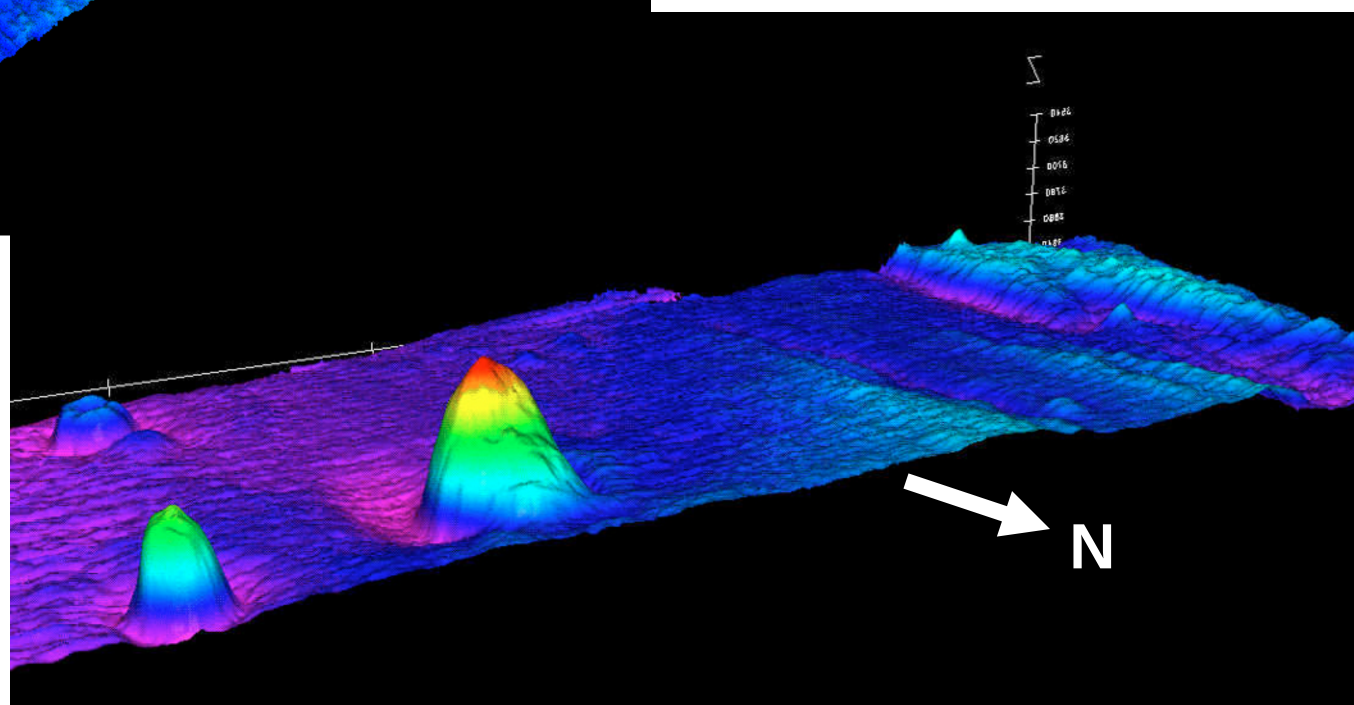

158° 00'W
157° 30'W
157° 00'W
156° 30'W
156° 00'W
155° 30'W
155° 00'W
19° 00'N
18° 30'N
18° 00'N
17° 30'N
17° 00'N
1000
1300
1600
1900
2200
2500
2800
3100
3400
3700
4000
4300
4600
4900
5200
5500
5800
61
Depths in meters



155° 20'W
155° 10'W
19° 00'N
18° 50'N
800 1100 1400 1700 2000 2300 2600 2900 3200 3500 3800 4100 4400 4700 5000 5300 5600 5900
Depths (m)
155° 15'W
Loihi Seamount
900
1200
1500
1800
2100
Data Values



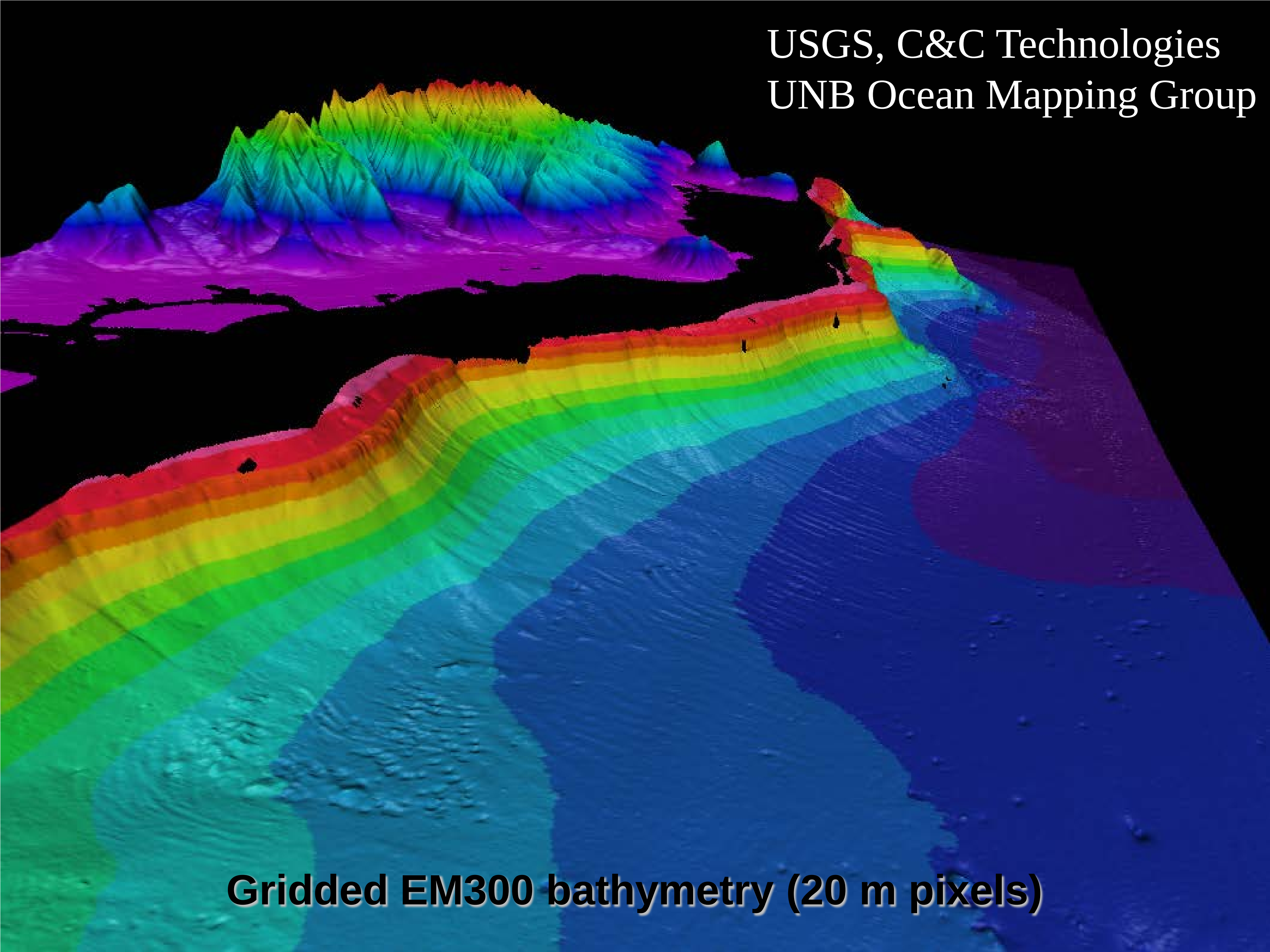
E-W Tracks



N-S Tracks

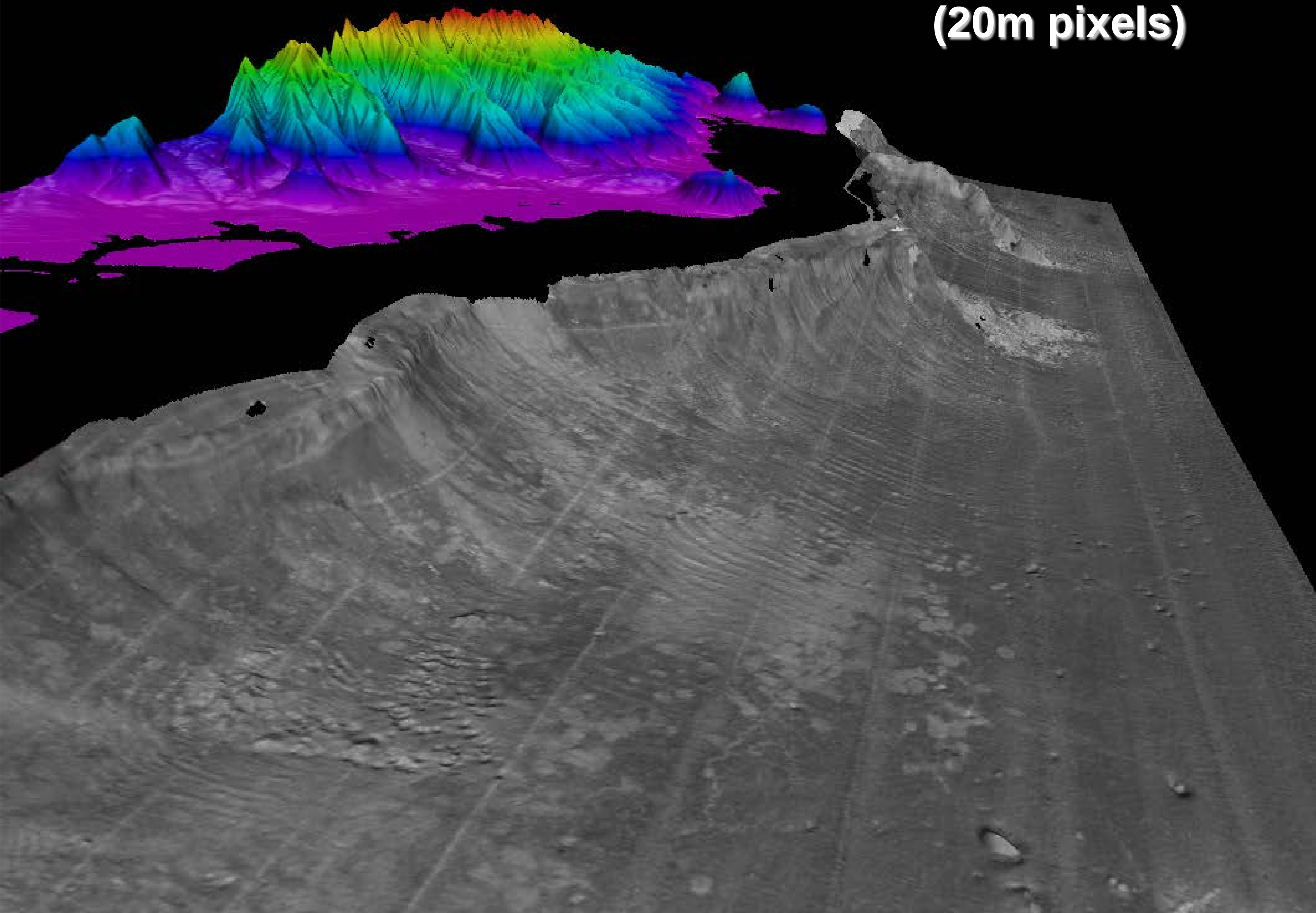
TECHNICAL CHALLENGES IN SEAFLOOR MAPPING:

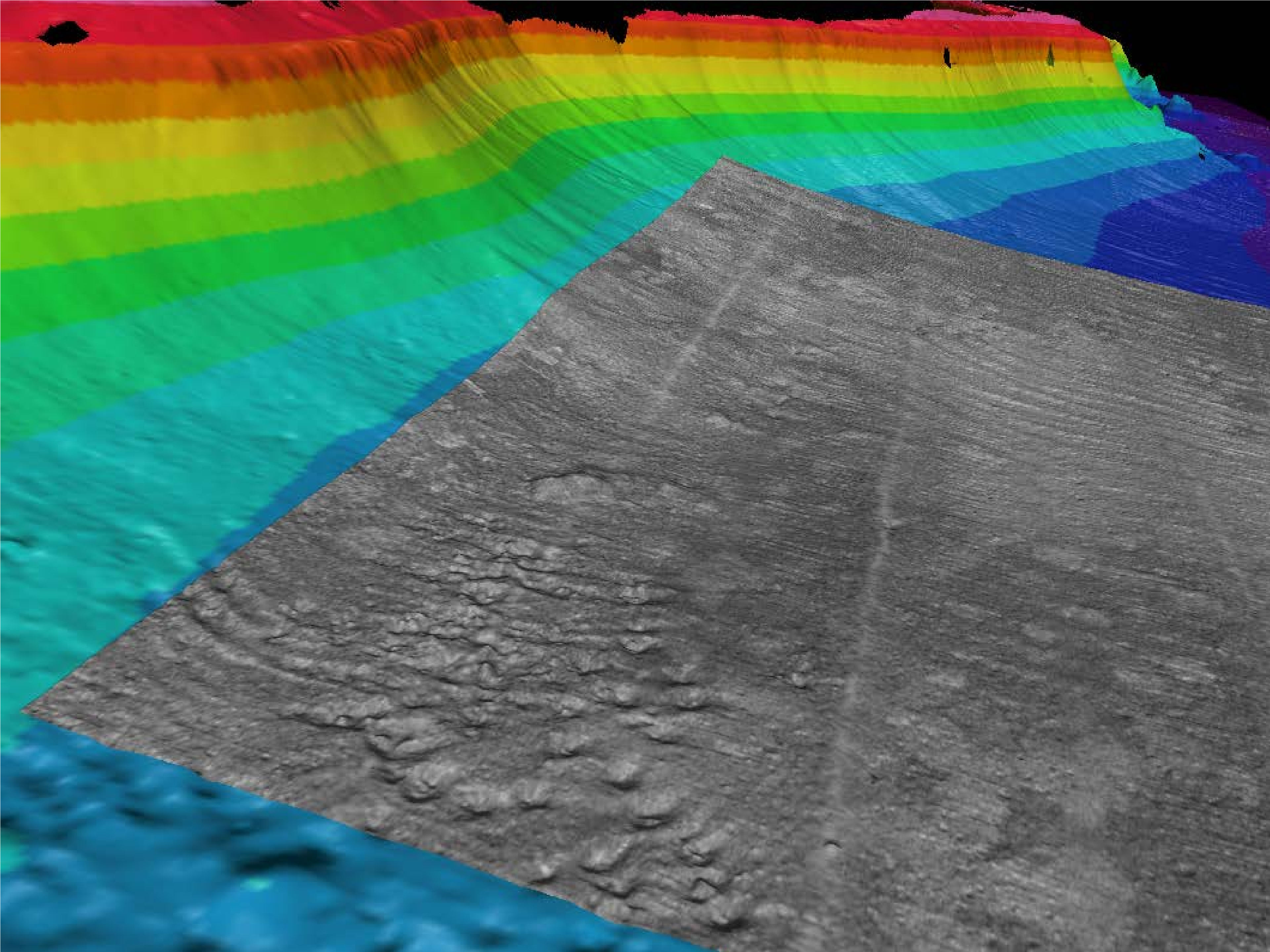
- **Attitude (roll, pitch, heading) accuracy <0.1º**
- **Knowledge of sound speed to ≤ 1m/s**
- **Offshore positioning < 0.5 m (x,y,z)**
- **Data storage, processing and display with input at > 100 Mb/h (>500 Mb/h in shallow water)**
- **Data transfer rates > 1Gb/min (100BaseT=1GB/80s)**
- **Database management**



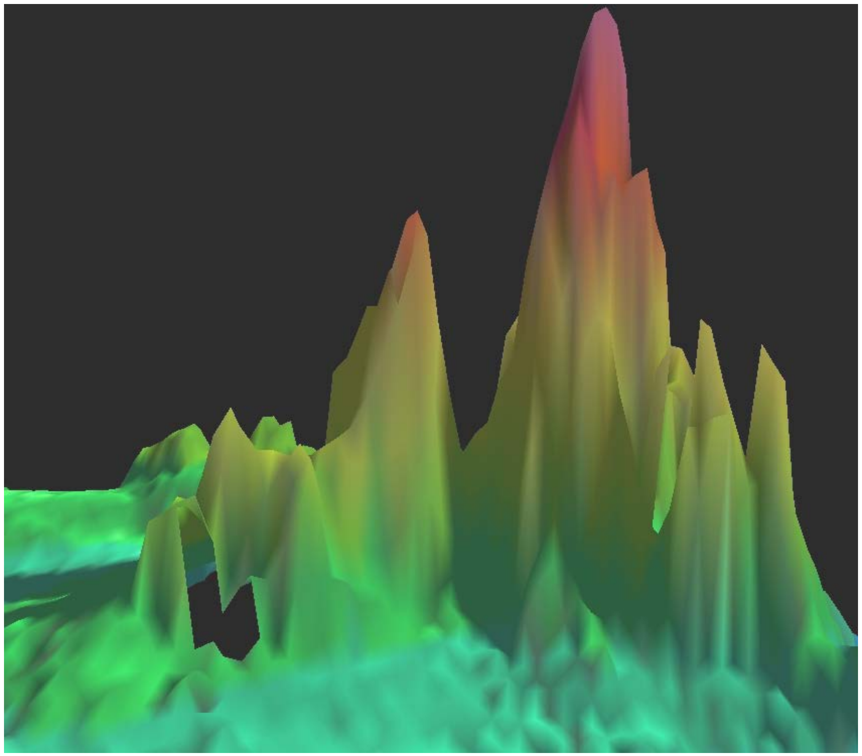
Gridded EM300 bathymetry (20 m pixels)

EM300 acoustic backscatter amplitude drapped on bathymetry (20m pixels)

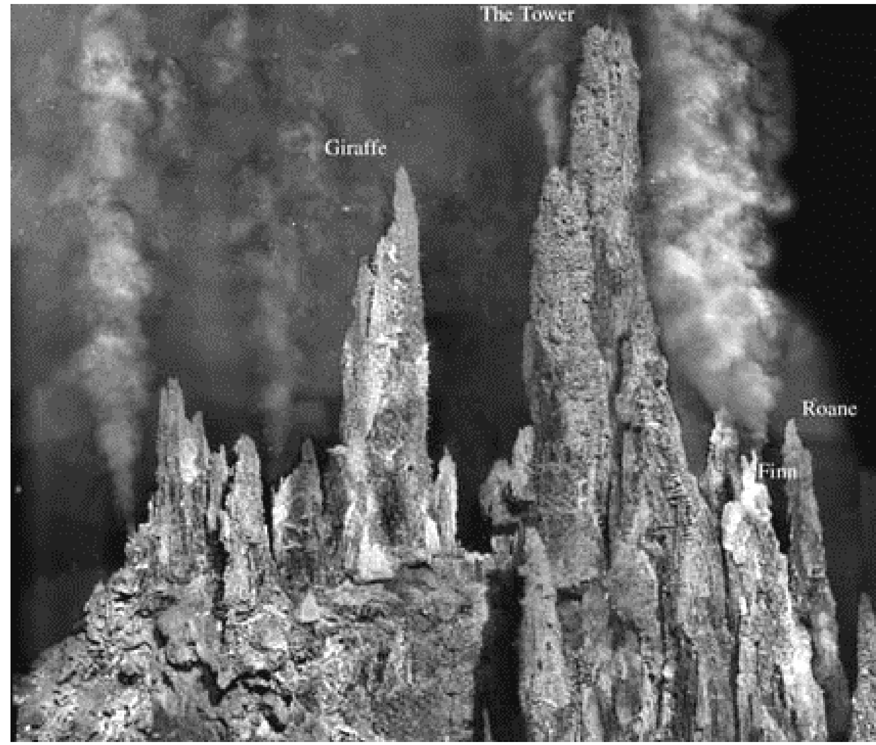




Juan de Fuca Ridge
Mothra Hydrothermal Field



3-D acoustic image of Mothra field from Imagenix sonar data - raw acoustic data from Univ. of Washington (J. Delaney)

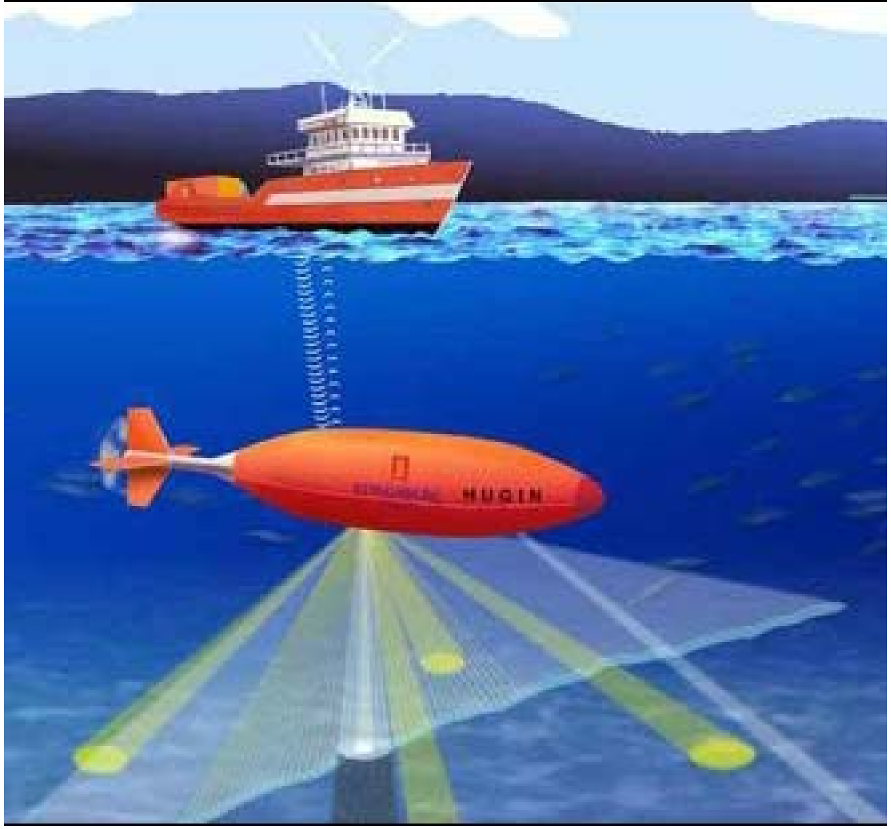


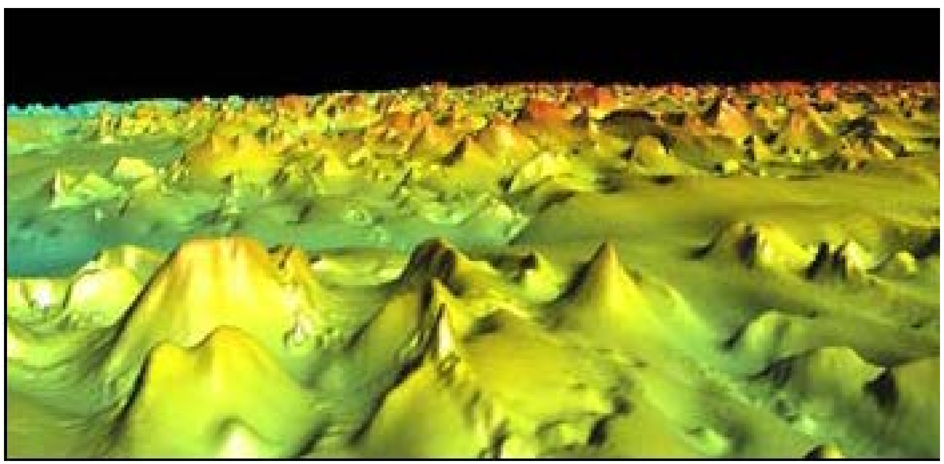
Photomosaic of Mothra field generated by Univ. of Washington

(L. Mayer, UNH)

Autonomous **U**nderwater **V**ehicle
at MPL (today…)

C&C Technologies





Ormen Lange Field, North Sea

HUGIN AUV (Kongsberg-Simrad)

AUV TECHNICAL CHALLENGES:

•High capacity and efficient energy sources

•Low power electronics and data acquisition systems

•Small & pressure tolerant sensors
with minimal impact on buoyancy

•Mission Planning & Control
-accurate inertial navigation (<0.5 m (x,y,z))
-realtime feedback on environmental conditions

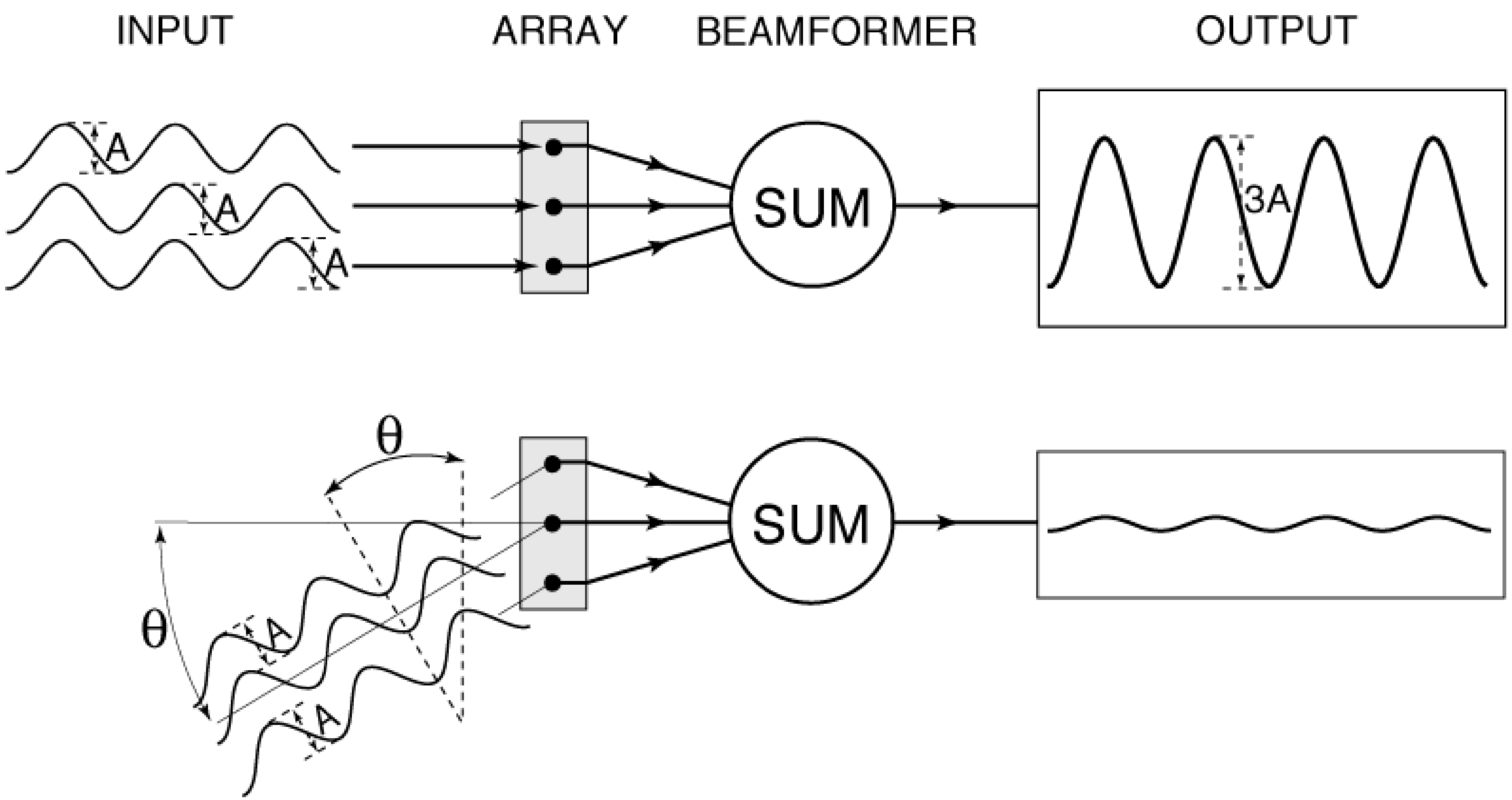
•Networking several AUVs for concurrent operations

MULTIBEAM SONAR METHODS

- SAMPLED APERTURE
- BEAMFORMING
- SPATIAL ALIASING
- BEAM STEERING (PHASE AND TIME DELAY)
- SIDELOBE CONTROL
- ARRAY GEOMETRIES (FLAT VS. CURVED, MILLS CROSS)
- TRANSMIT STEERING FOR (YAW, PITCH, ROLL) COMPENSATION
- FFT BEAMFORMING

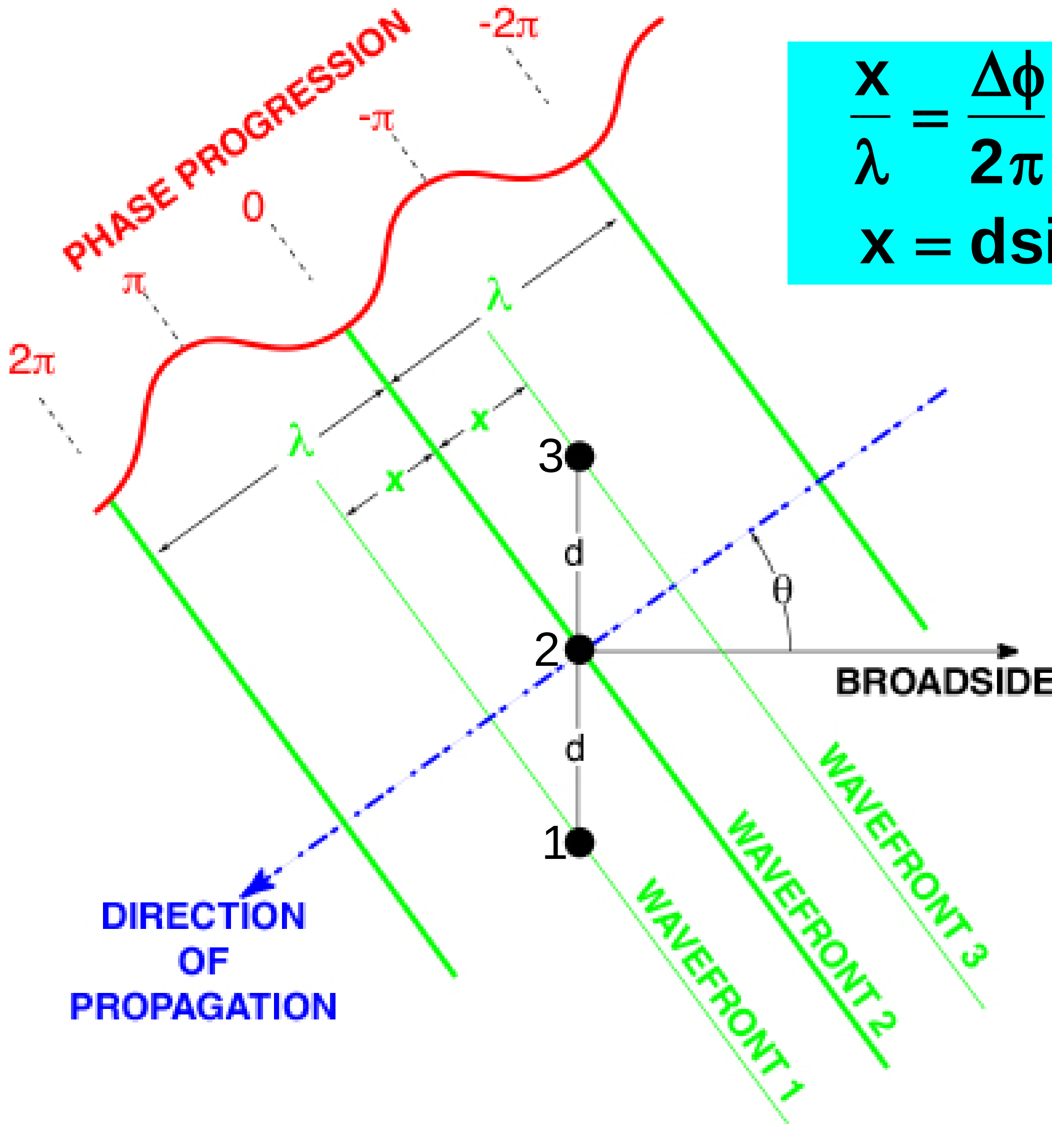
ARRAY BEAMFORMING: BROADSIDE BEAM PATTERN

Maximum output when all three signals arrive in phase (wavefront parallel to the array elements' plane)



Minimum output when phases sum to zero (wavefront at some angle to the array elements' plane)

Phase Relationships Between The Outputs Of 3 Equidistant Hydrophones As A Function Of Angle Of Arrival (θ) Relative To Broadside

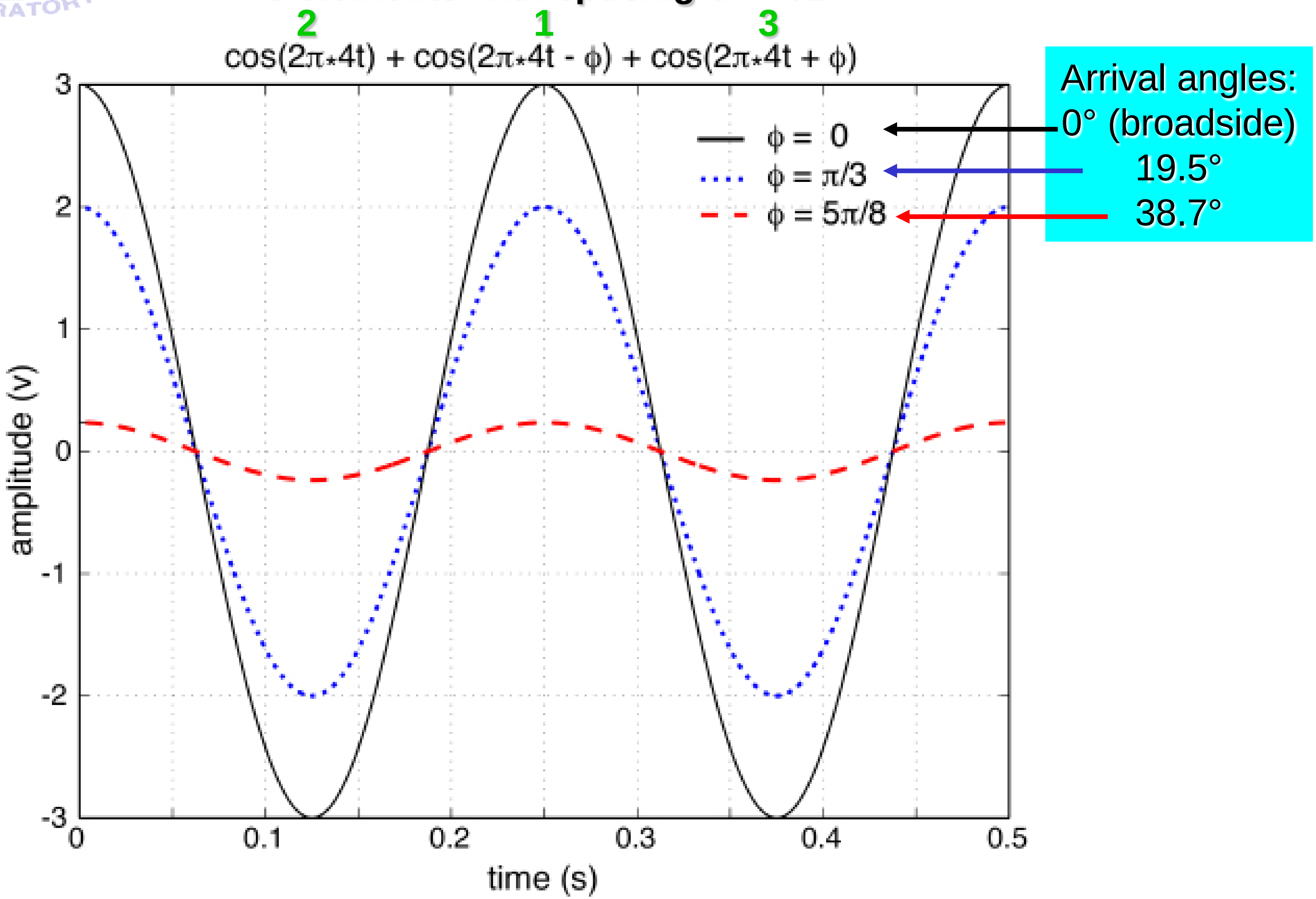


$$\left.\begin{array}{l} \dfrac{x}{\lambda} = \dfrac{\Delta\phi}{2\pi} \\ x = d\sin\theta \end{array}\right\} \Rightarrow \Delta\phi = \frac{2\pi d \sin\theta}{\lambda}$$

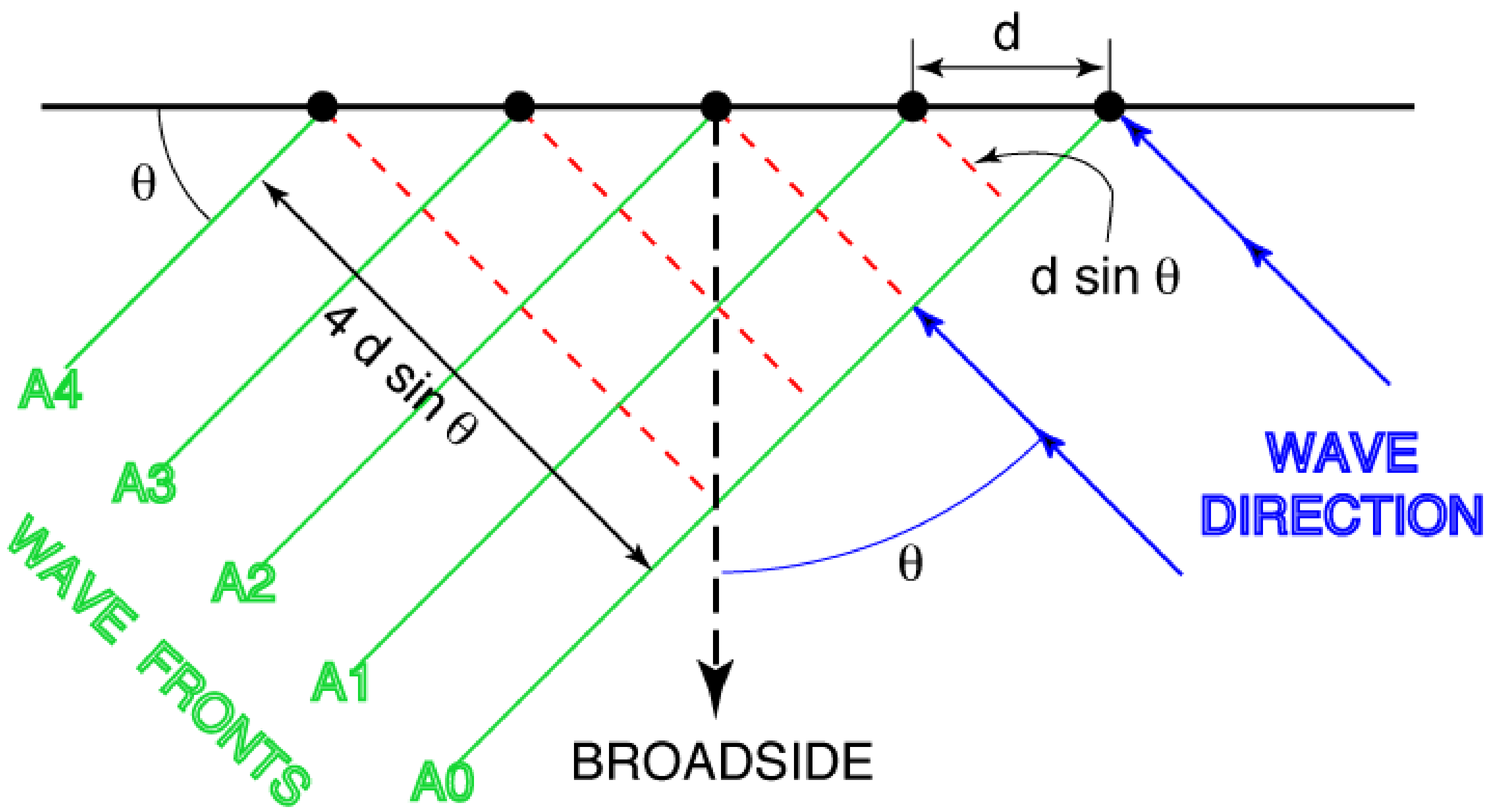
d and λ are known
measure Δϕ
compute θ

BEAMFORMER OUTPUT FOR INCREASING PHASE DELAYS

3 elements with spacing d = $\lambda/2$



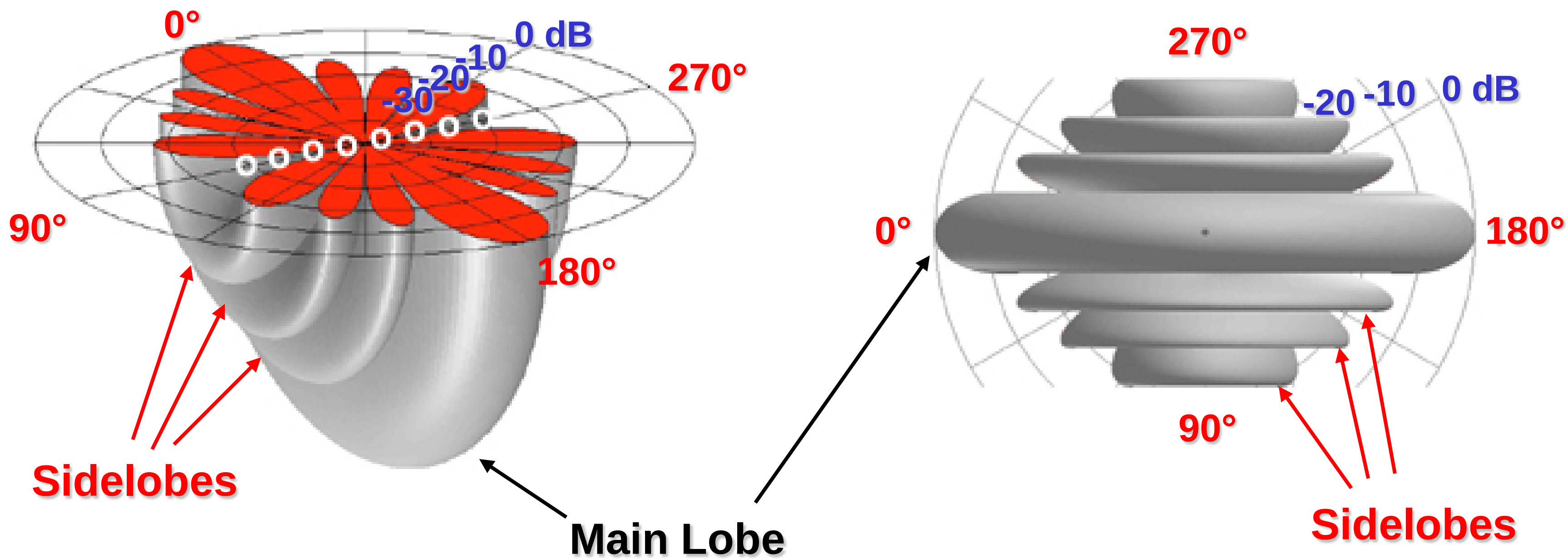
LINE ARRAY OF EQUALLY SPACED ELEMENTS



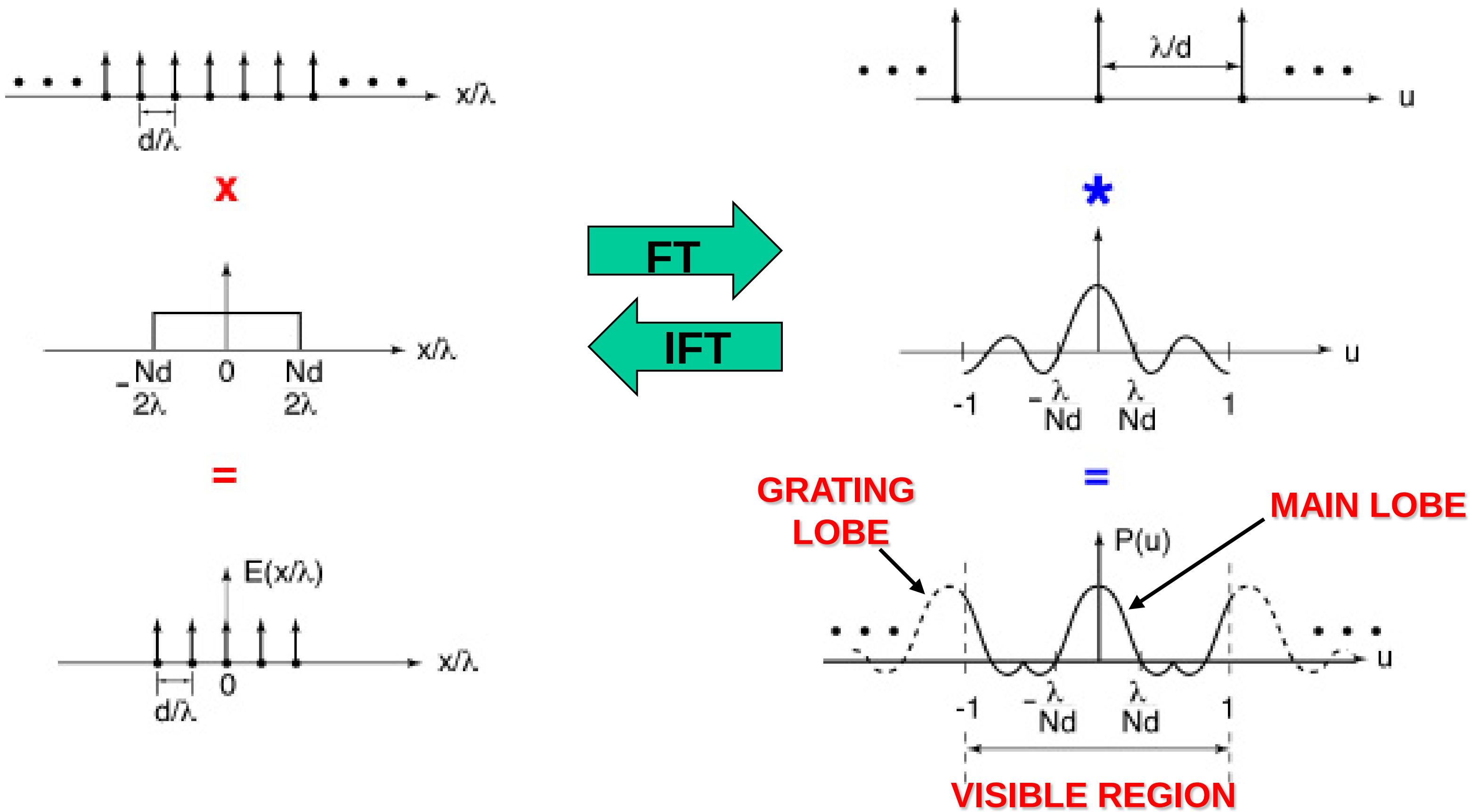
FOR EACH DIRECTION θ, SUM THE OUTPUT OF EACH ELEMENT

$$f(\theta) = \text{SUM}\,[A_n \exp(jn\psi)], \;\; \text{with} \;\; \psi = 2\pi \frac{d \sin\theta}{\lambda}$$

8 ELEMENT ARRAY FACTOR
$\lambda/2$ SPACING



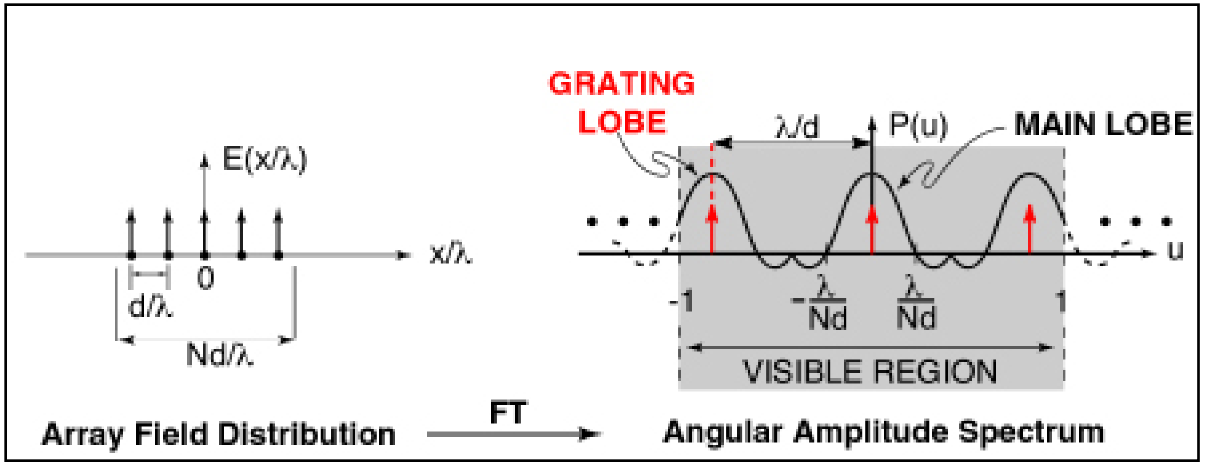
SPACE **SPATIAL FREQUENCY**

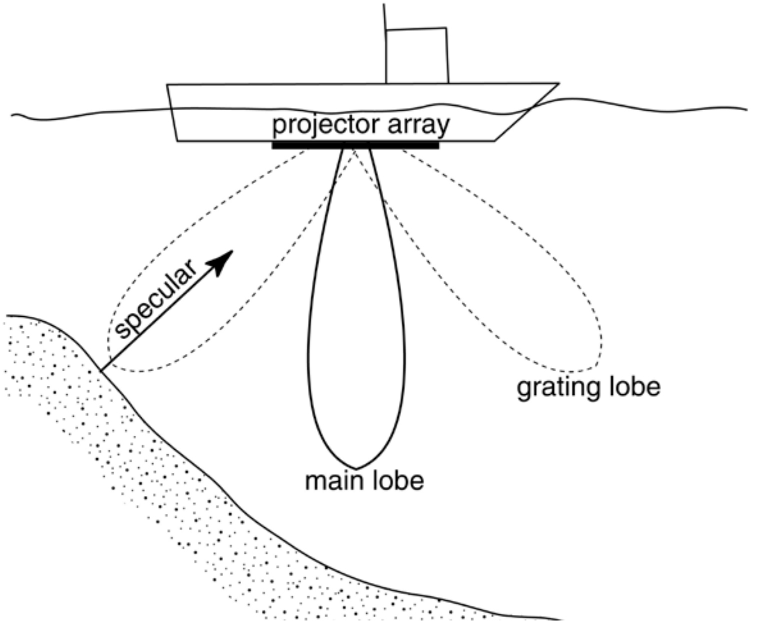


ARRAY ELEMENTS FIELD DISTRIBUTION

AMPLITUDE RADIATION PATTERN

SPATIAL ALIASING: GRATING LOBES

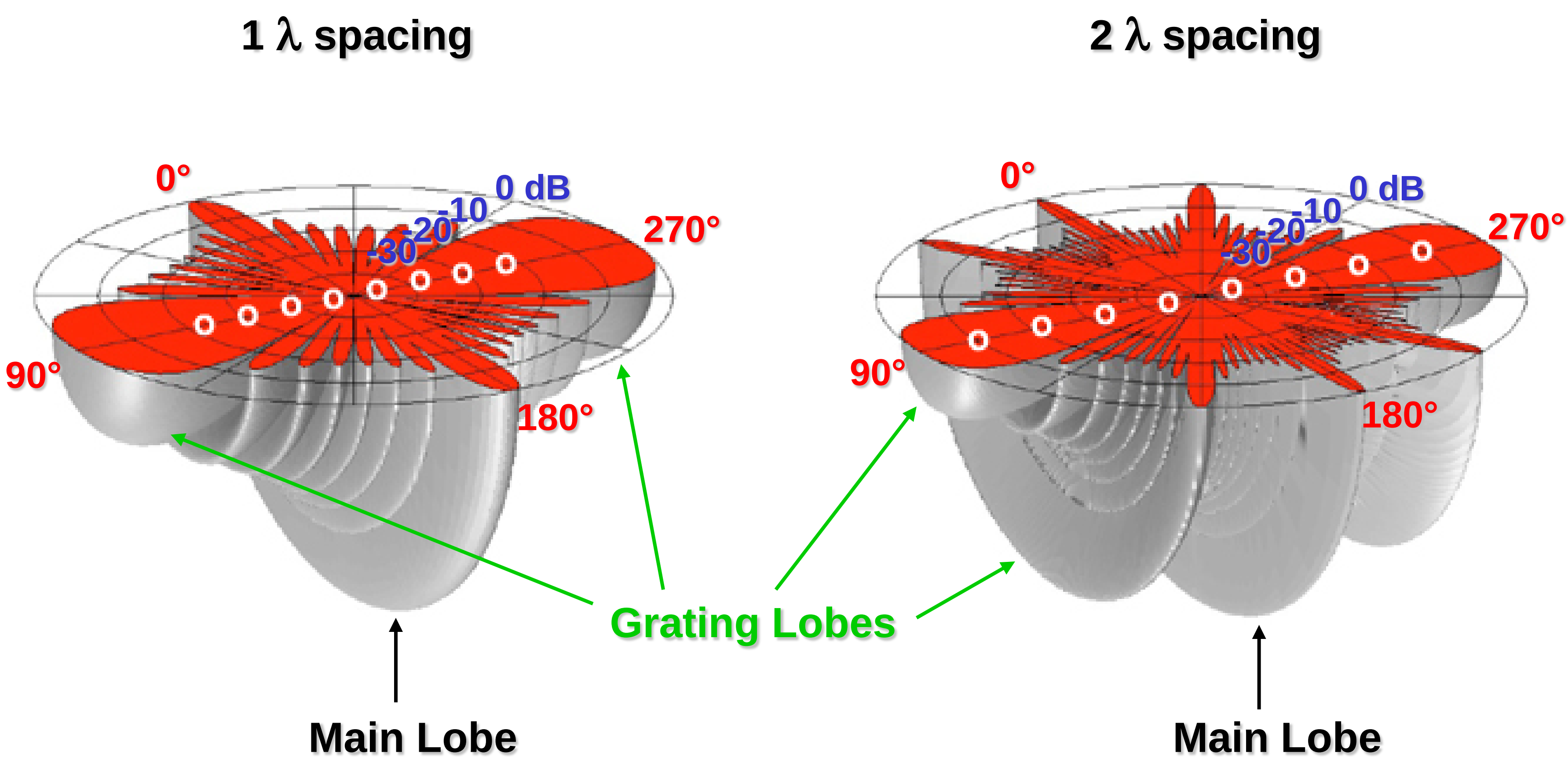




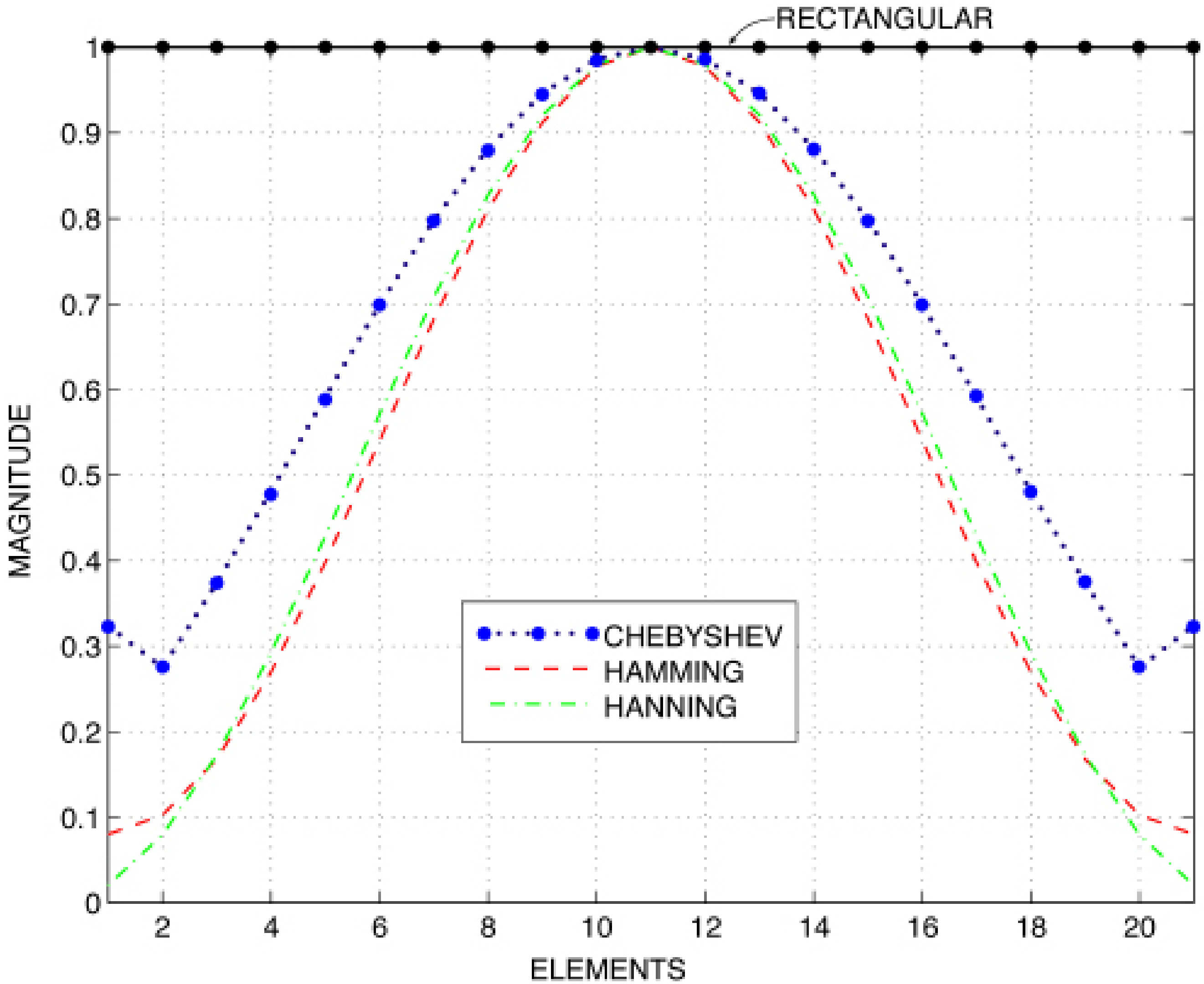
Grating lobes are replicas of the main lobe in the visible region.

Potential ambiguities in the direction of arrival of echoes (receiver) or undesirable transmission through multiple lobes.

SPATIAL ALIASING
8 ELEMENT ARRAY FACTOR

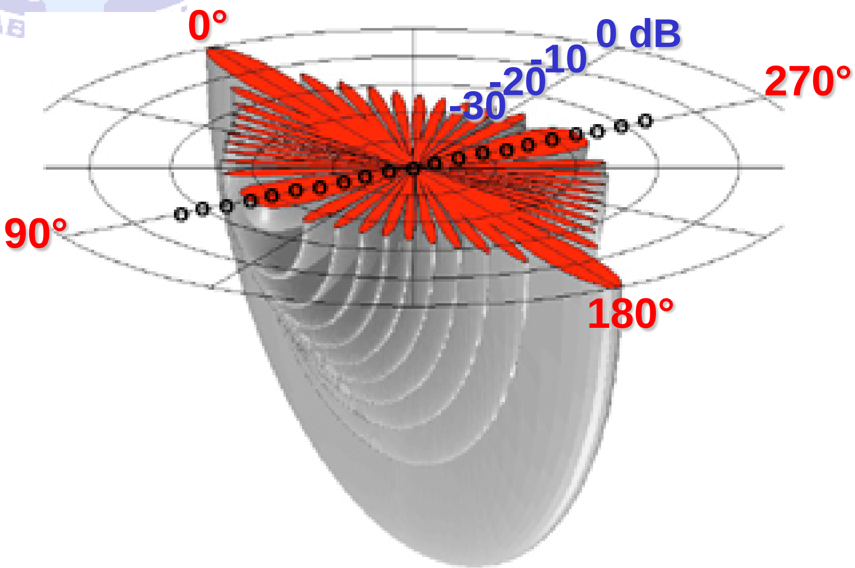


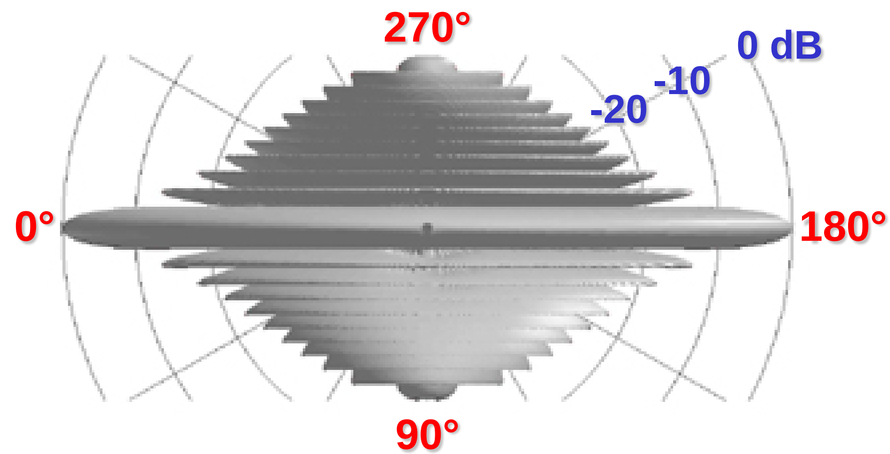
SIDELOBE CONTROL THROUGH AMPLITUDE SHADING

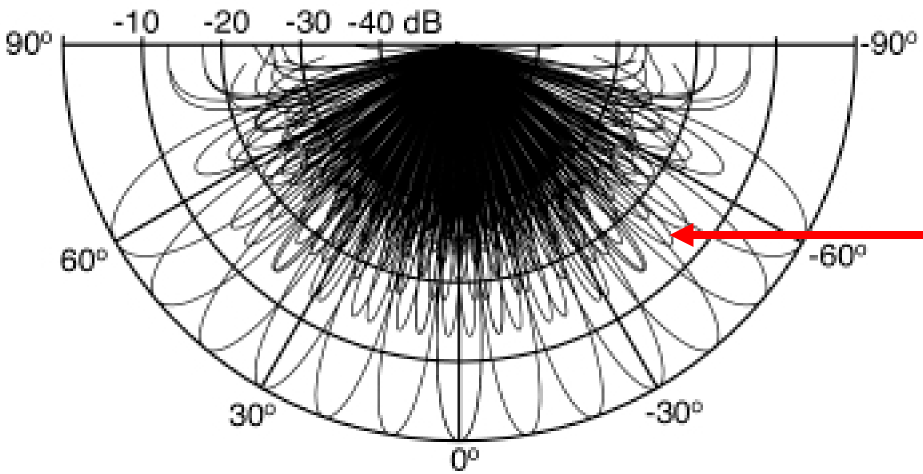


Shading window functions for an array of 21 equally spaced elements

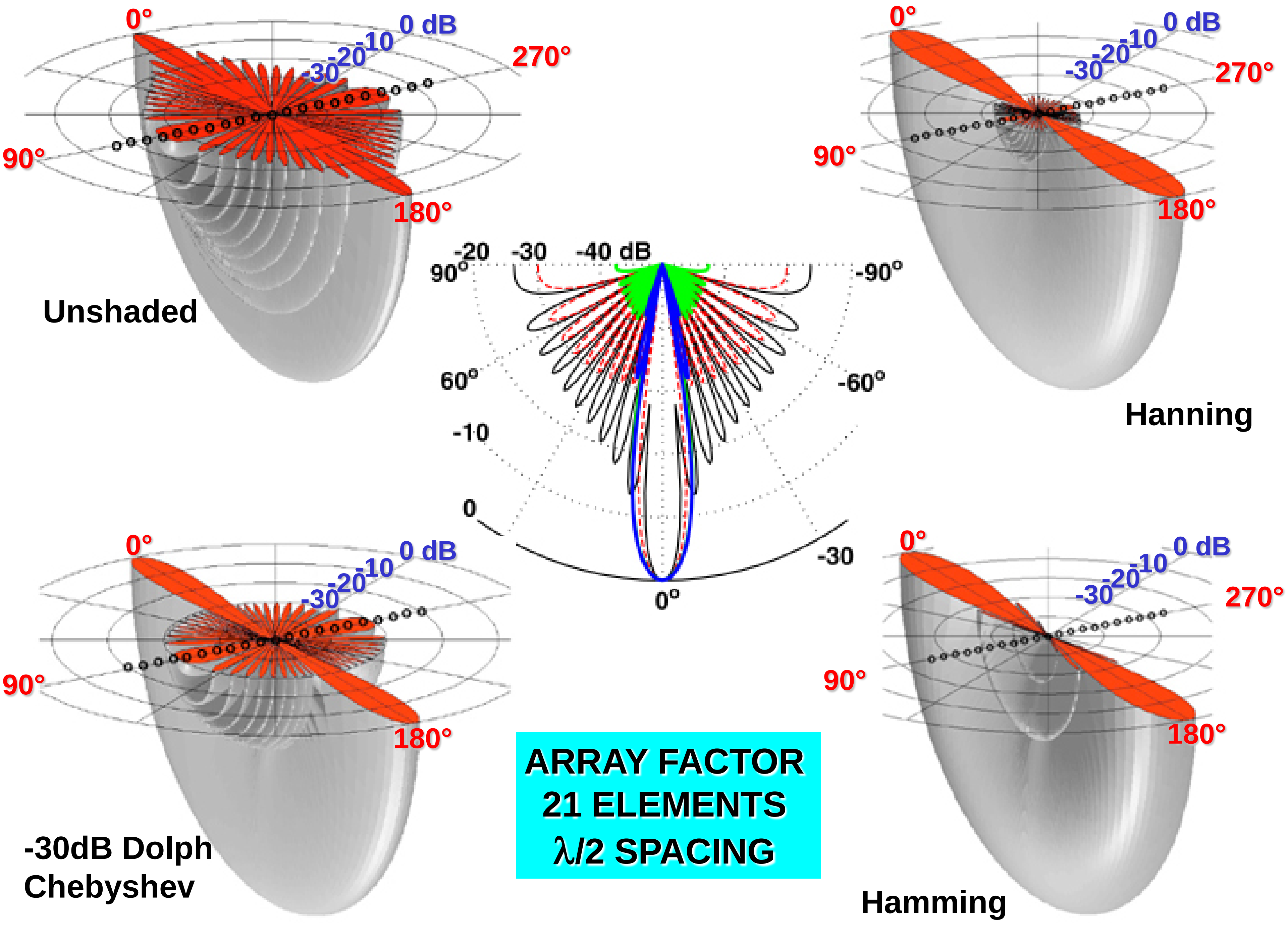
SIDELOBE CONTROL TO IMPROVE SPATIAL RESOLUTION





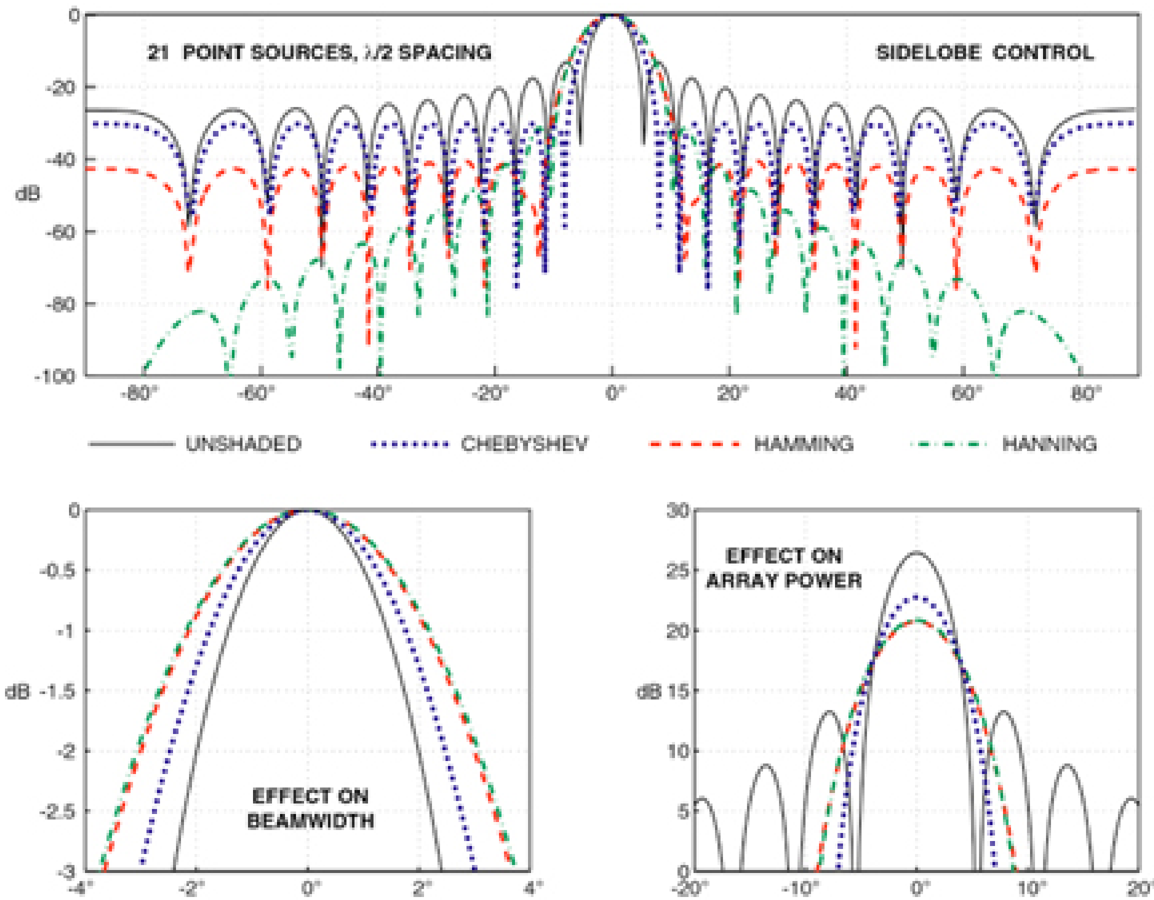


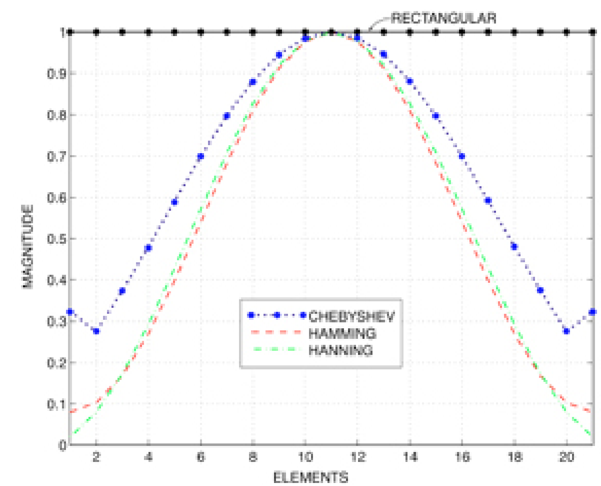
If the array elements all have the same amplitude weight (rectangular window function), the first sidelobes appear at -13dB for all steered beams



ARRAY FACTOR
21 ELEMENTS
λ/2 SPACING

SIDE EFFECTS OF SIDELOBE CONTROL

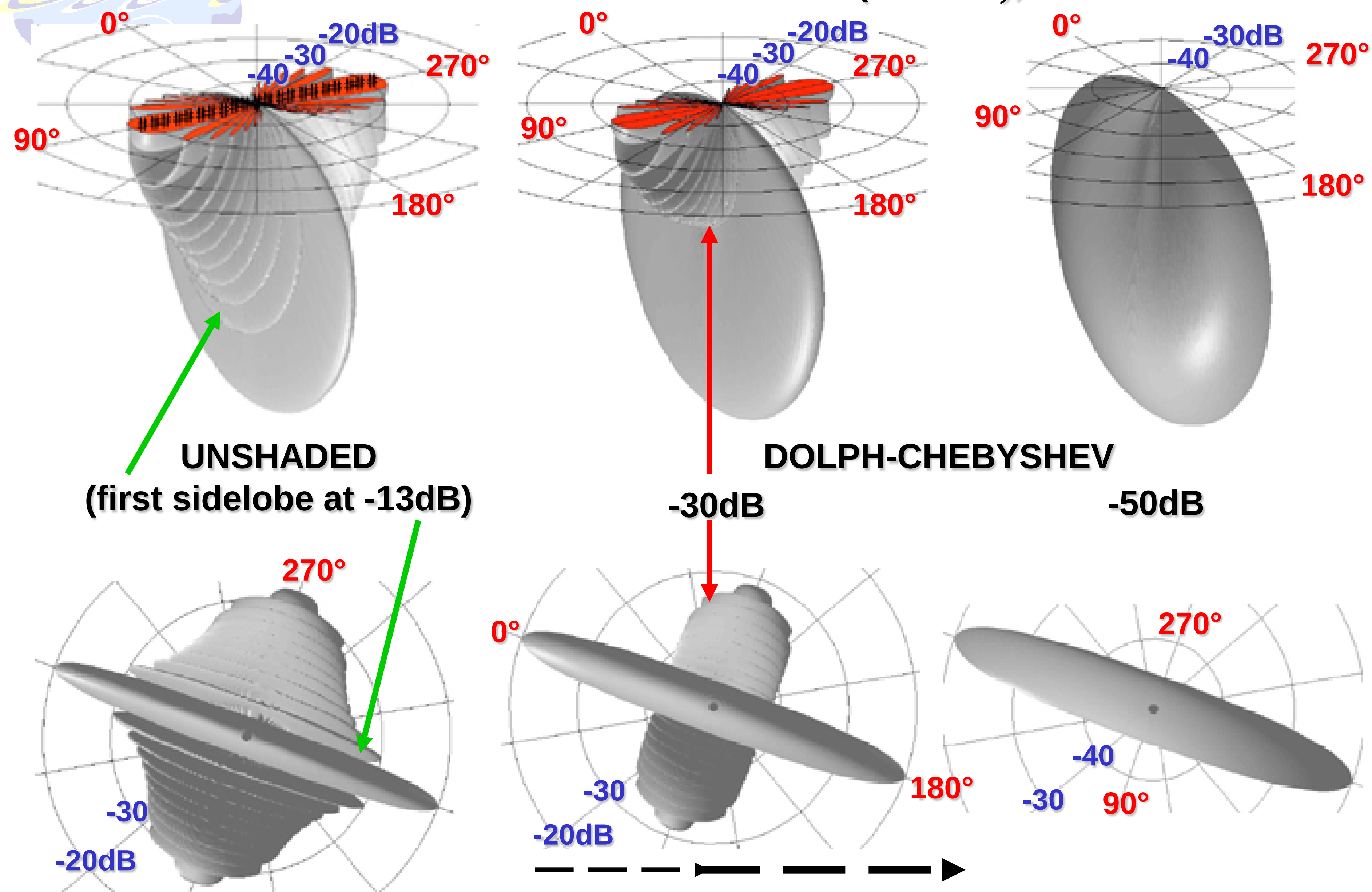




WINDOW FUNCTIONS

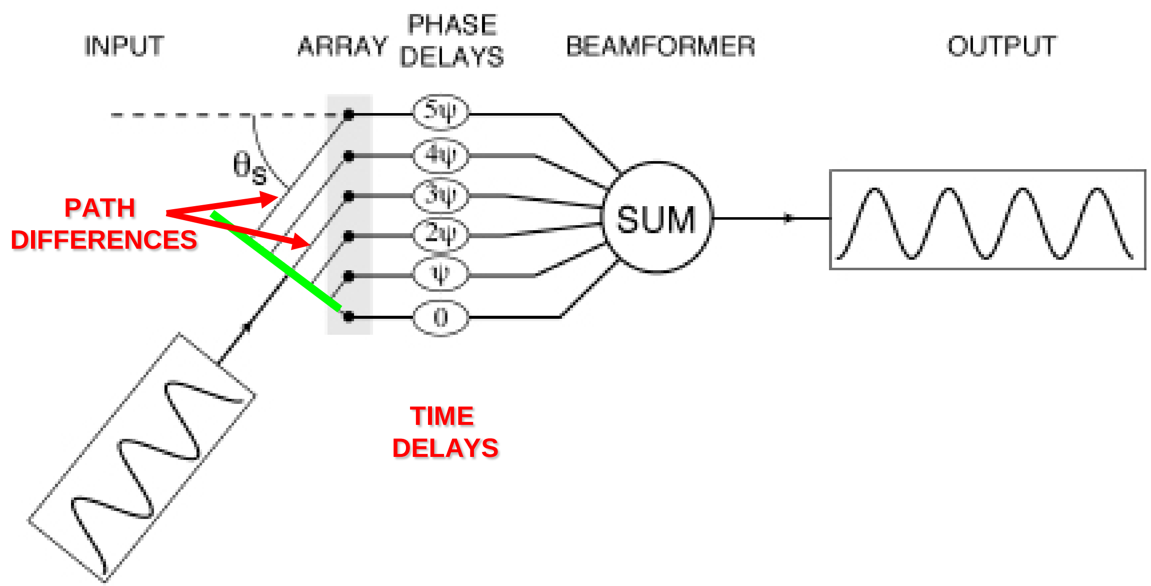
Cost of sidelobe control = broader beam widths & lower array gain

ARRAY OF 21 RECTANGULAR ELEMENTS (1λ x λ/4), λ/2 SPACING

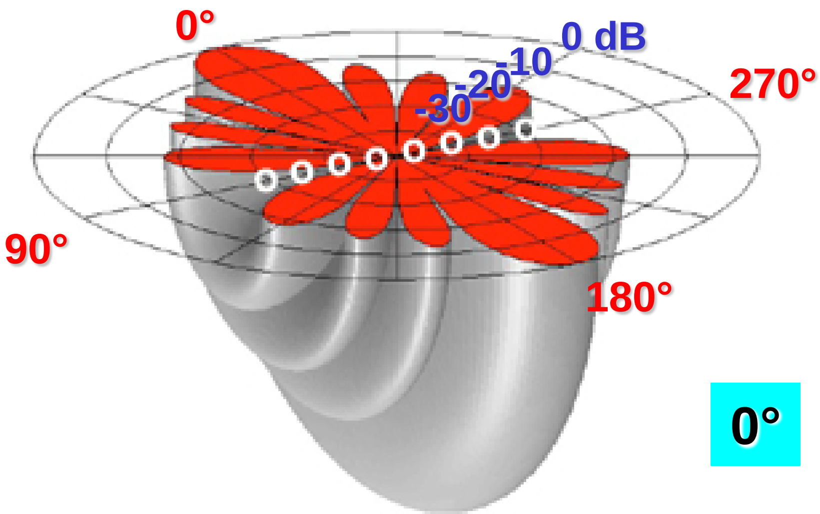


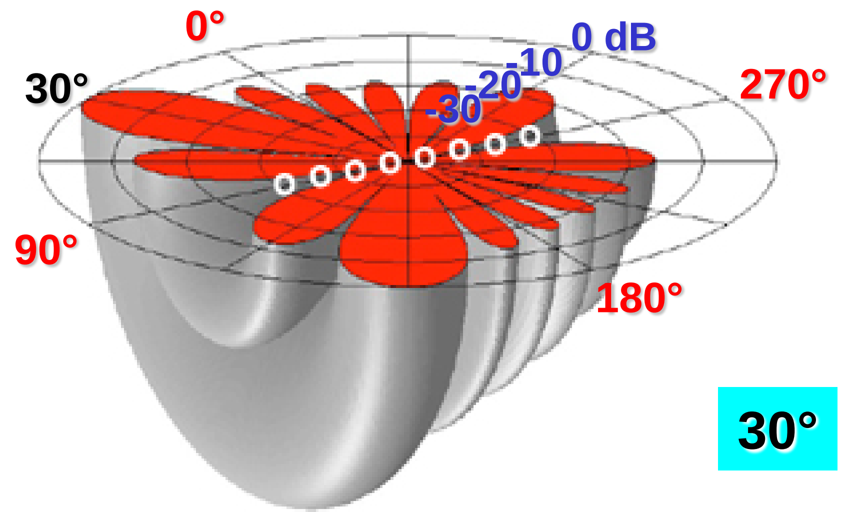
broadening of mainlobe with sidelobe reduction

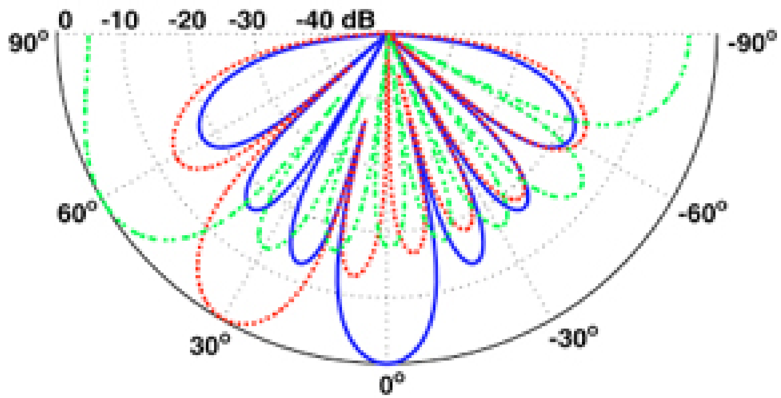
BEAM STEERING WITH TIME OR PHASE DELAYS

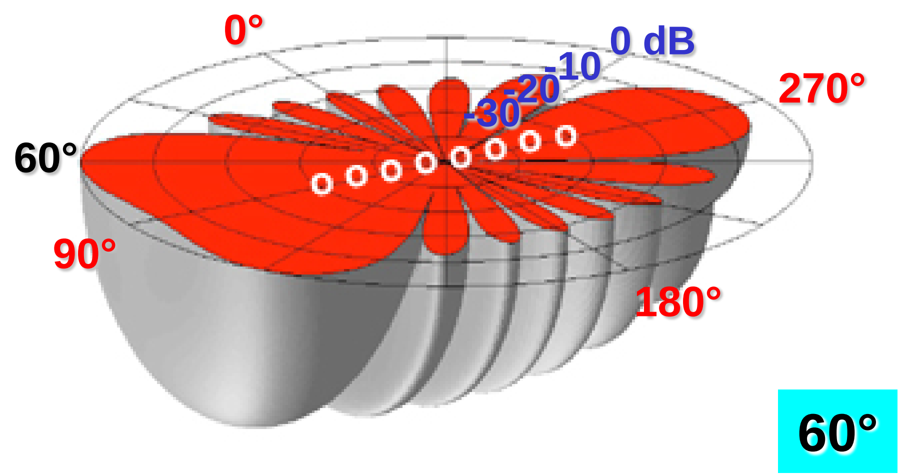


BEAM STEERING
8 ELEMENT ARRAY FACTOR, λ/2 SPACING



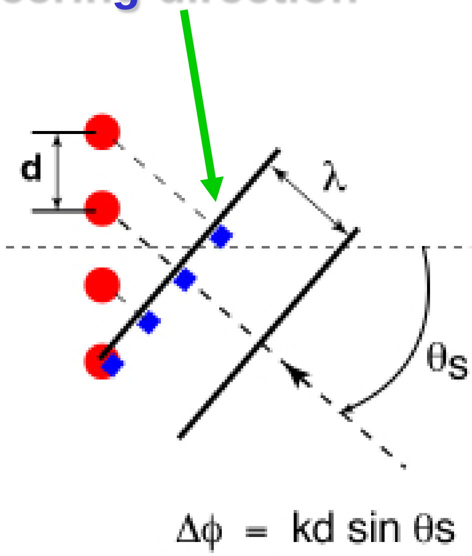


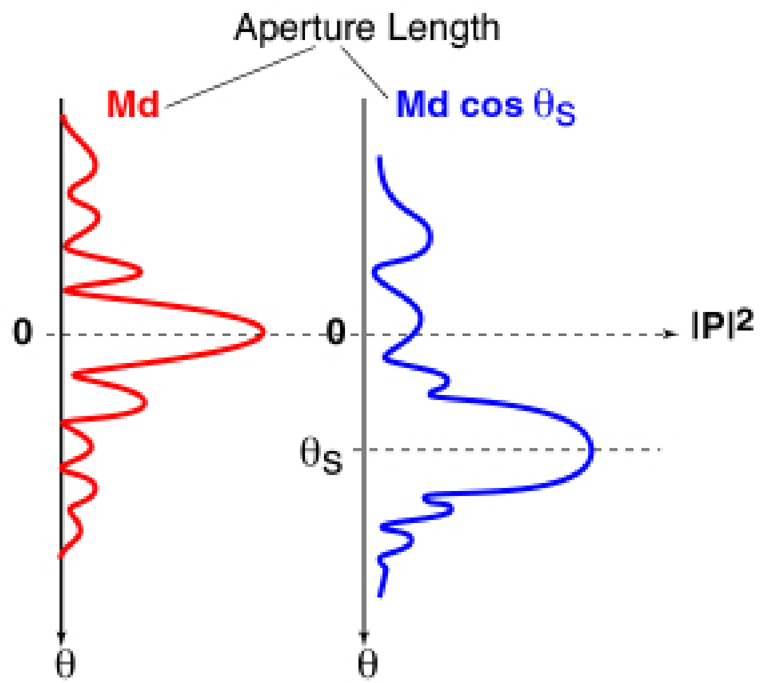




BEAMWIDTH OF STEERED BEAMS

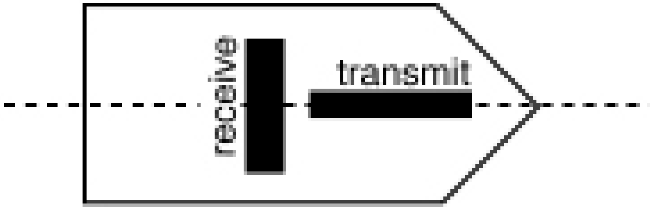
Virtual array projected on plane perpendicular to steering direction

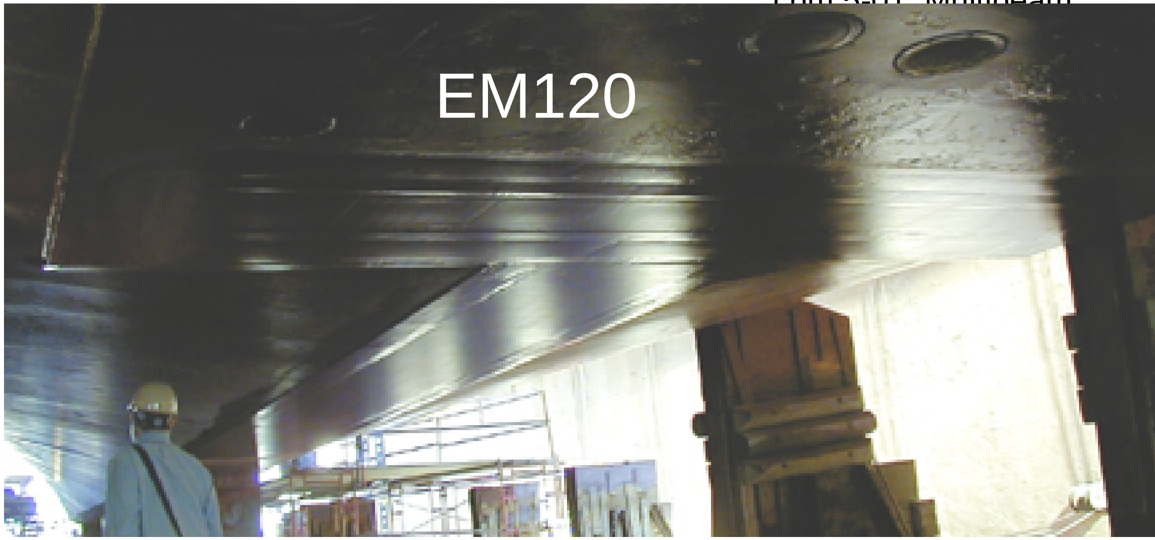




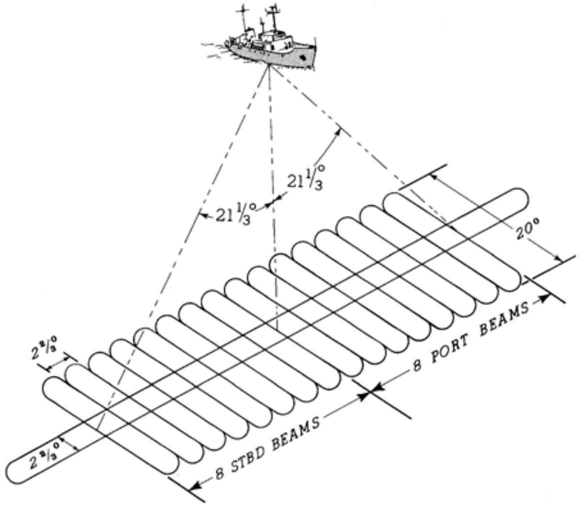
BROADSIDE BEAMWIDTH: $0.88\lambda/Md$ (rad)

STEERED BEAMWIDTH: $0.88\lambda/Md\cos\theta_s$ (rad)

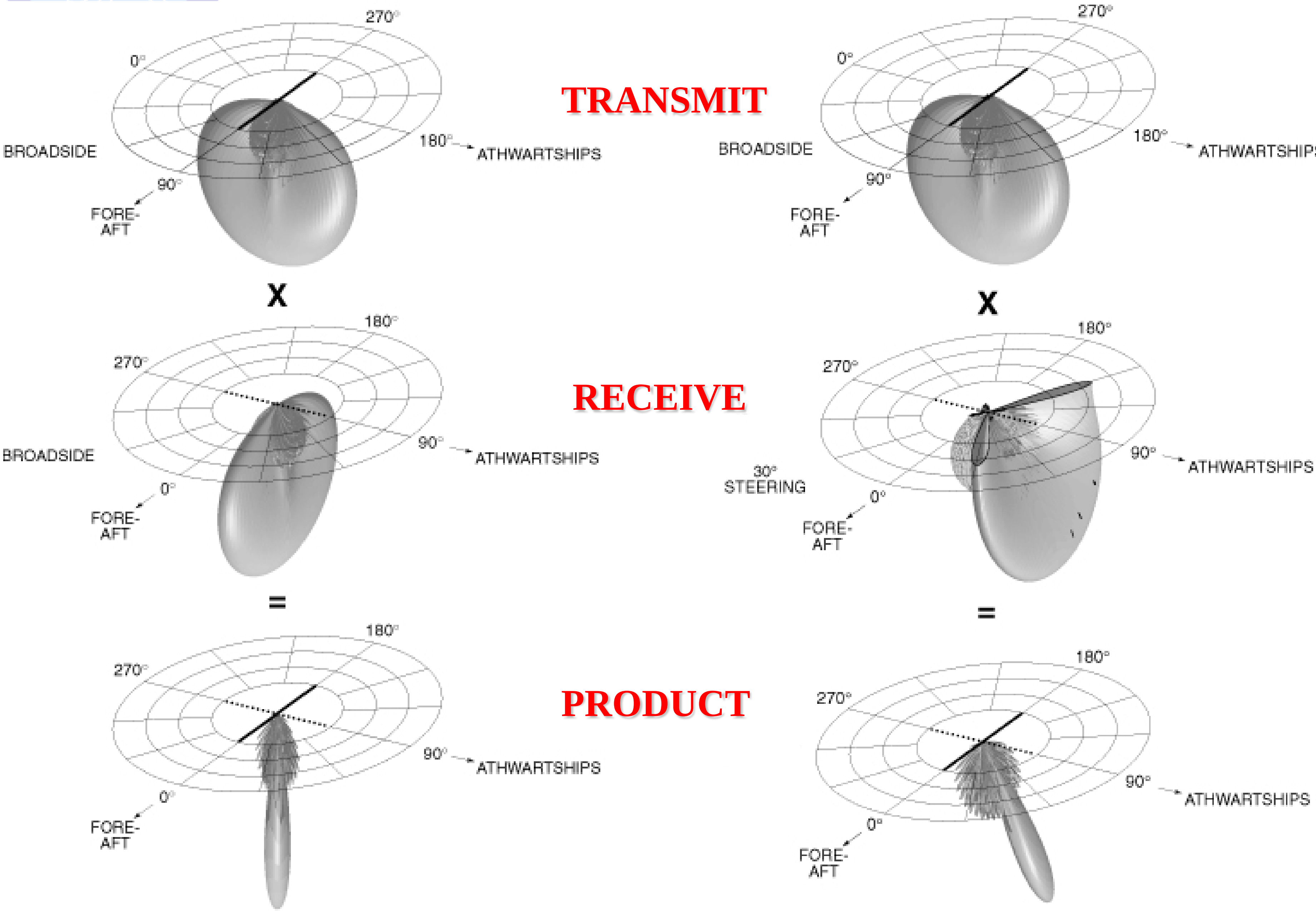

receive
transmit


EM120


8125

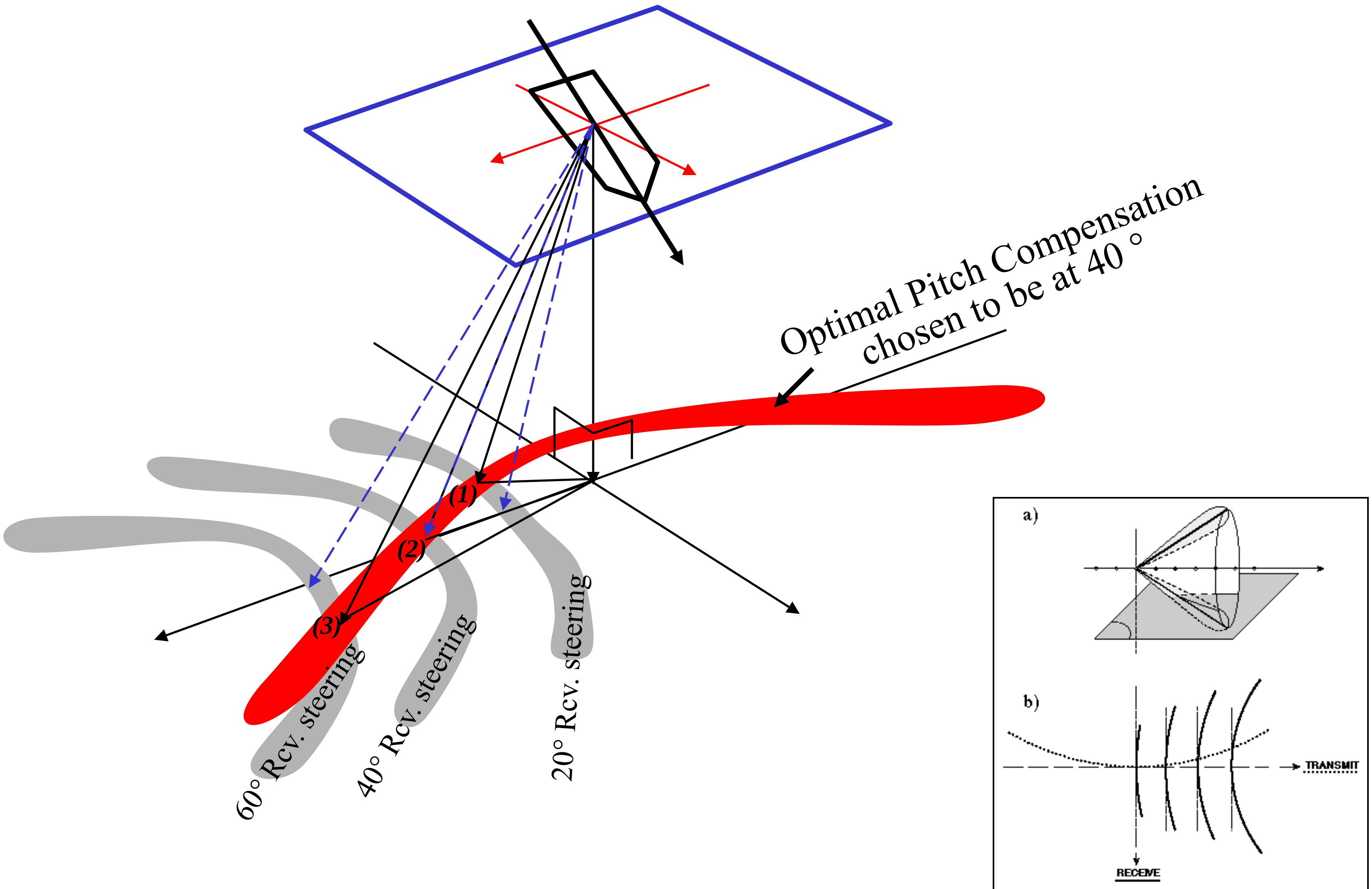

21 1/3°
21 1/3°
20°
2 2/3°
2 2/3°
8 STBD BEAMS
8 PORT BEAMS

ARRAYS OF 21 ELEMENTS WITH $\lambda/2$ SPACING

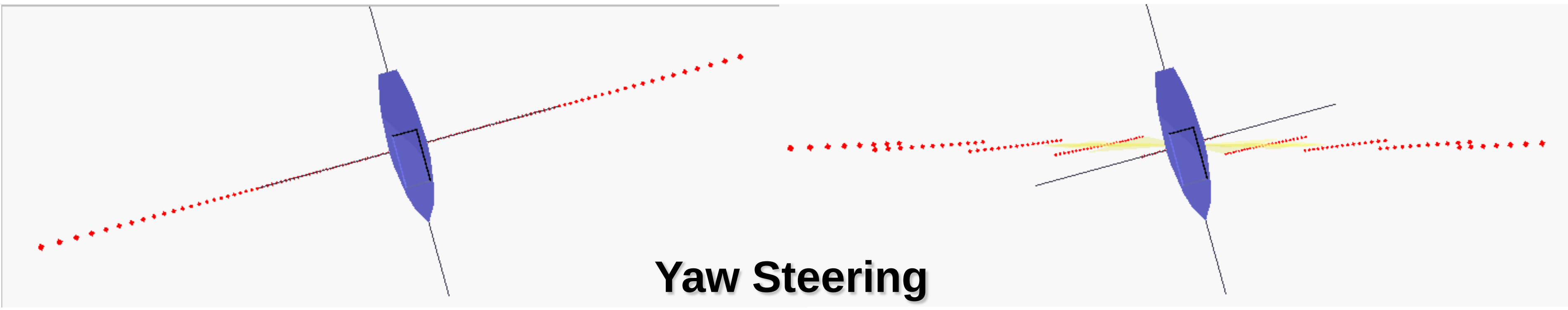


TRANSMIT BEAMWIDTH

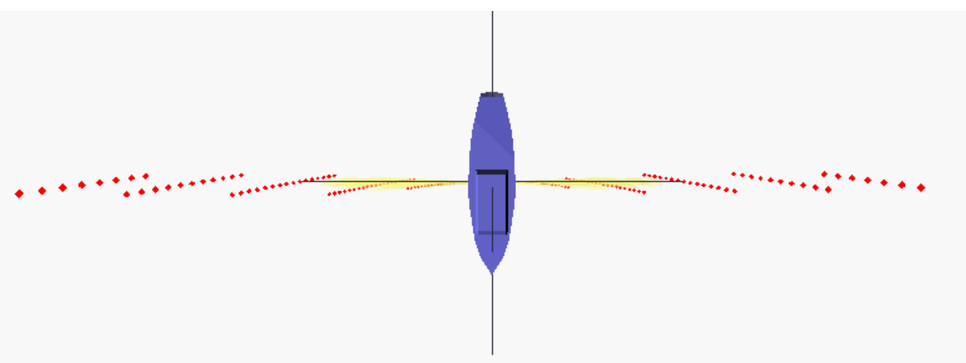
Pitch Stabilization e.g. bow down at transmit (JHC)



Pitch Steering



Yaw Steering

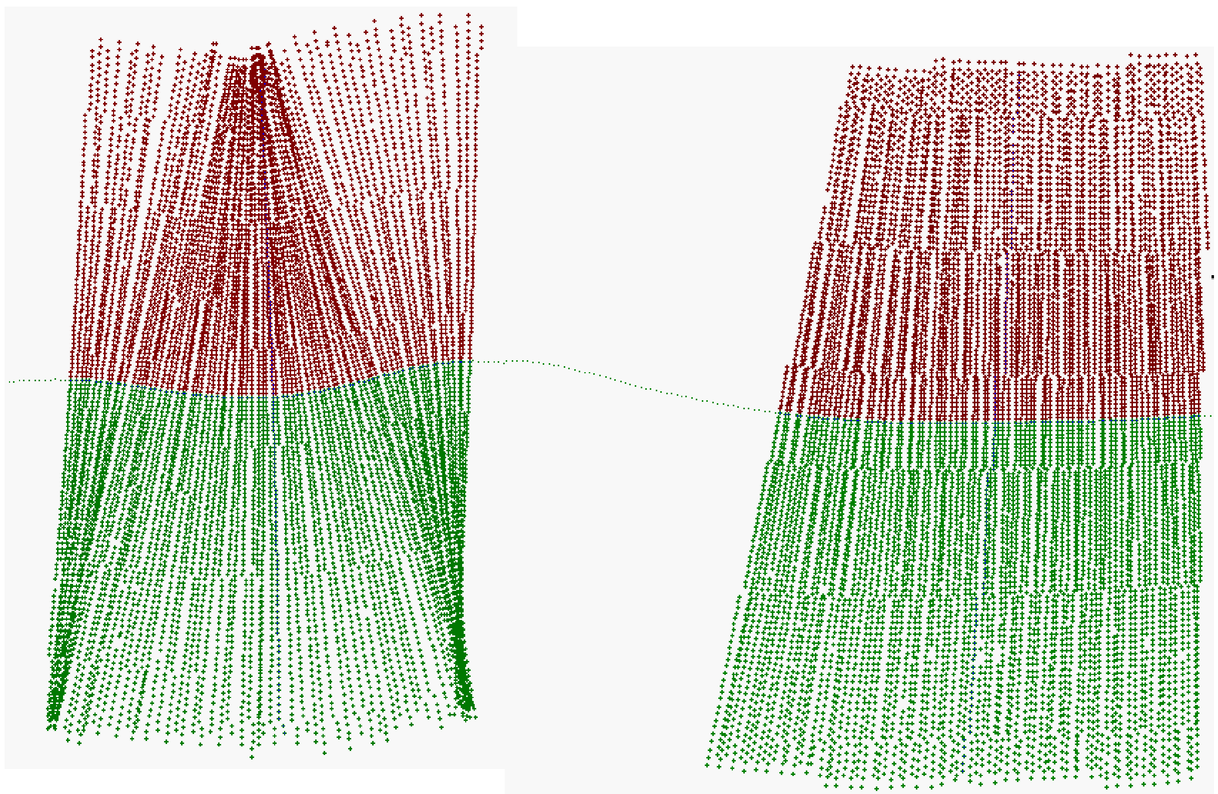


Multi-Sector Yaw/Pitch/Roll Compensation on Transmit

OMG/UNB

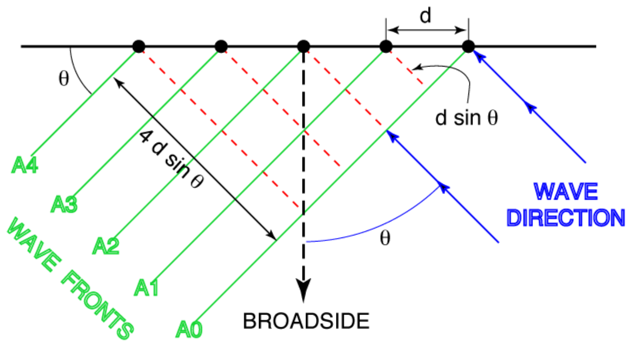
Hughes Clarke, 1997

EM300 Without and With Multi-Sector Steering



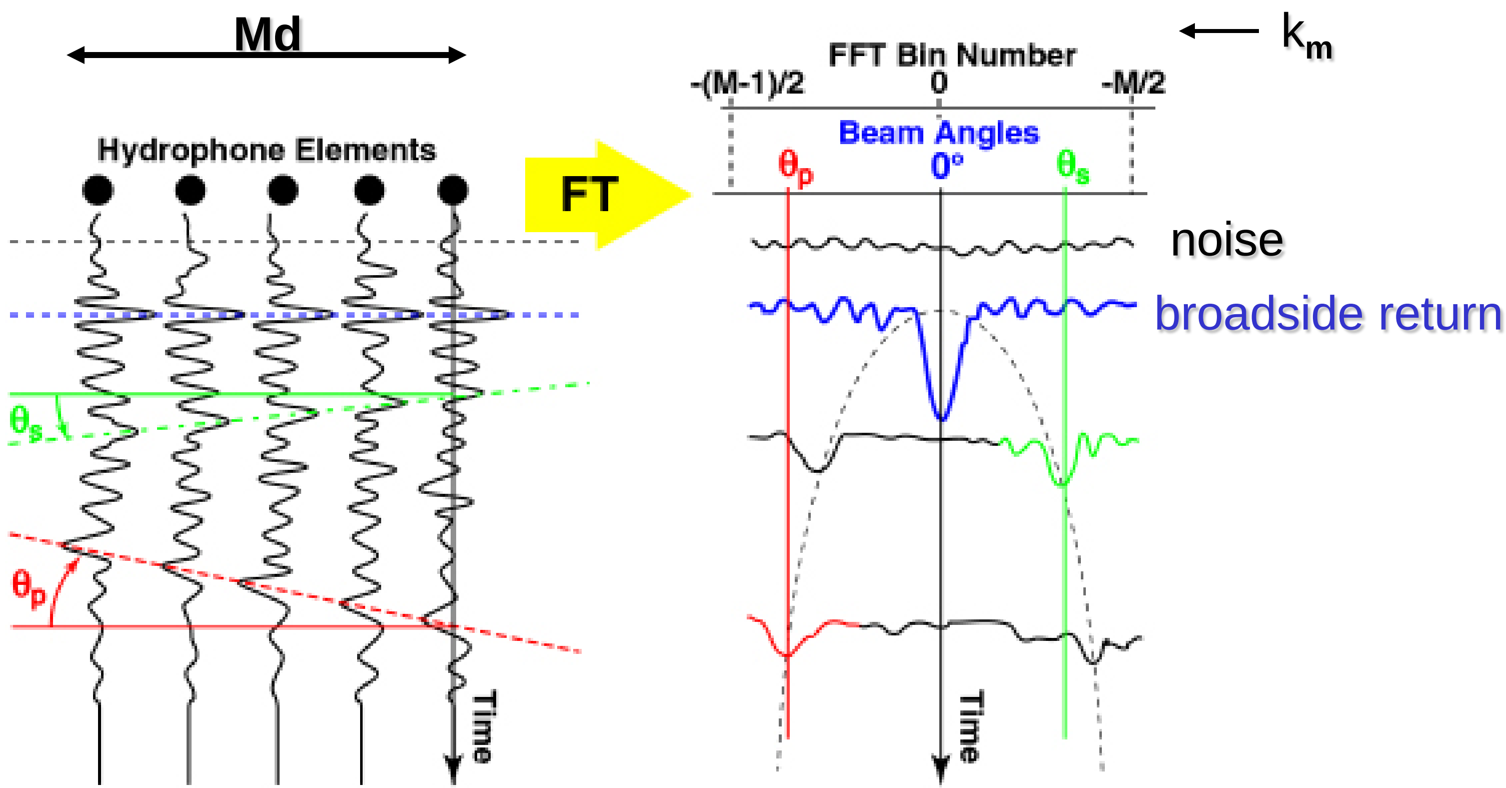
(OMG/UNB, USGS, C&C Technologies, Hughes Clarke, 1997)

FFT BEAMFORMING FOR RECEIVE BEAMS ON FLAT ARRAYS WITH UNIFORM ELEMENT SPACING



For each time slice, perform an FFT computation to determine angles of arrival relative to broadside

$$\theta_s = \sin^{-1}\left(\frac{\lambda k_m}{Md}\right)$$

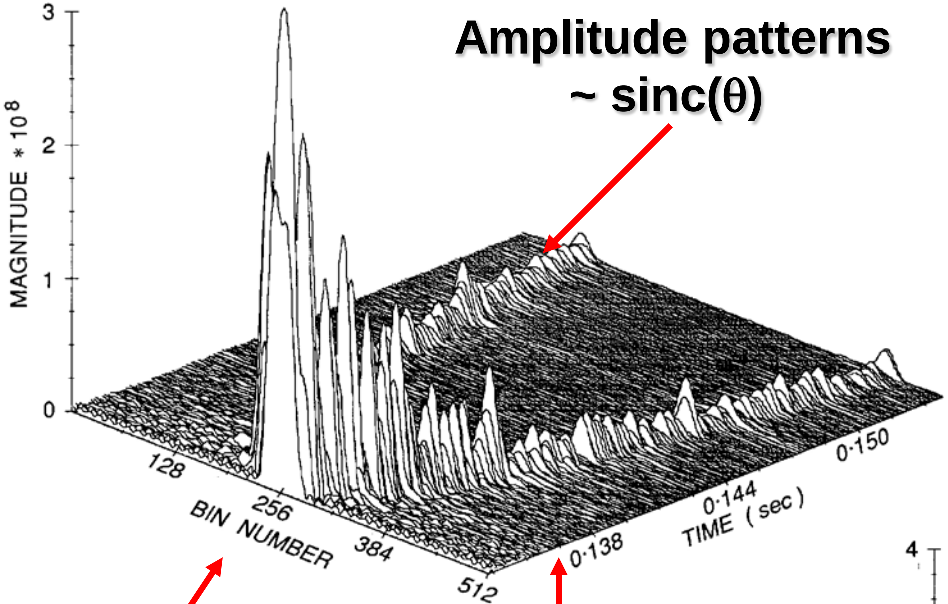


OUPUT OF FFT BEAMFORMING

FFT beamforming simulation on a horizontal line array of 44 elements 0.7λ apart, set 100 m above a flat bottom.

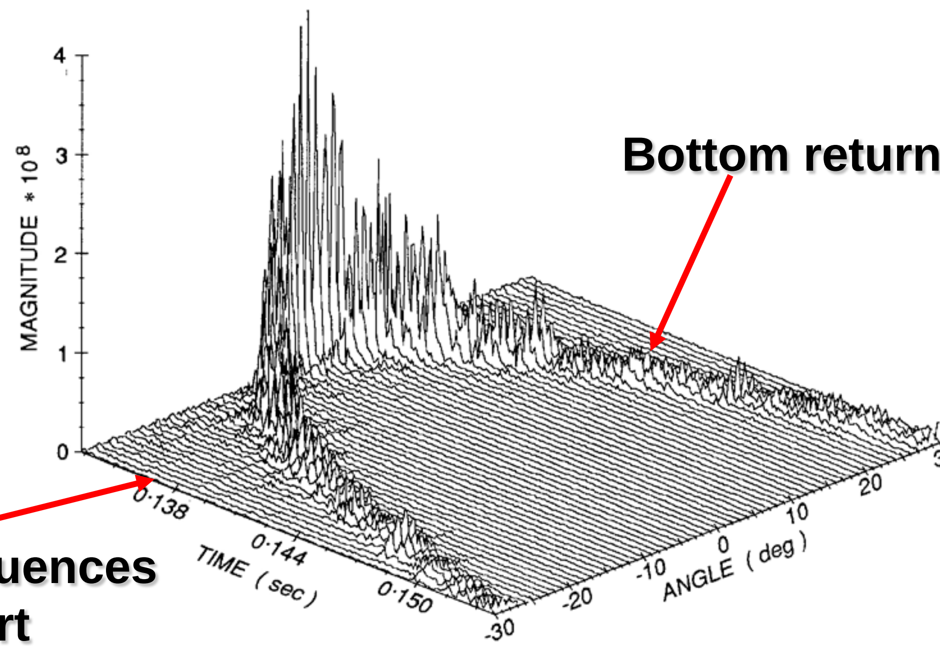
512 point FFT with -40 dB Dolph-Chebyshev shading. Acoustic Frequency = 100 kHz

Amplitude patterns ~ sinc(θ)



Bin 256 = broadside
FFT output for each time slice

Bottom returns



Same output converted into time sequences for 61 beam directions spaced 1° apart within ±30° of broadside

SUMMARY

• Access to individual elements in an array makes it possible to form beams and to point (steer) them in specific direction.

•Signals arriving synchronously from multiple directions can be resolved if they are received in individual beams.

•Importance of array element spacing to control grating lobes. General rule: $\lambda/2$ spacing avoids all grating lobes.

• Sidelobe control to maintain desired angular spatial resolution. Tradeoffs with increased beamwidth and reduced array gain.

SUMMARY (cont.)

- **FLAT ARRAYS:** **beamwidth increases with 1/cos(steering_angle)**

- **CURVED ARRAYS:** **constant beamwidths for all broadside beams.**

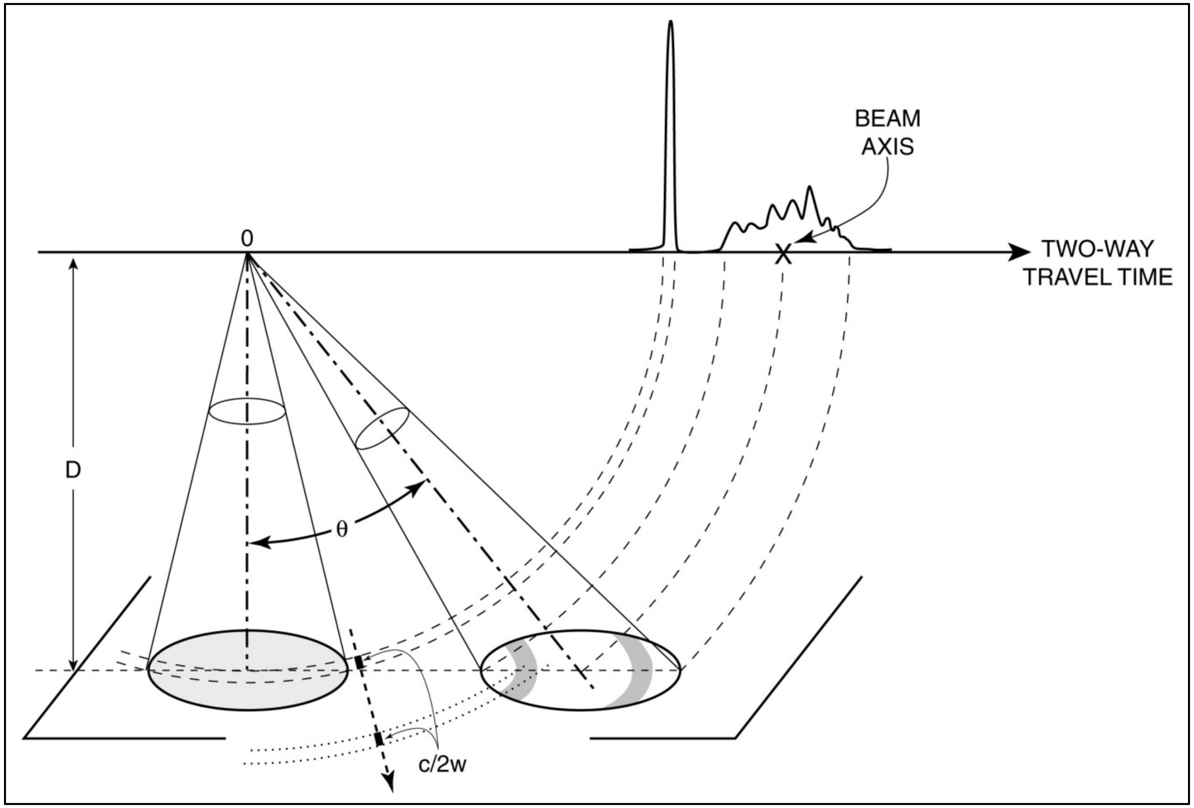
- **Transmit beam steering to compensate for pitch, yaw and roll.**

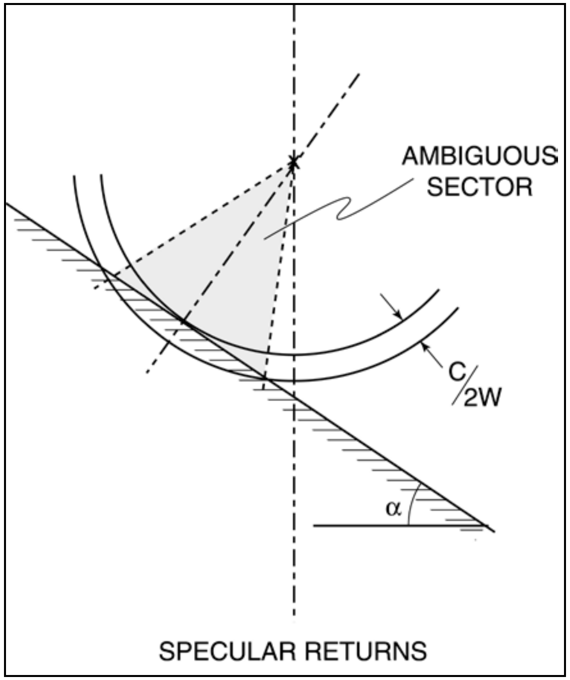
- **All beamforming and beam steering operations depend on the acoustic wavelength (λ=C/F), hence importance of knowing the sound speed at the face of the array**

Bottom detection methods in multibeam bathymetry

1. Fixing angular direction a priori and estimating the time of arrival for that direction.
2. Implementing a split-aperture correlator.
3. Estimating an angle of arrival for all the echoes received at each time sample.

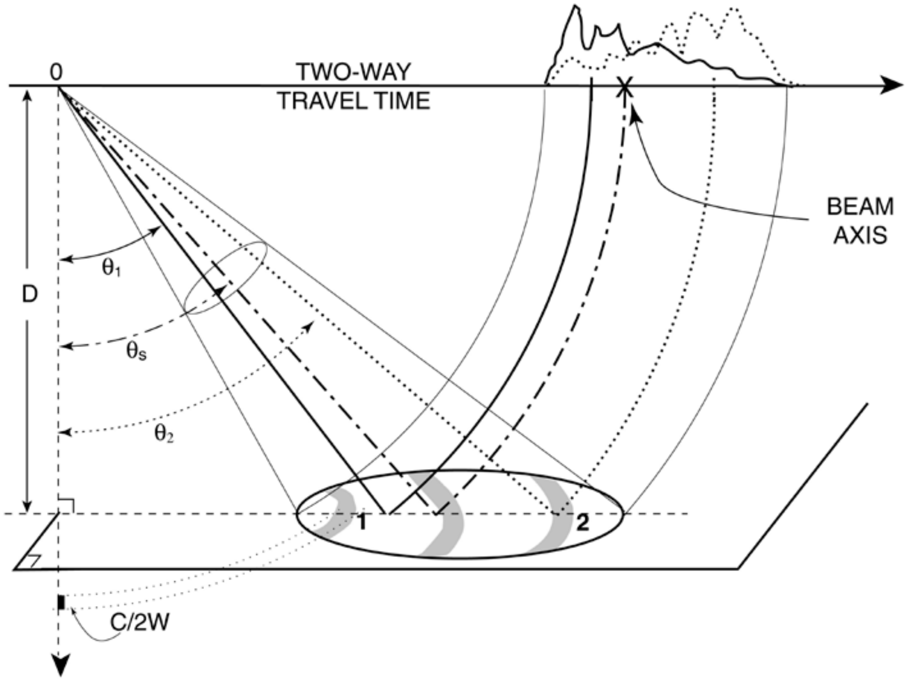
BOTTOM DETECTION

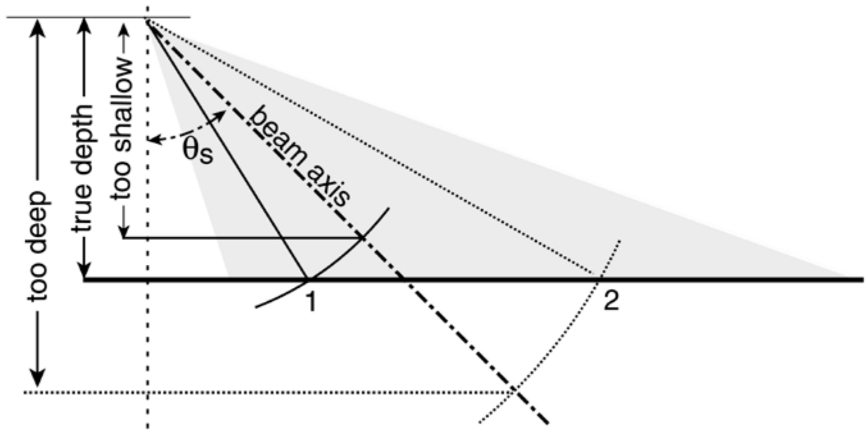




Backscatter Geometry	beam limited for near-specular returns pulse limited for oblique incidences

BOTTOM DETECTION

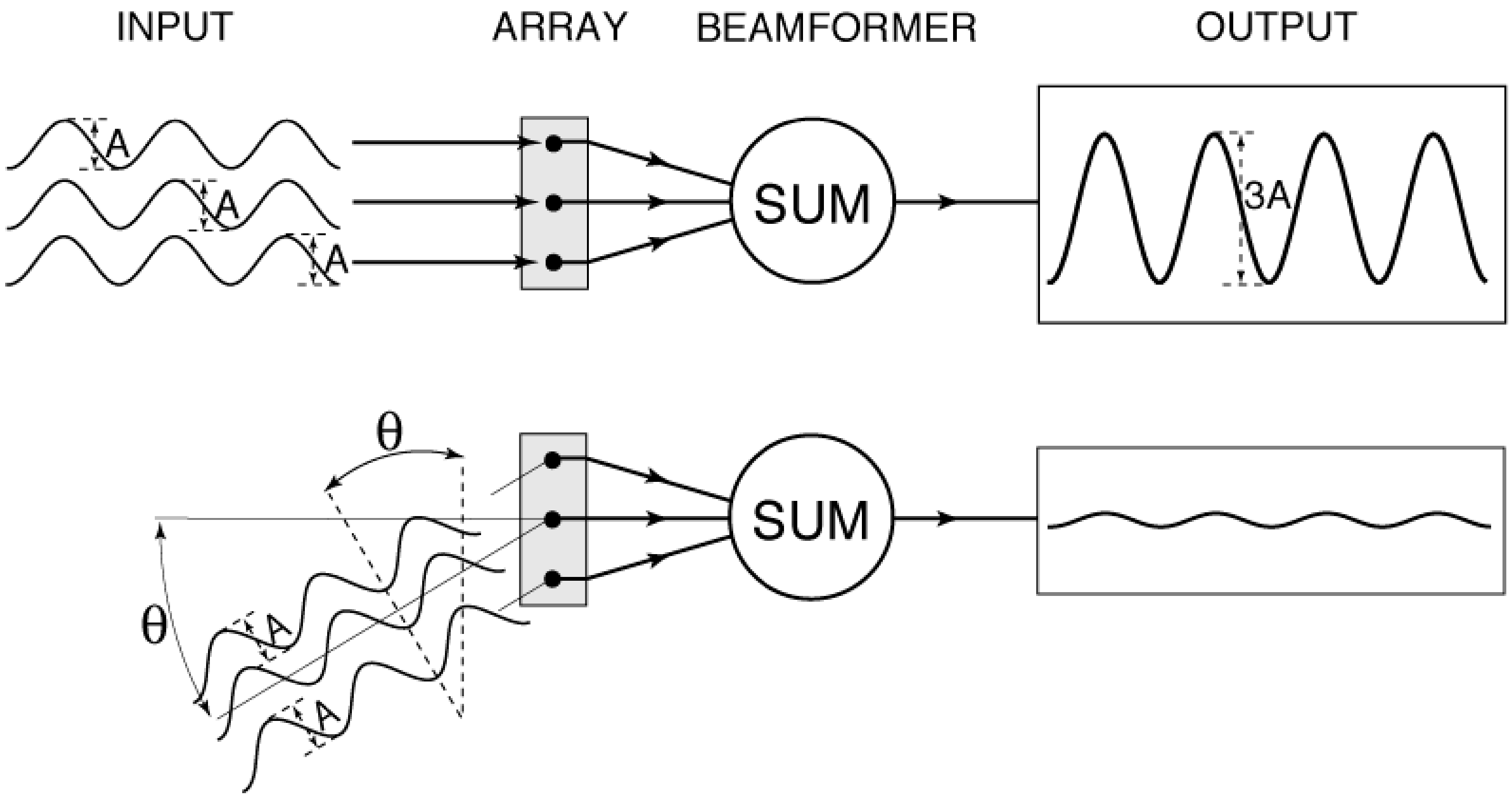




Amplitude	**W**eighted **M**ean**T**ime best for near-specular geometry biased for oblique incidence

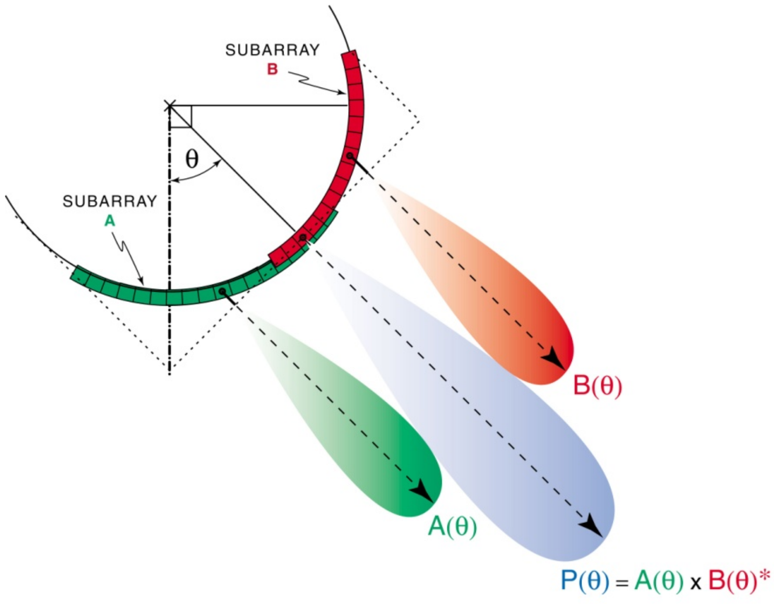
ARRAY BEAMFORMING: BROADSIDE BEAM PATTERN

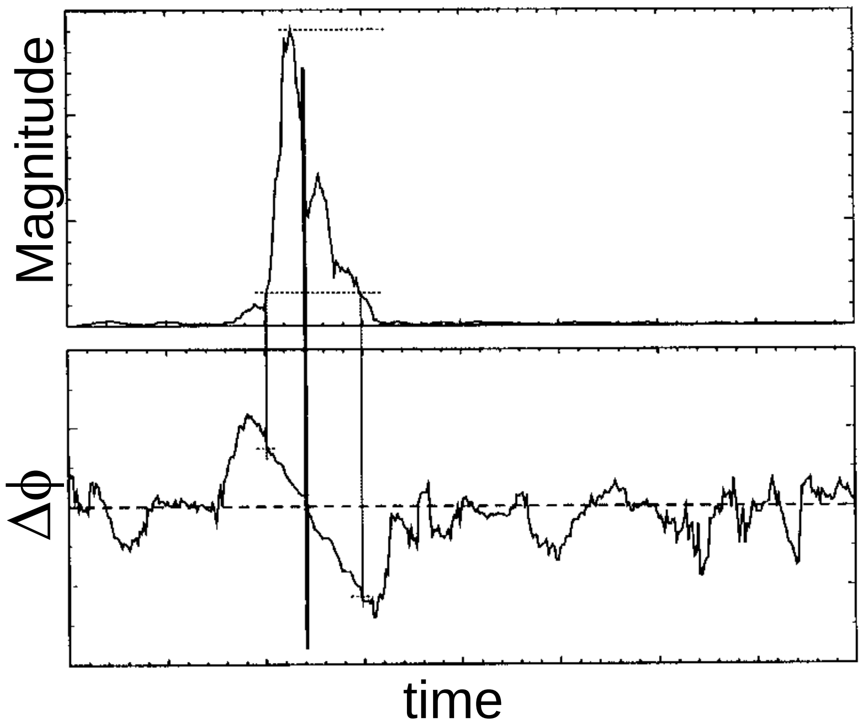
Maximum output when all three signals arrive in phase (wavefront parallel to the array elements' plane)



Minimum output when phases sum to zero (wavefront at some angle to the array elements' plane)

BOTTOM DETECTION



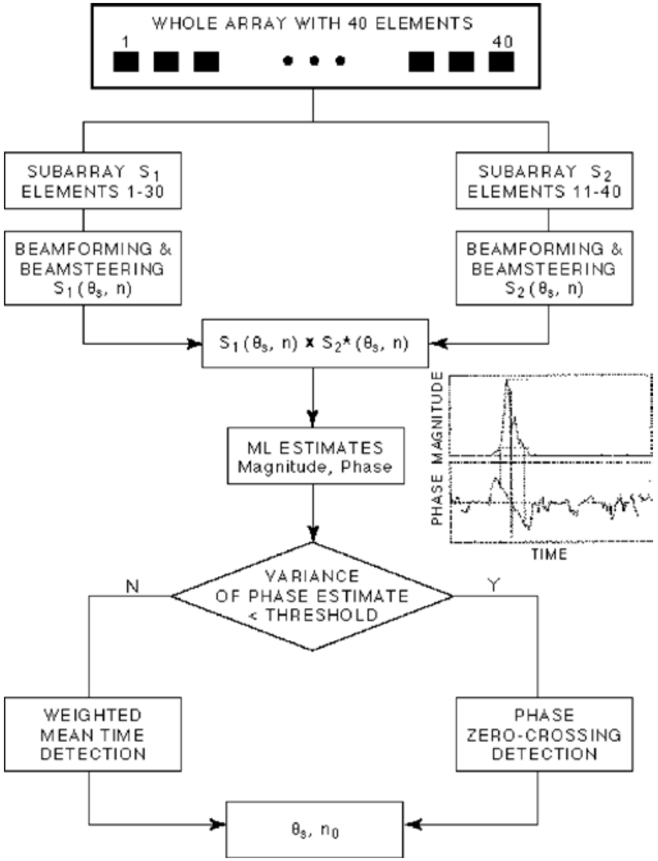


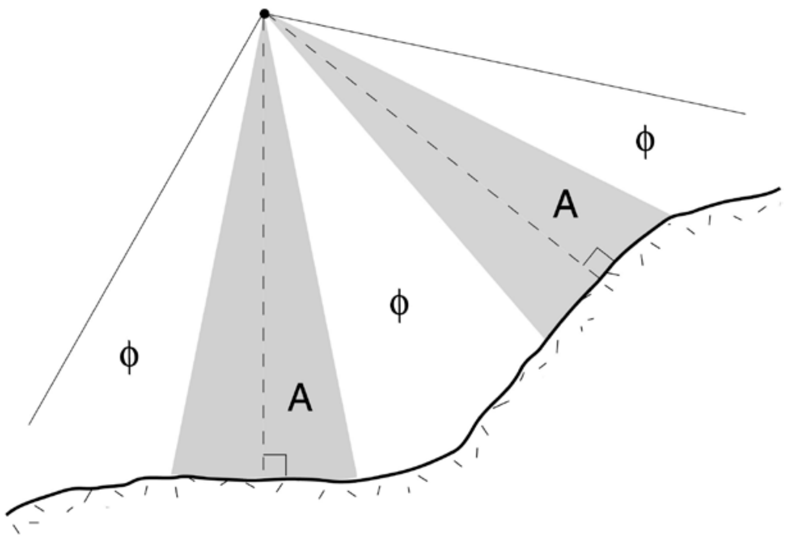
Split Aperture

divide the array into two sub-arrays
measure the **phase difference** of echoes received by these arrays

zero phase difference = maximum response axis of array pair

BOTTOM DETECTION





Amplitude	weighted mean time near specular backscatter
and	
Phase	zero crossing of phase at oblique incidence

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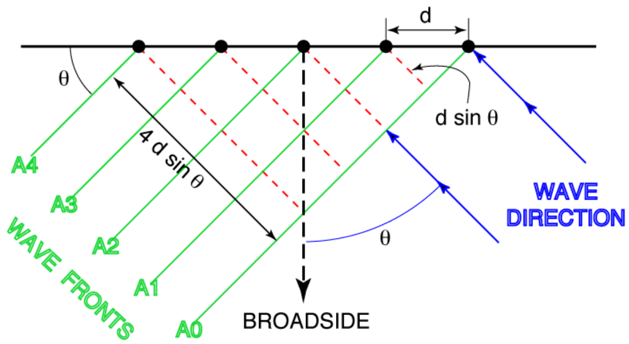

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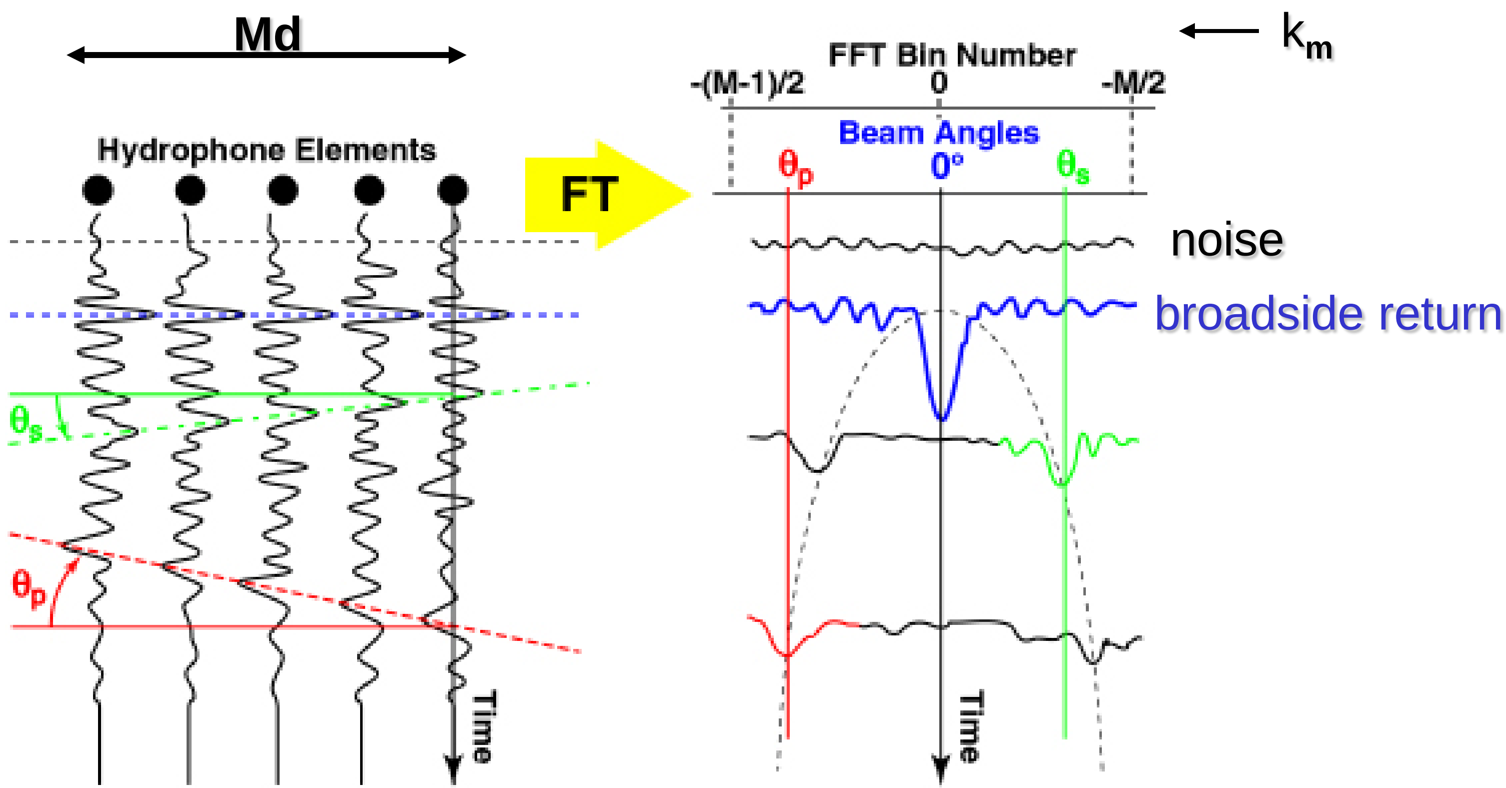

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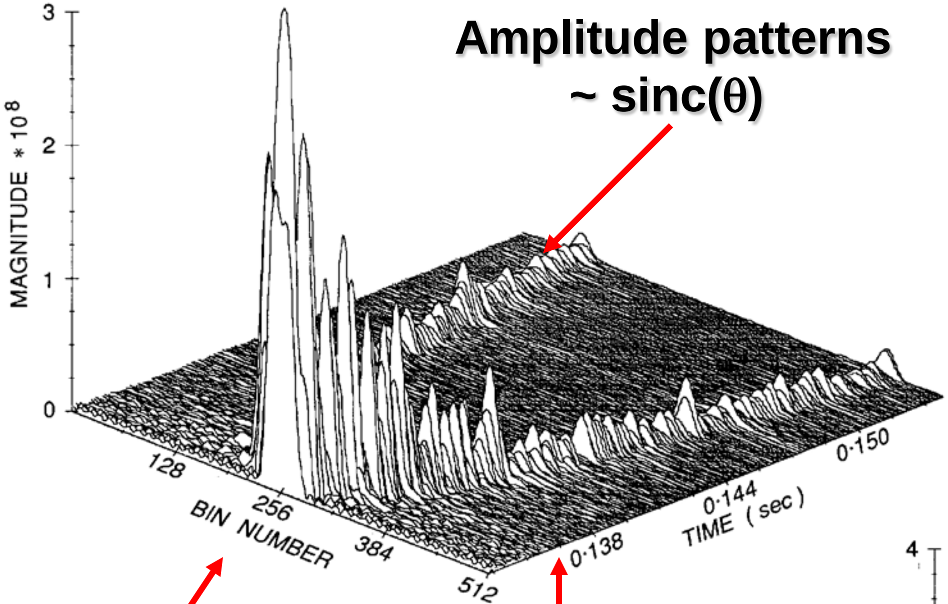

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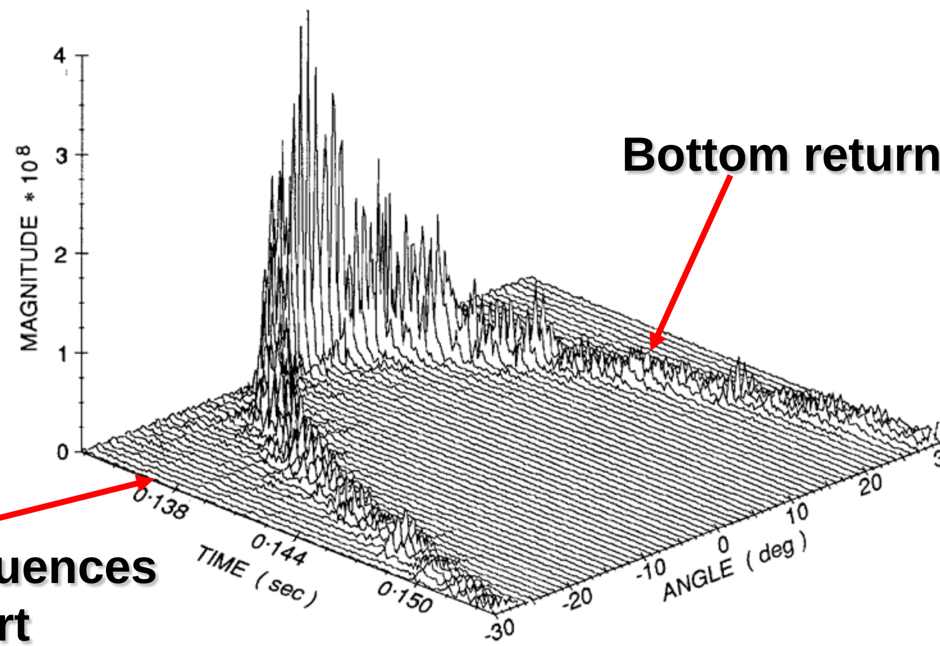
Bin 256 = broadside

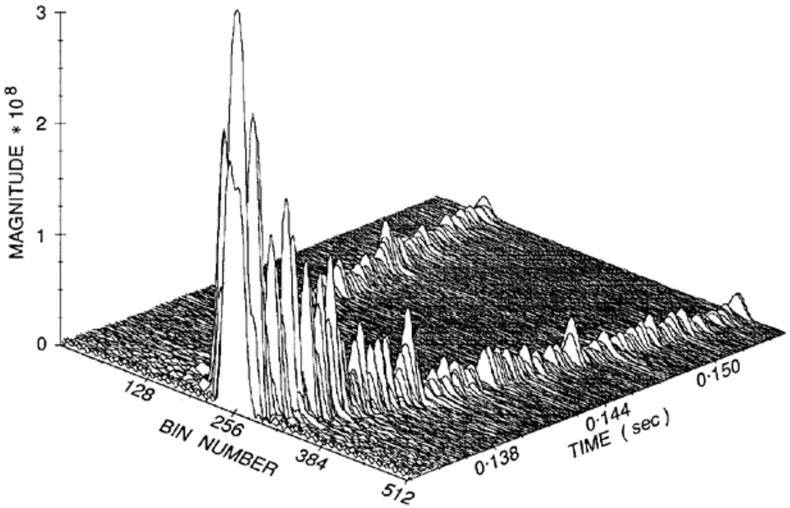
FFT output for each time slice

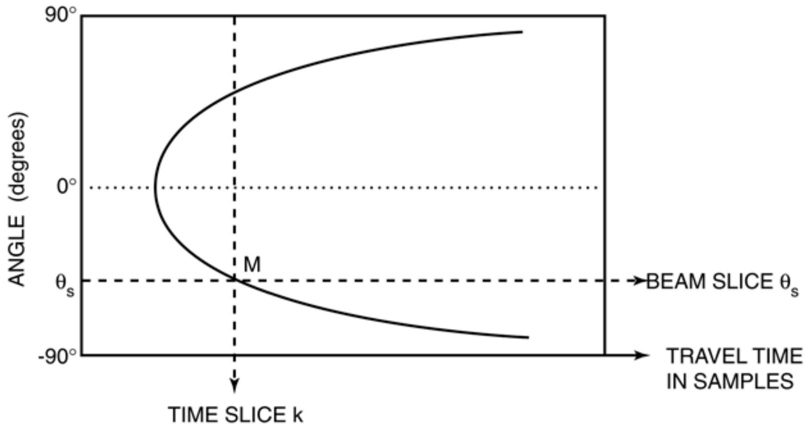


Bottom returns

Same output converted into time sequences for 61 beam directions spaced 1° apart within ±30° of broadside

BOTTOM DETECTION





Angle of Arrival

Beam **D**eviation **I**ndicator method

applicable to FFT beamforming

for each arrival time, retain angles of arrival and corresponding echo magnitudes