Littoral Underwater Acoustic Tracking Using Collaborating Autonomous Ocean Craft:

Improving Communications through Dynamic Encoding and Adaptive Vehicle Motion

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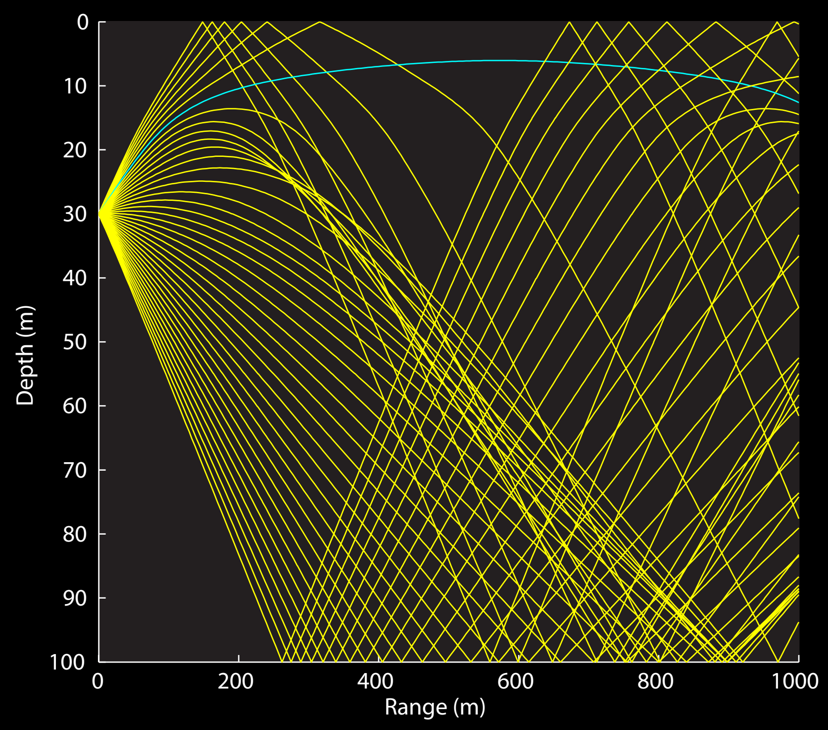


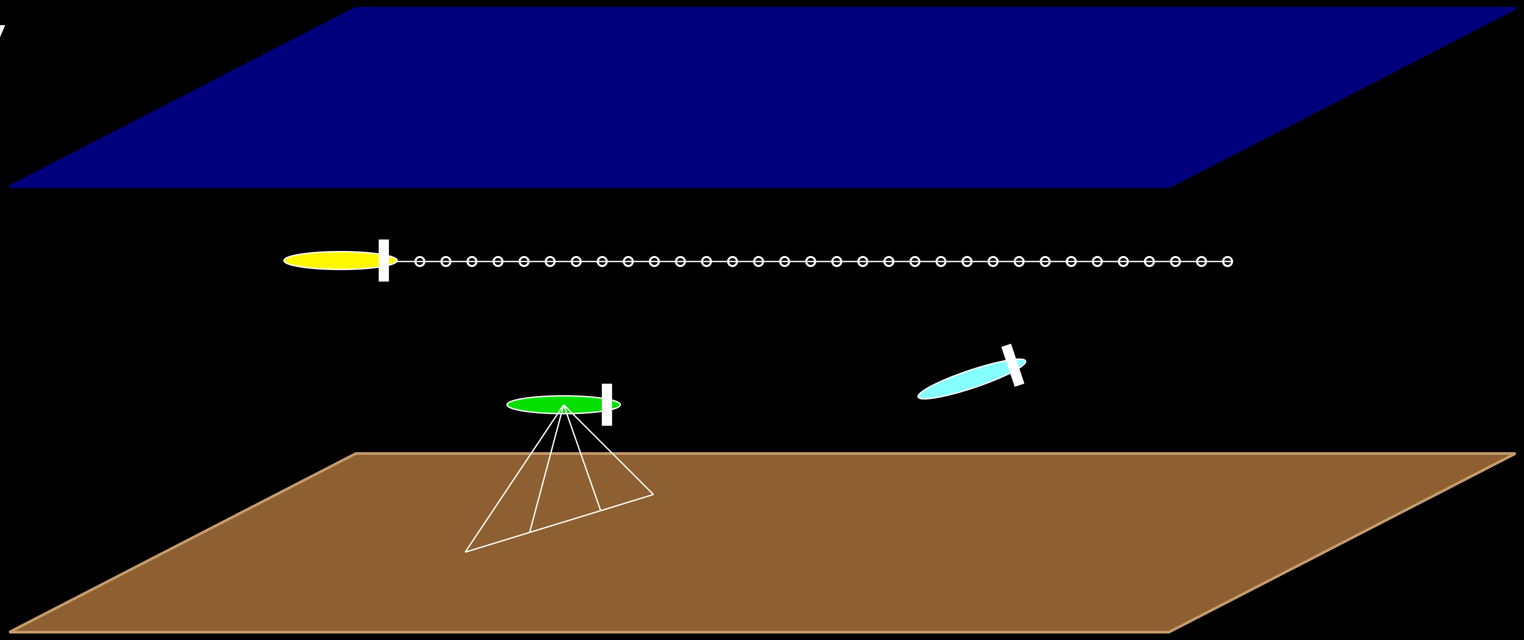
Problem | Collaborative Exploration

Multiple autonomous underwater vehicles (AUVs) tasked on a mission:

- target tracking (submarines, marine mammals)
- geological survey
- mine countermeasures

Why multiple craft?

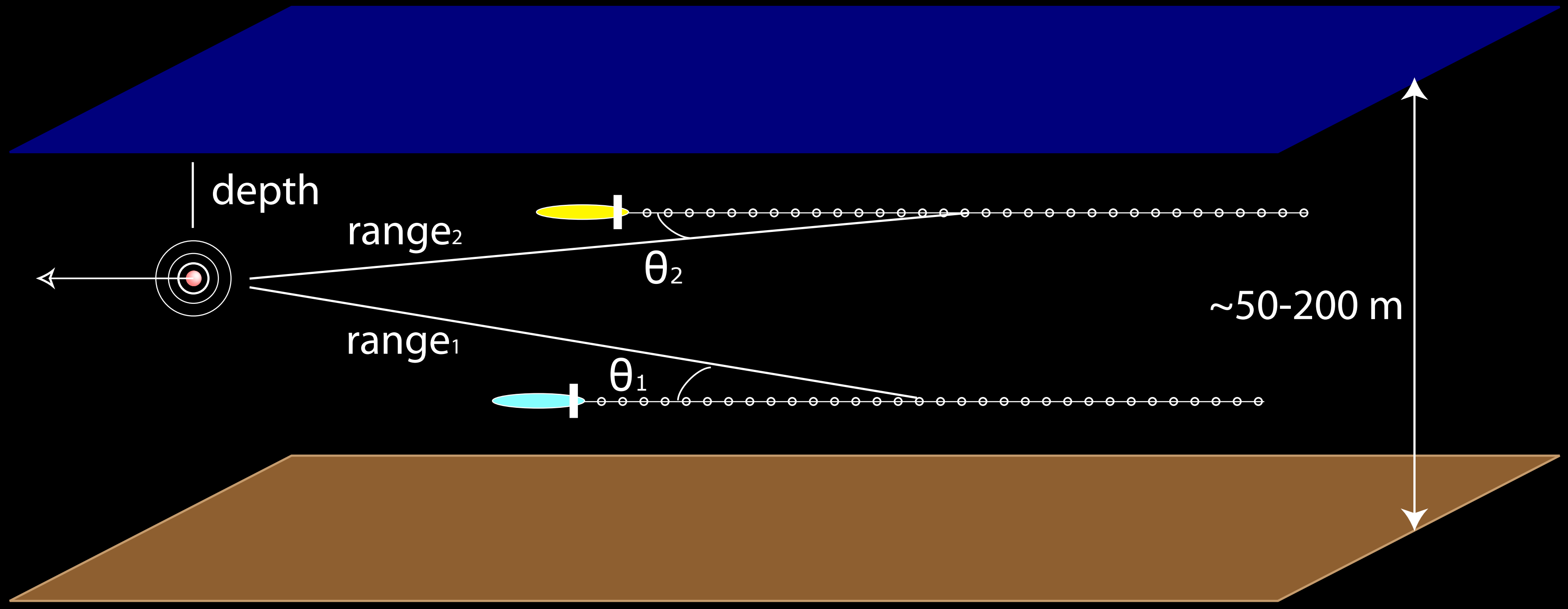
- specialization
- redundancy
- spatial distribution



Problem | Acoustic Target Tracking

How do we get find source information:

- heading: hydrophone array gives (left/right ambiguous) heading through traditional beamforming. can break ambiguity by vehicle motion.
- range: use waveguide invariant, or triangulate using multiple craft.
- depth: modal energy distribution?

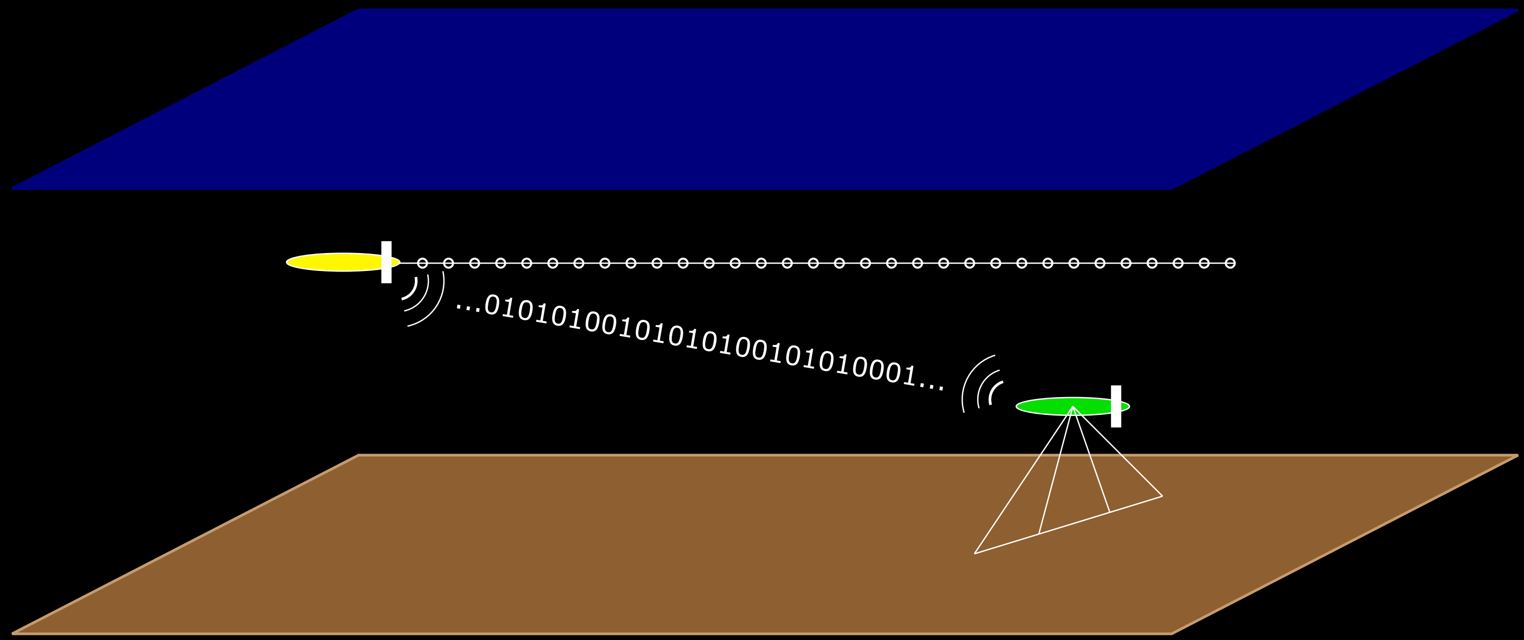


Problem | Intervehicle Communication

Multiple AUVs must share data:

- broad operational goals
- status (pose and health)
- environmental data (sound speed profile)
- tracking data (probabilistic?)

Acoustic communication (acomms) is the only practical long range solution, as electromagnetic waves are rapidly attenuated in water.

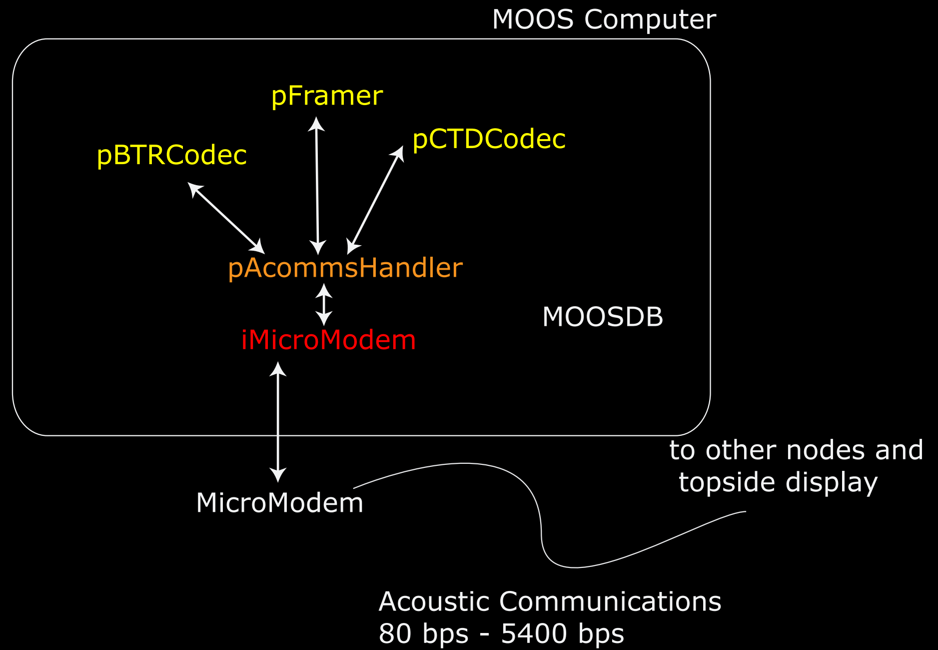


Acomms | Network

We use an acoustic network based on the WHOI MicroModem (rate C: ~25 kHz carrier)

- application layer: encoding: various message codecs, queuing: pAcommsHandler
- transport layer: MOOS driver iMicroModem
- link layer: MicroModem firmware
- hardware: MicroModem (allows frequency shift / phase shift keying (FSK/PSK) from 80 to 5400 bits/sec).

By nature of the channel, throughput highly limited (low bandwidth, high error rate)



Acomms | Dynamic Encoding

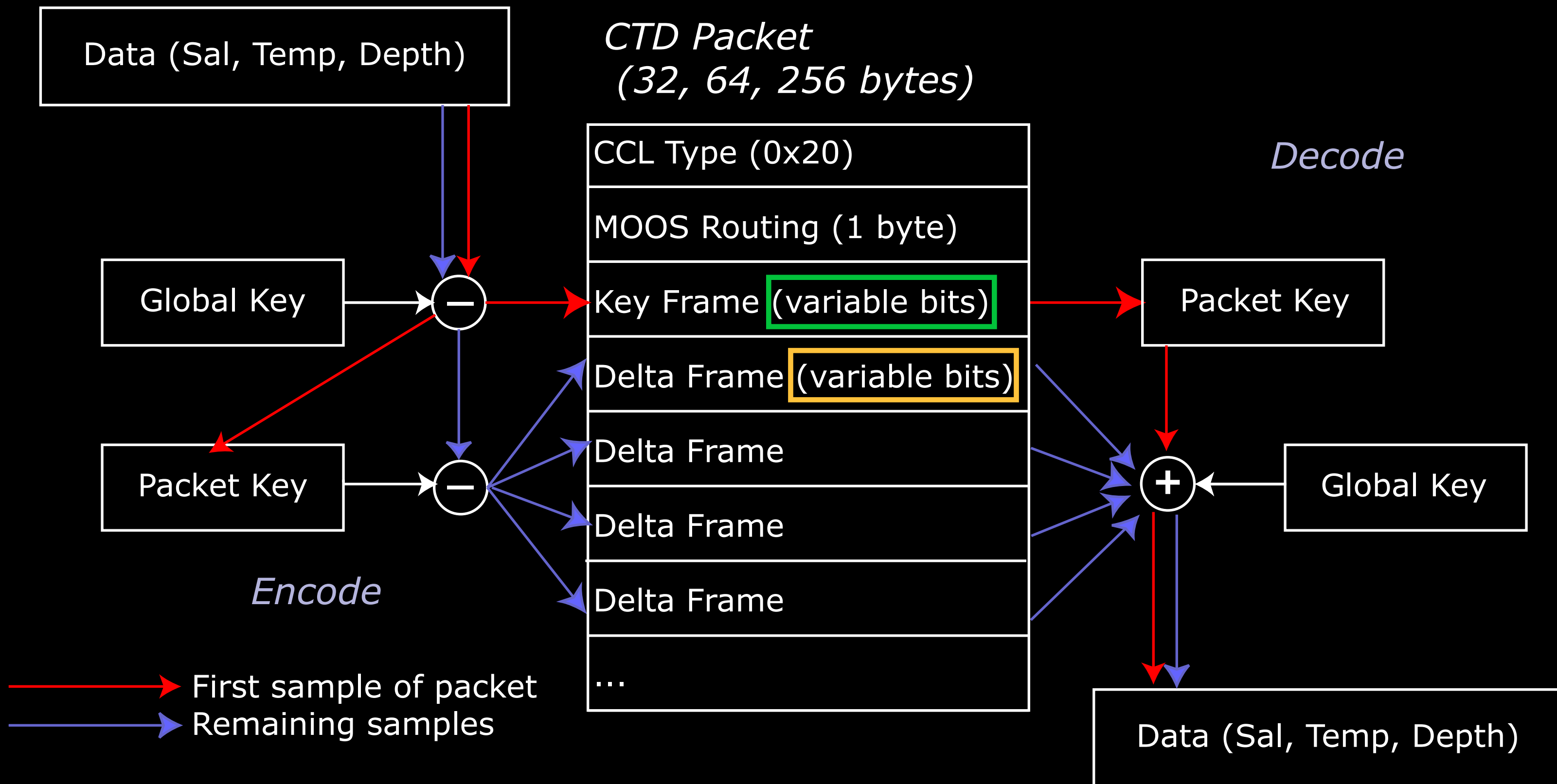
pCTDCodec - example of highly compressed encoding scheme. need to send: time, sal, temp, depth, lat, lon. can derive sound speed at receiver.

Ideas to save space:

- global key: preshared data comprising operational parameters (i.e. some $[val_{min}, val_{max}]$ not to be exceeded). e.g. global key for salinity can be [25, 40] (or tighter for specific region).
- key frame: within a packet, key all frames after the first to the values in the first (assumes data samples are related).
- dissolve byte boundaries.
- discard unused precision (decimal places). e.g. 12.200 becomes 12.2

Acomms | Dynamic Encoding

pCTDCodec - encoding scheme



$$val_{key,encoded} = \text{round}((val_{key} - val_{min}) * 10^{precision})$$ (Similar to Excess N scheme)

$$val_{delta,encoded} = \text{round}((val_{delta} - val_{key} + delta) * 10^{precision})$$

$$\boxed{size_{key\_piece}} = \text{ceil}(\log_2((val_{max} - val_{min}) * 10^{precision}))$$

$$\boxed{size_{delta\_piece}} = \text{ceil}(\log_2((2 * delta) * 10^{precision}))$$

Acomms | Dynamic Encoding

pCTDCodec: performance at GLINT08 sea trials (Pianosa, Italy):

Used in three vehicles (Bluefin21, OEX, Folaga).

Given operational parameters:

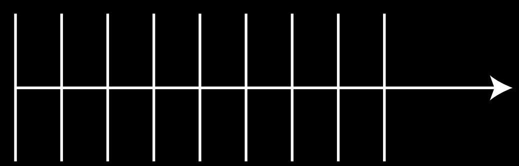
- 32 byte (FSK) message: 3 CTD samples (85.3 bits / sample)
- 64 byte (PSK) message: 7 CTD samples (73.1 bits / sample)
- 256 byte (PSK) message: 31 CTD samples (66.1 bits / sample)

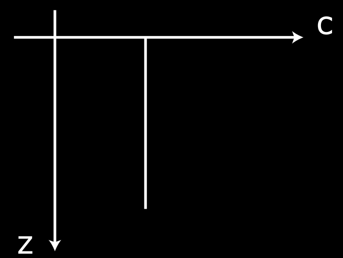
Compare to WHOI CCL format: 128 bits/sample

Qualitative observation at GLINT08: dropped messages seemed highly linked to vehicle depth. can we explain / improve?

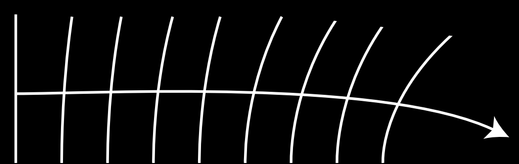
Ray Tracing (Intuition)

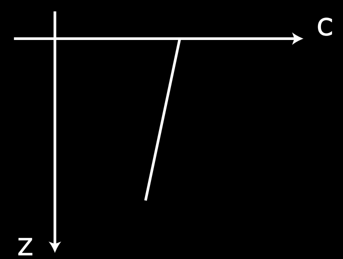
Plane wave in homogeneous fluid:





Plane wave in linearly varying sound speed profile:





Ray tracing follows path of rays launched at a fan from a point source. High number of rays passing through the receiver point corresponds to low transmission loss and vice versa.

Ray Tracing (Mathematics)

Ray equations (derived from the Helmholtz equation):

$$\frac{dr}{ds} = c\xi(s), \quad \frac{d\xi}{ds} = -\frac{1}{c^2}\frac{dc}{dr}$$

$$\frac{dz}{ds} = c\zeta(s), \quad \frac{d\zeta}{ds} = -\frac{1}{c^2}\frac{dc}{dr}$$

$(r(s),\, z(s))$ - trajectory of ray along arclength s

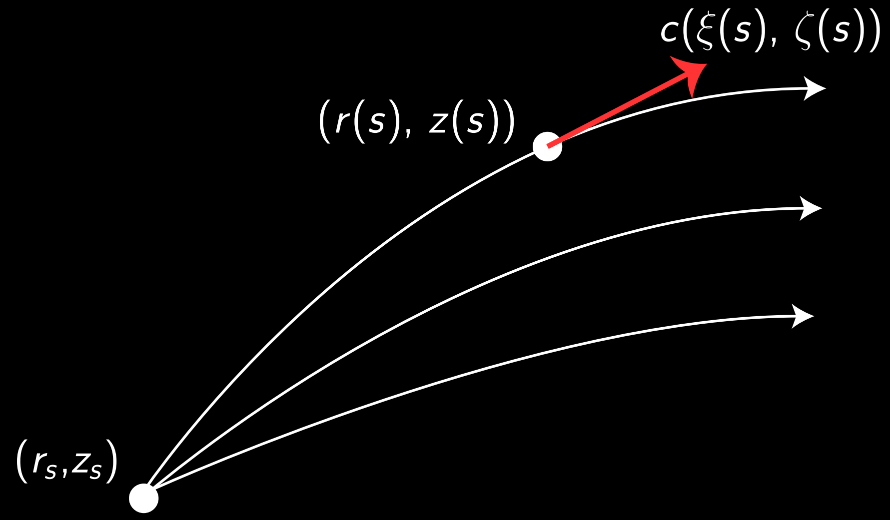
$c(\xi(s),\, \zeta(s))$ - tangent vector to ray

with these initial conditions for a fan of rays each with angle θ to the source:

$$r = r_s, \quad \xi = \frac{\cos\theta}{c(0)}$$

$$z = z_s, \quad \zeta = \frac{\sin\theta}{c(0)}$$

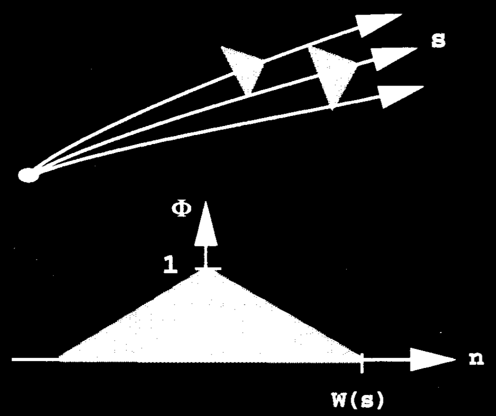
(r_s, z_s) - source position



Reference: F.B. Jensen, W.A. Kuperman, M.B. Porter, H. Schmidt. *Computational Ocean Acoustics.*

Ray Tracing (BELLHOP model)

BELLHOP uses finite element rays:



Amplitude of the ray ($A_0(s)$) is computed by the dynamic ray equations:

$$\frac{dq}{ds} = cp(s), \quad \frac{dp}{ds} = \frac{1}{c^2(s)}\frac{d^2c}{dn^2}q(s) \qquad q(0) = 0, \quad p(0) = \frac{1}{c(0)}$$

n - direction normal to ray path

$$A_0(s) = \frac{1}{4\pi}\left|\frac{c(s)\cos(\theta)}{rc(0)q(s)}\right|^{1/2}$$

For high frequency problems, ray tracing is fast compared to normal modes and sufficiently accurate.

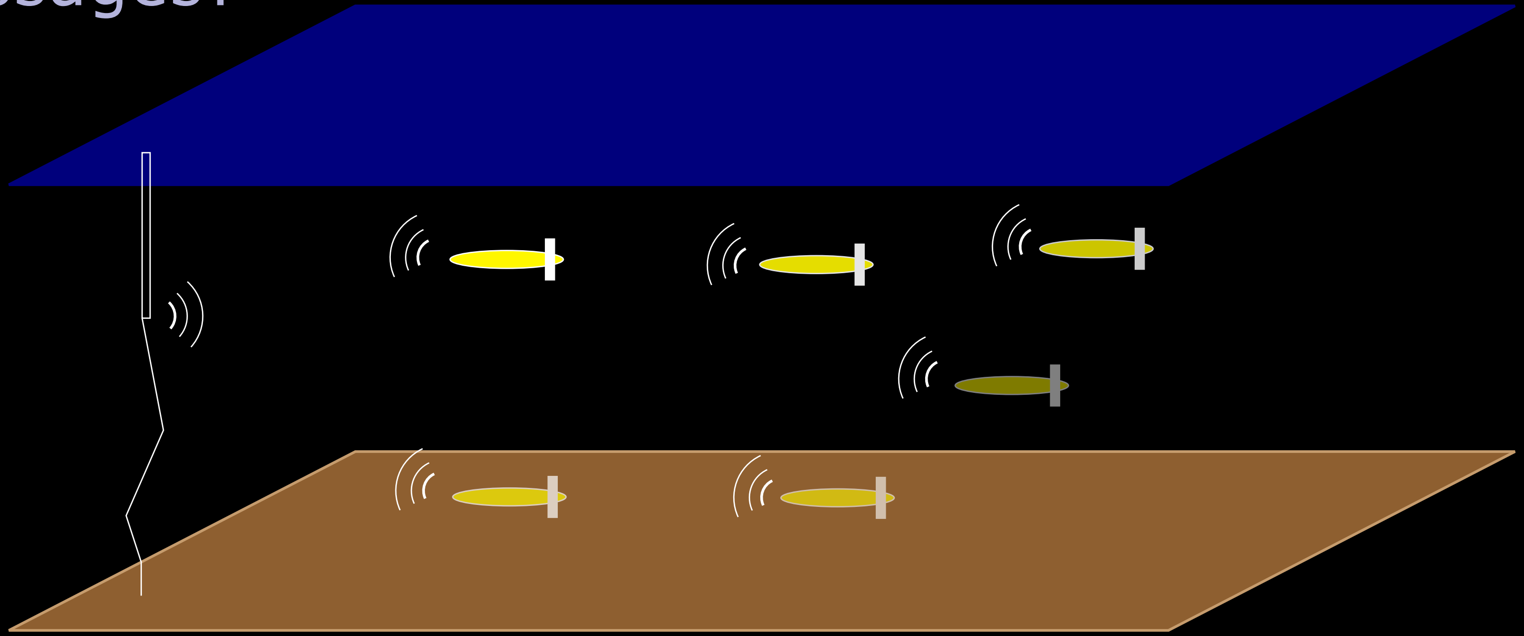
References: M.B. Porter, Y-C Liu. *Finite Element Ray Tracing,* Theoretical and Computational Acoustics
F.B. Jensen, W.A. Kuperman, M.B. Porter, H. Schmidt. *Computational Ocean Acoustics.*

Ray Tracing Setup | GLINT08

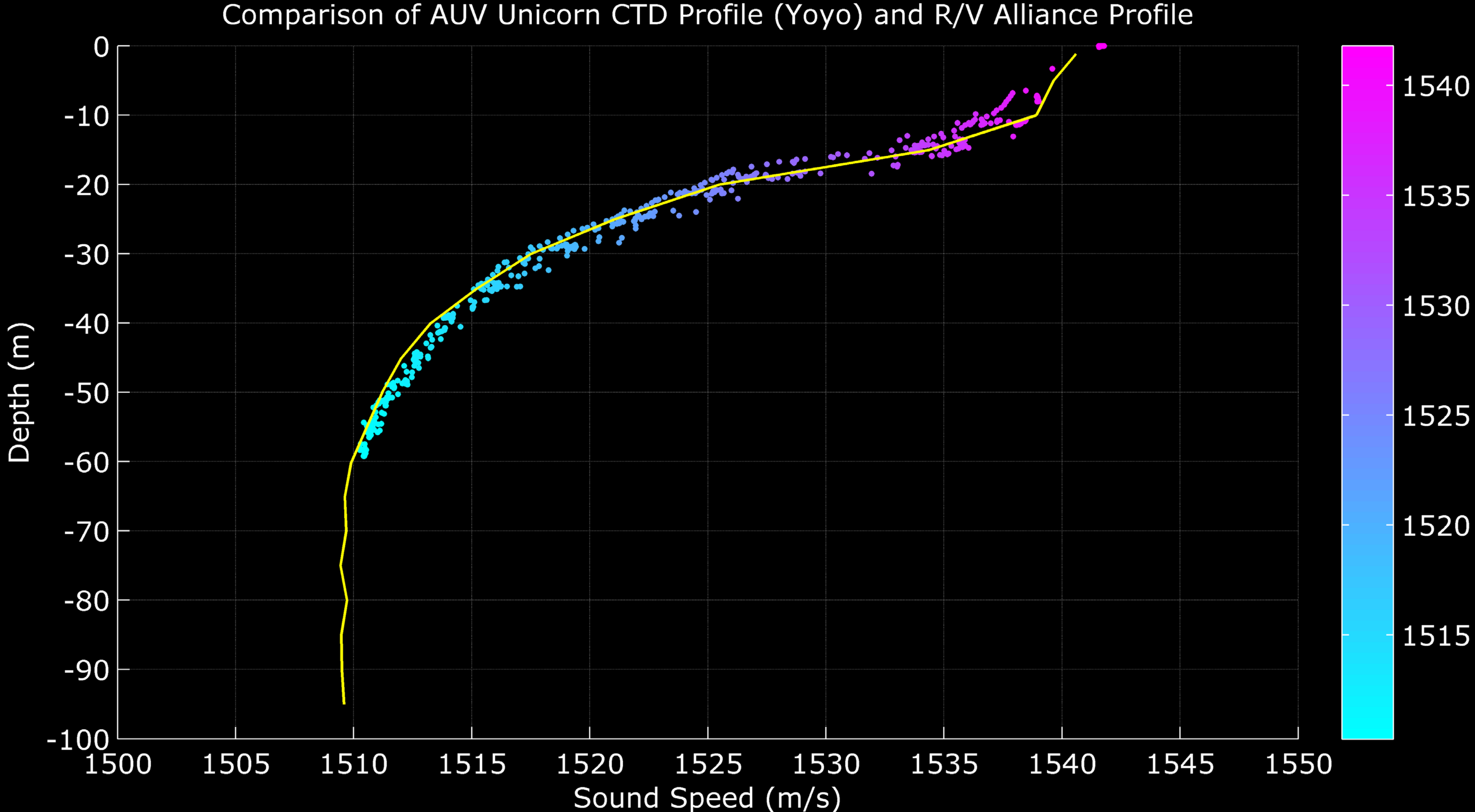
Experimental setup:

- single AUV performing a variety of missions that we can consider here to place it at arbitrary locations (with range < 2km) relative to communications buoy (30 m depth).
- water depth ~100 m (assume constant).
- silt bottom: c = 1600 m/s, ρ = 1.8 g/cm^3, attenuation: 0.5 dB/λ

Can we correlate modeled transmission loss to quality of received messages?



Ray Tracing Setup | GLINT08

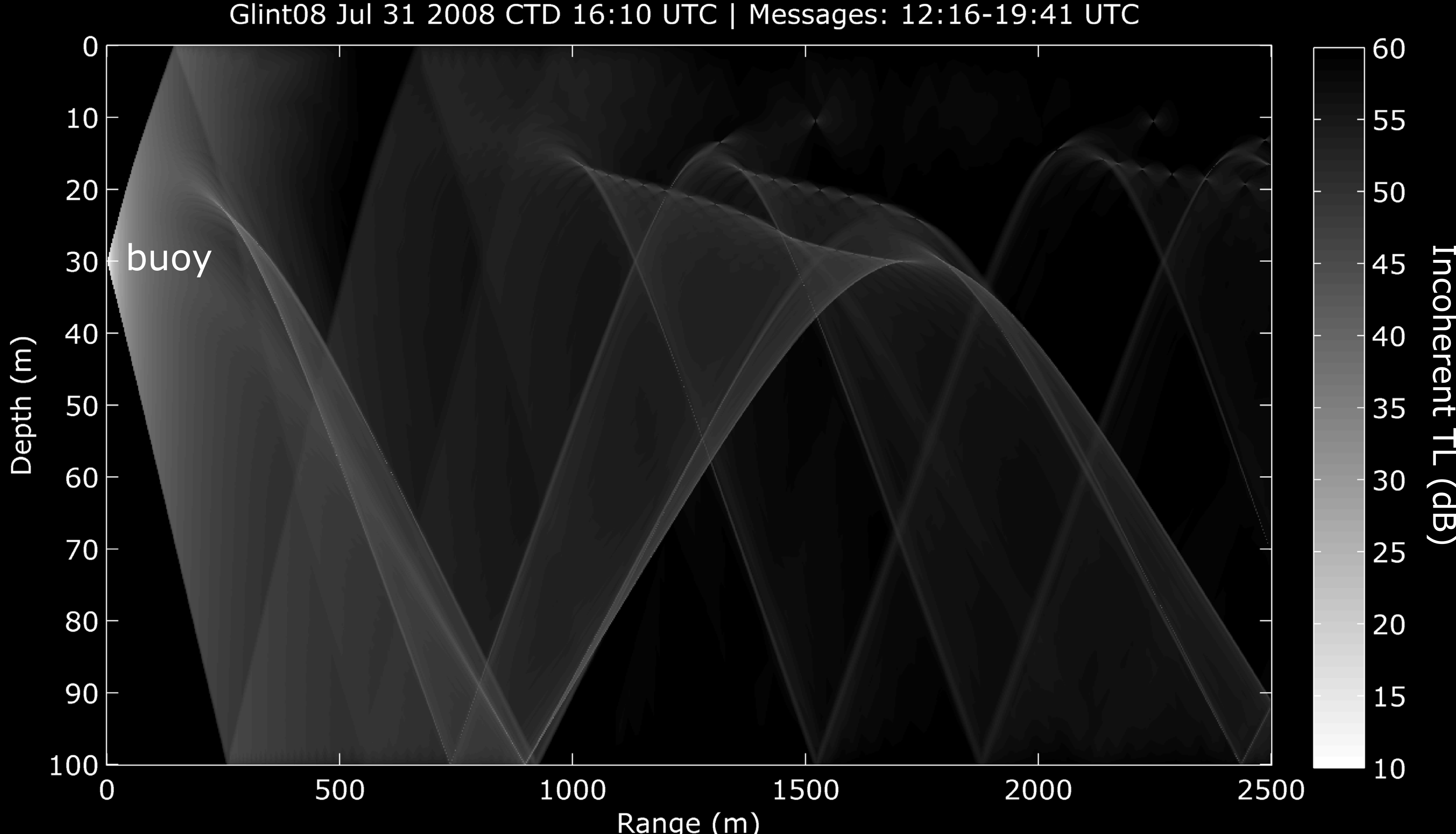


dots: AUV sampled profile (Jul 31 2008 12:16-19:41 UTC)

yellow line: ship cast profile (Jul 31 2008 16:10 UTC)

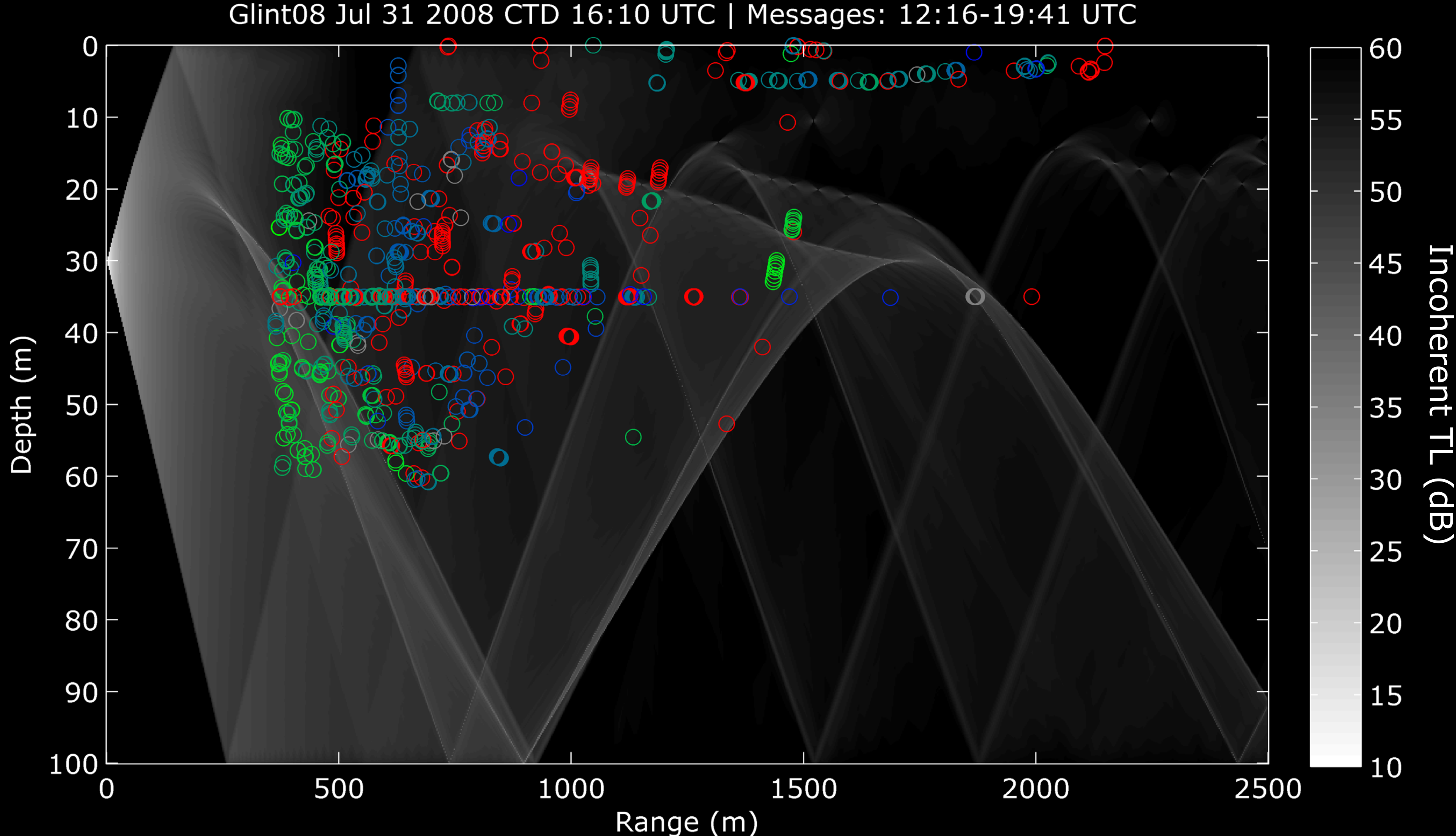
Single ship cast acceptable approximation

Ray Tracing Results | GLINT08



Incoherent transmission loss for R/V Alliance CTD profile (Jul 31 2008 16:10 UTC) from a 30 m source (buoy) in a 100 m homogenous (in range) waveguide with silt bottom.

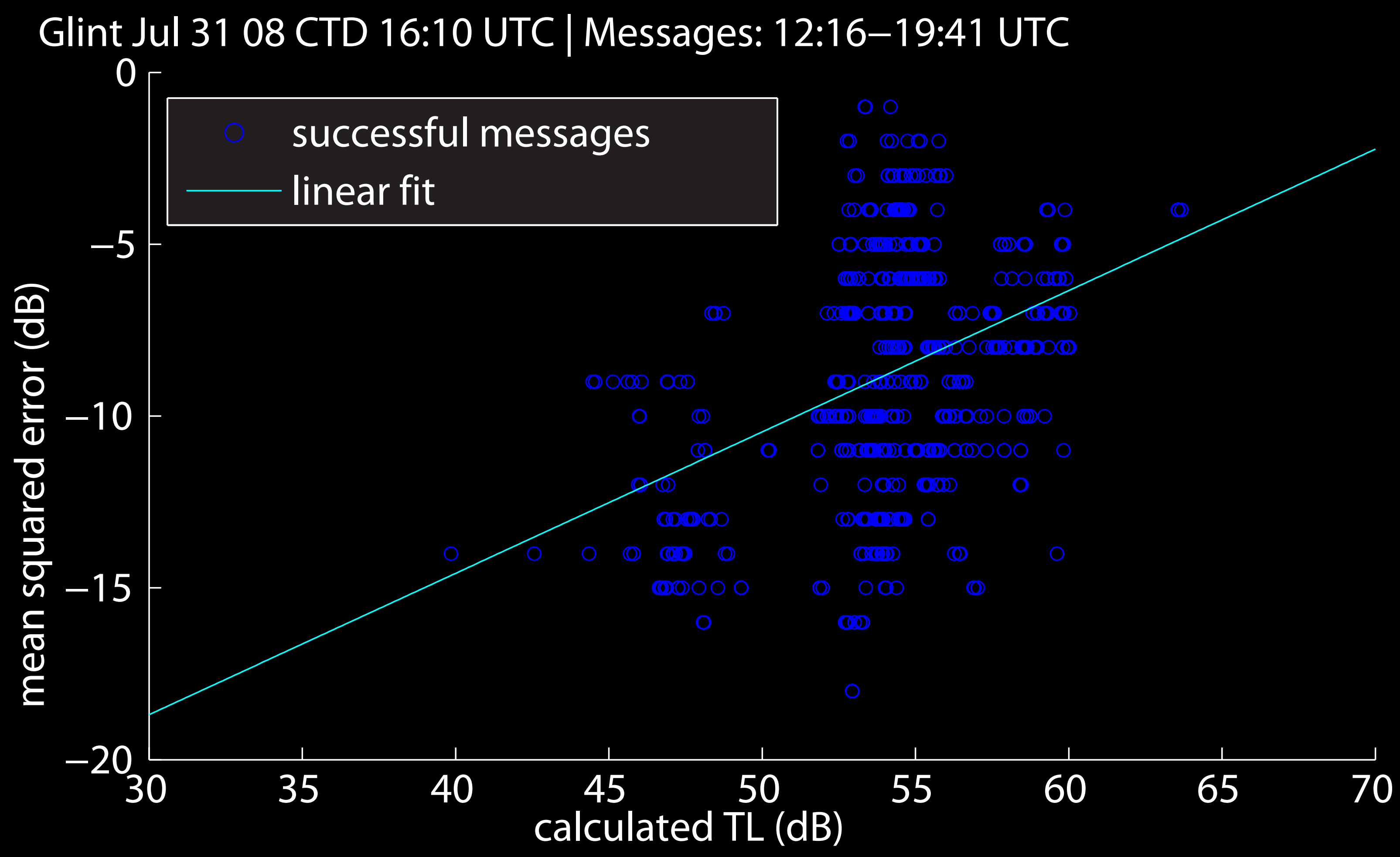
Ray Tracing Results | GLINT08



successfully decoded: low error high error

dropped message:

Ray Tracing Results | GLINT08



Proposed Applications

Back to target tracking example:

- initial research suggests it is impractical to adjust depth to improve beamforming on target.[1]
- therefore, it may be advantageous to make a depth-varying communications optimizing behavior (leaving heading / speed to behaviors responsible for present mission)

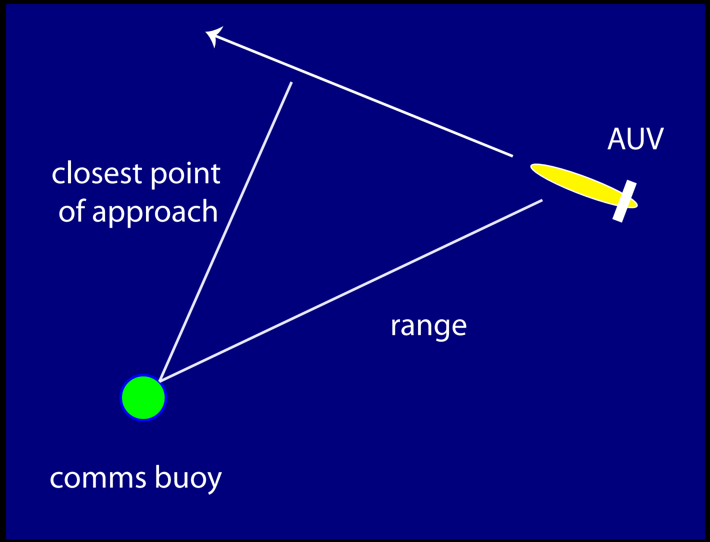
Also, it may be useful to choose a message rate to satisfy a desired probability of reception (as higher rates tolerate less error).

[1] K. Cockrell, H. Schmidt. *Depth dependence of plane wave beamformed data with a horizontal array in a waveguide.* Presentation at 153rd ASA meeting, New Orleans.

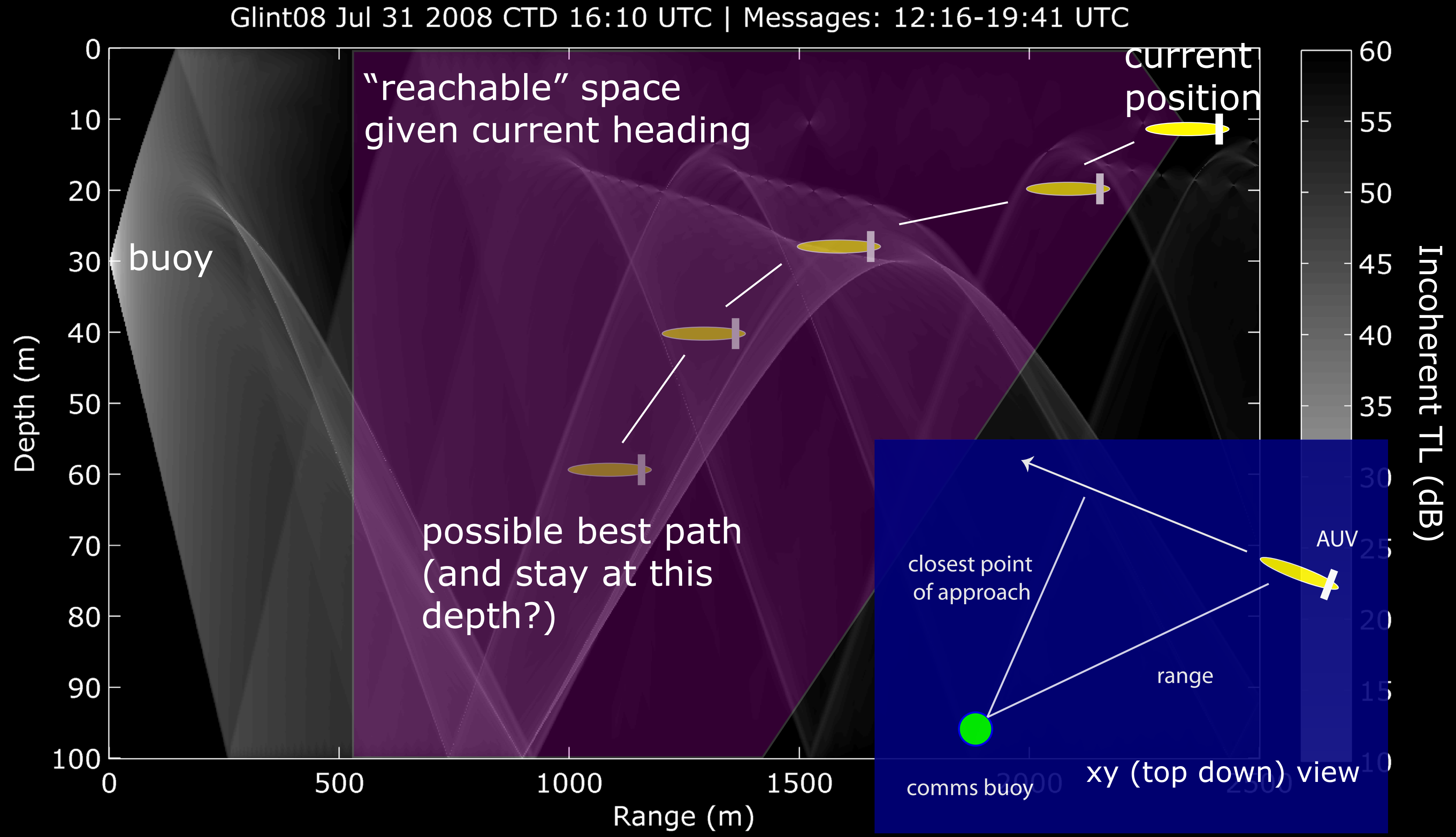
Acomms Improvement Behavior

Scenario:

- AUV undergoing mission that requires certain path in xy-plane but does not mandate any particular depth (e.g. target tracking)
- AUV has a certain (known) maximum dive/surface rate.
- want to minimize depth maneuvers to keep array straight and save power.



Acomms Improvement Behavior

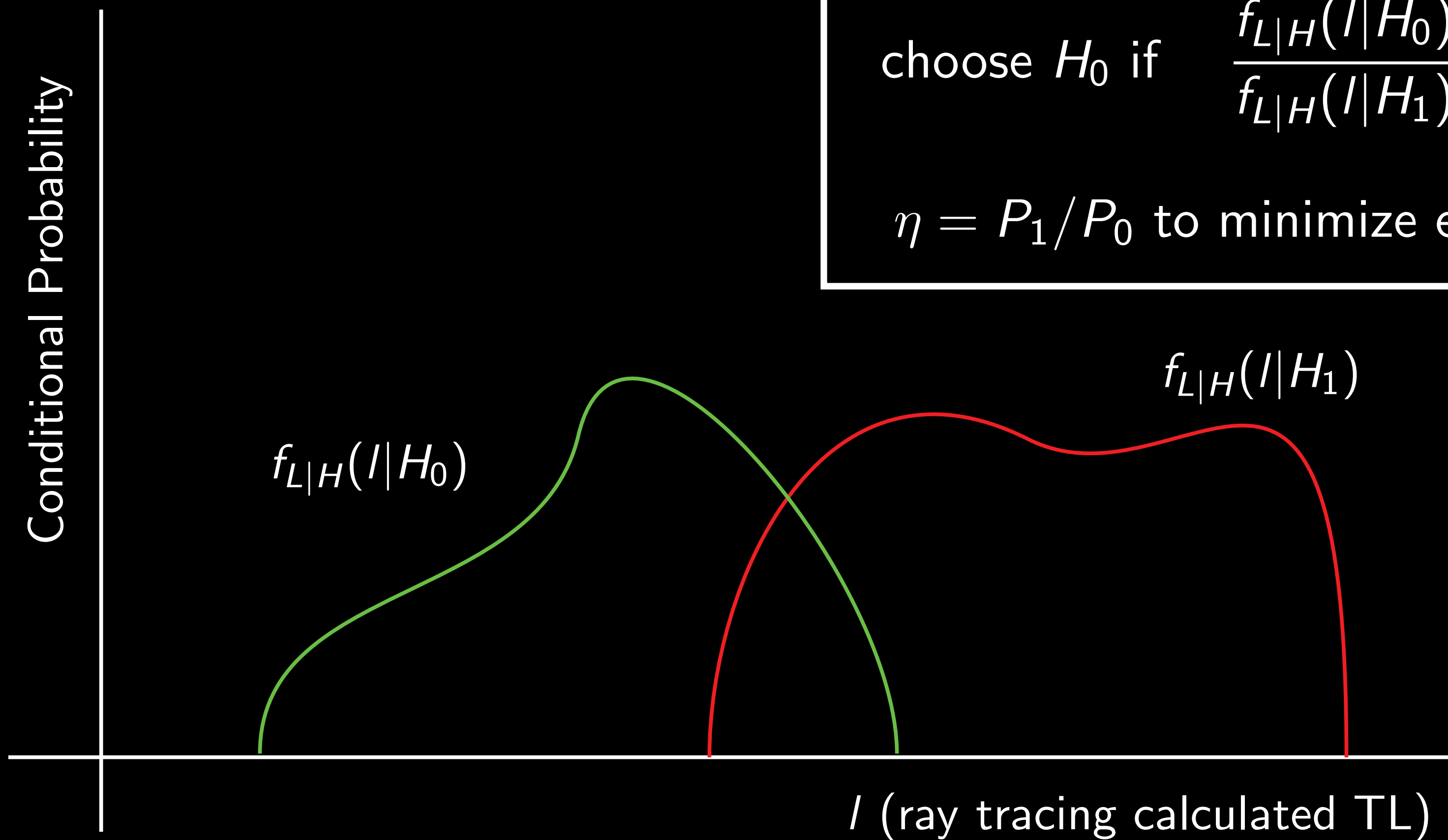


Given sound velocity profile and position of receiving vehicle (or buoy), change depth to optimize placement in sound field.
currently being implemented, then test in simulation.

Hypothesis Testing

$$\text{choose } H_0 \text{ if } \quad \frac{f_{L|H}(l|H_0)}{f_{L|H}(l|H_1)} > \eta$$

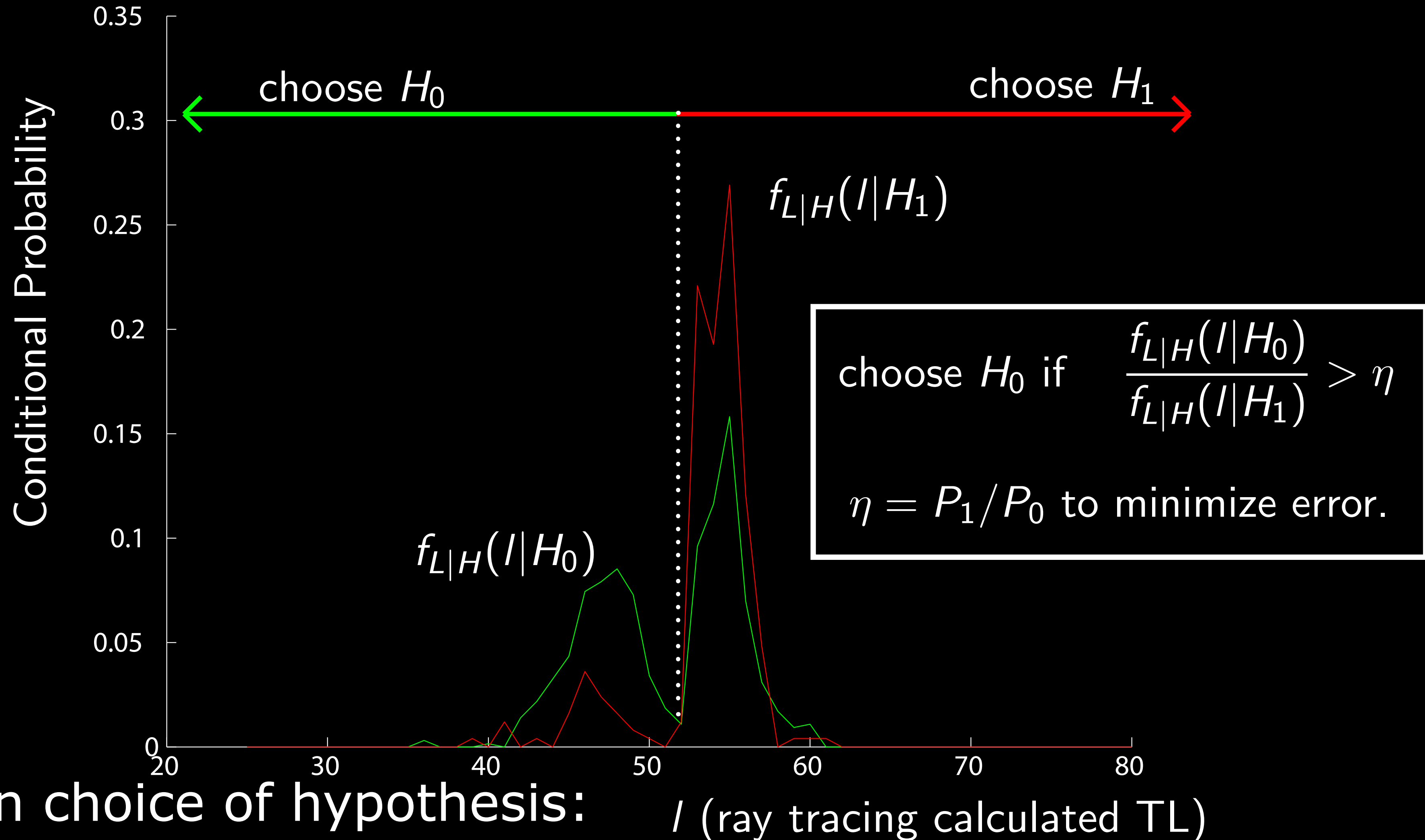
$$\eta = P_1/P_0 \text{ to minimize error.}$$



Want to “decide” before sending a message whether it will be received

- hypothesis 0: message will be received
- hypothesis 1: message will be dropped

Hypothesis Testing | GLINT Jul 31 08

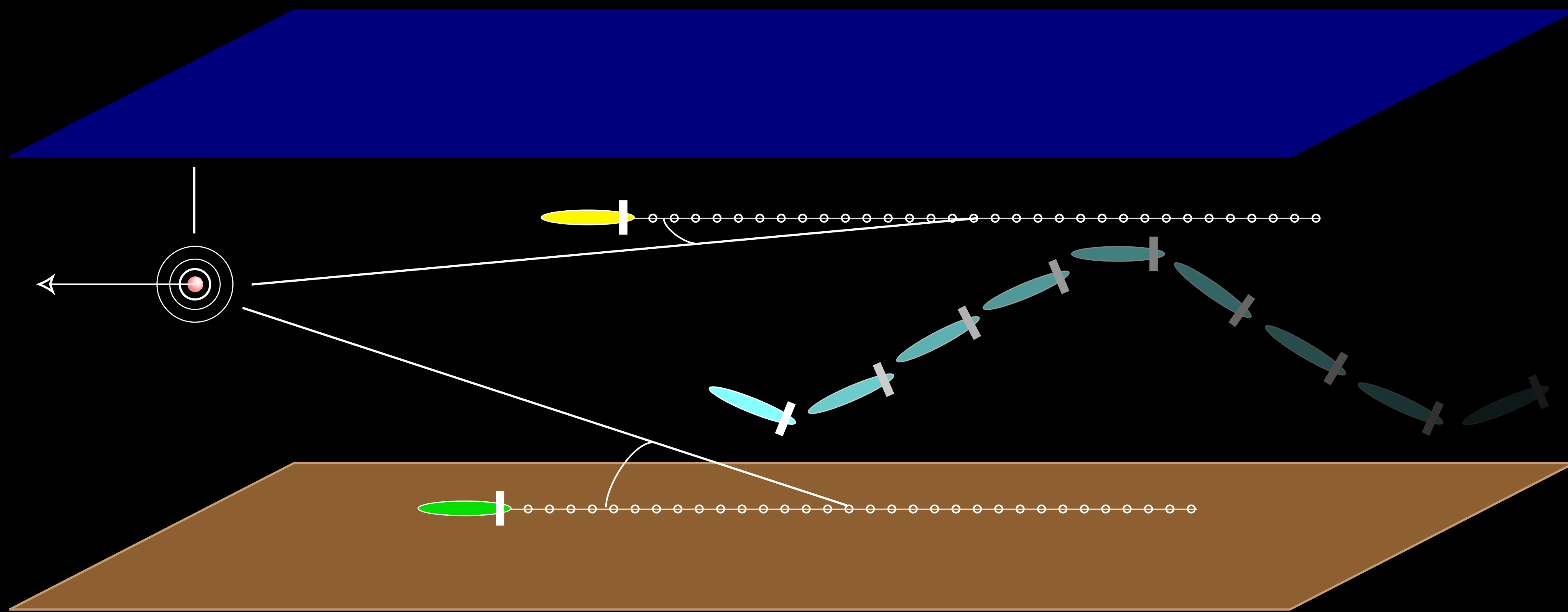


Given choice of hypothesis:

- transit to depth within 'H_0' regime or
- choose different rate (which will have a different set of conditional probability densities)

Proposed Multivehicle Experiment

- small environmental AUV takes sound velocity profile with depth yoyo.
- small AUV transmits profile acoustically to two (or more) tracking AUVs with arrays.
- array AUVs localize and track source, varying depth to improve communication.



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