Undersea Optical Communications

Presented at Quantum Communication Workshop: Secure Information Transmission in the Maritime Environment

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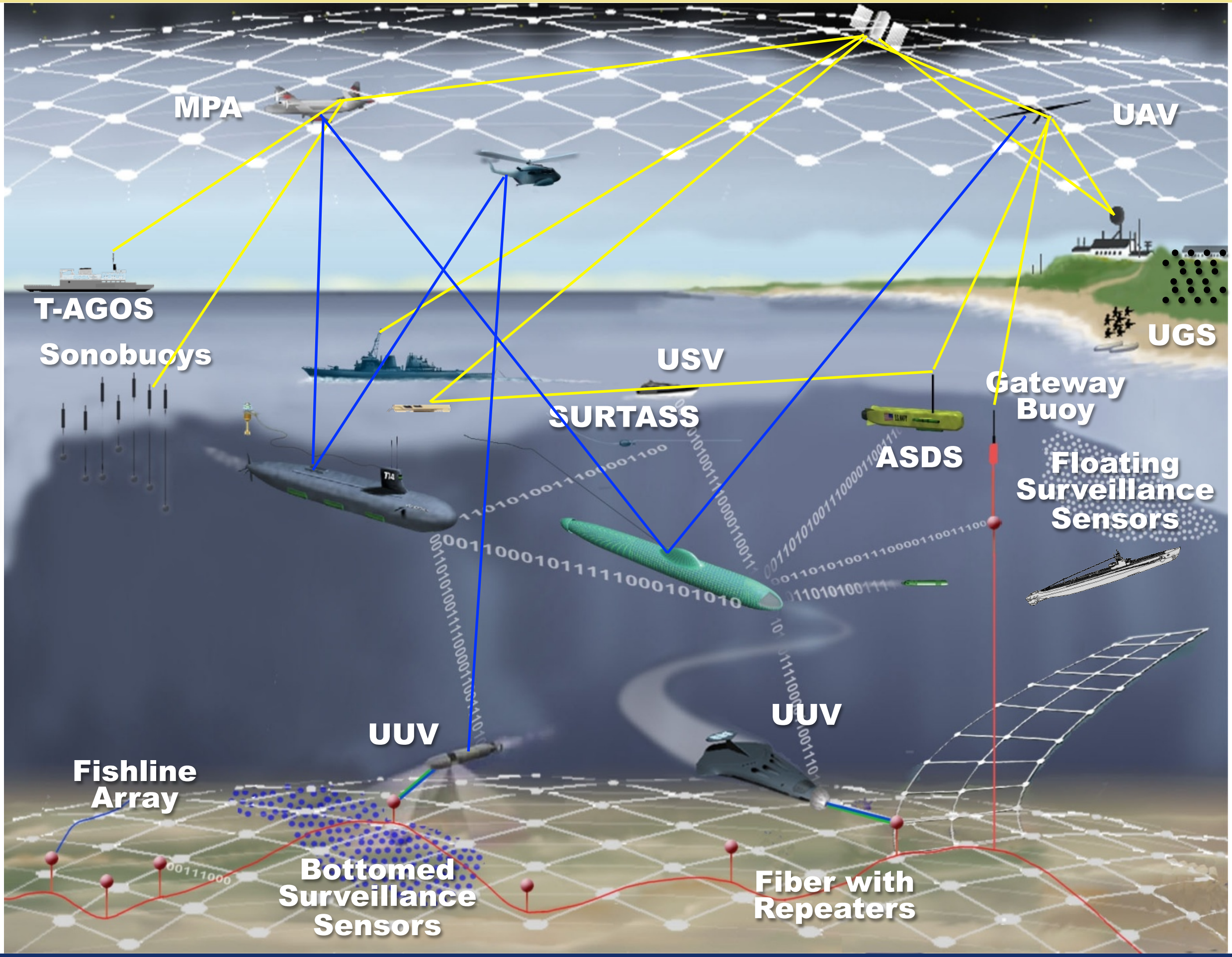
What Are You Going to Hear?

- The Navy's view of connecting the C4ISR network
- Possible underwater Optical Laser Communications (OLC) architectures supporting a wide range of critical Naval missions
- An overview of the fundamental physics of the all-underwater and underwater/above-water propagation channel and the impact on communications performance
- The state of the art in OLC performance modeling and environmental characterization
- An example of the relationship of OLC architecture and laser and narrowband optical filter selection

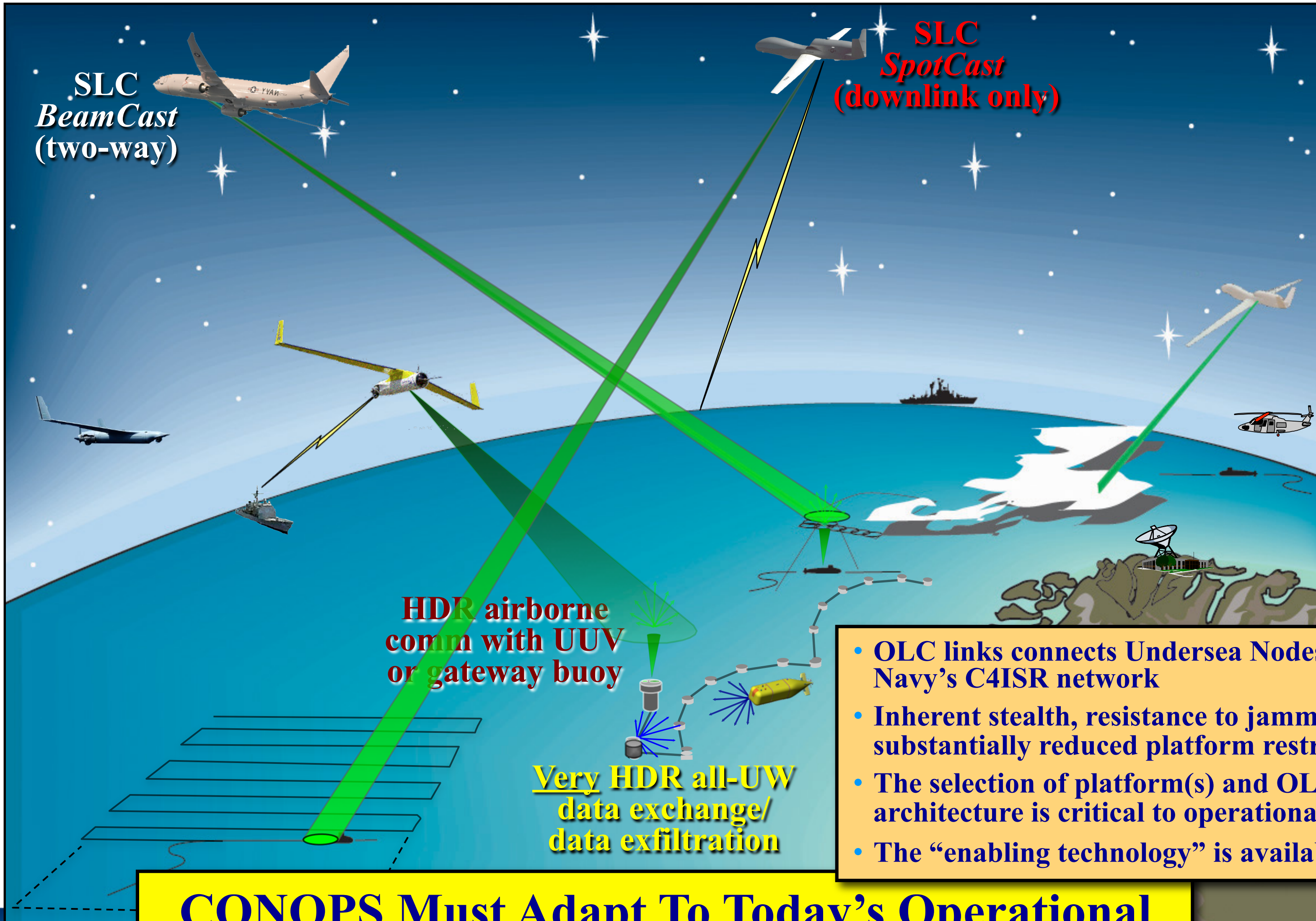
Connecting the C4ISR Network: Both Above-Water and Undersea Nodes

Comm Links
- Yellow = RF
- Blue = Laser
- Red = Hard Wired
- 00110 = Acoustics



GOAL: Communicate with underwater assets at operationally useful depths/ranges at operationally useful data rates

OLC Platform Options and Architectures In Support of Naval Undersea Dominance



- OLC links connects Undersea Nodes to the Navy's C4ISR network
- Inherent stealth, resistance to jamming and substantially reduced platform restrictions
- The selection of platform(s) and OLC architecture is critical to operational utility
- The "enabling technology" is available NOW

CONOPS Must Adapt To Today's Operational and (Most Importantly) Today's *Fiscal Realities*

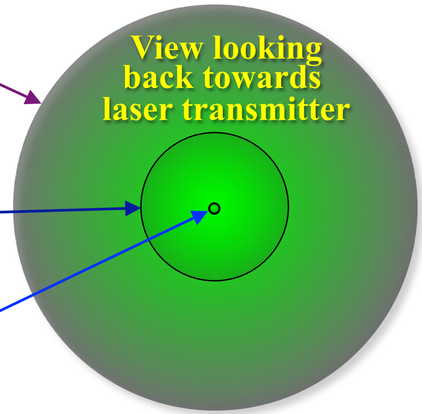
Architecture, Depth and Data Rate Requirements Define the OLC Geometry

- Two OLC comm modes: (1) **all-underwater** (terminal-to-terminal), and (2) **through the air-water interface** (UW terminal comm with an above-water terminal)
- ***All-underwater*** OLC propagation phenomenology and OLC technology can be significantly different than the *through-the air/water-interface* link
  - Solar background is generally not a dominating noise source
  - Data rate capability and/or requirements can be substantially larger
  - SWaP terminal requirements are generally much more demanding
- Communications ***through the air-water interface*** propagation channel is *much more complicated* and *much more dependent* on geometry and the environment
  - Requirement for daytime operation drives many of the technology and architecture options (e.g., narrowband optical filters and high peak-power lasers)
  - Generally demands much more SWaP and complicated technology (e.g., SLC)
  - To be efficient (especially daytime), requires collection of multiple scattered signal (placing heavy demands on high peak power lasers and wide FOV filters)
  - Real-time adapting of system parameters is required to optimize performance in real-world conditions (e.g., anamorphic zoom, adaptive-data-rate-comm)

Initial signal acquisition for 2-way comm links (or SpotCast OPAREA scan) is generally the most complicated operation & defines CONOPS

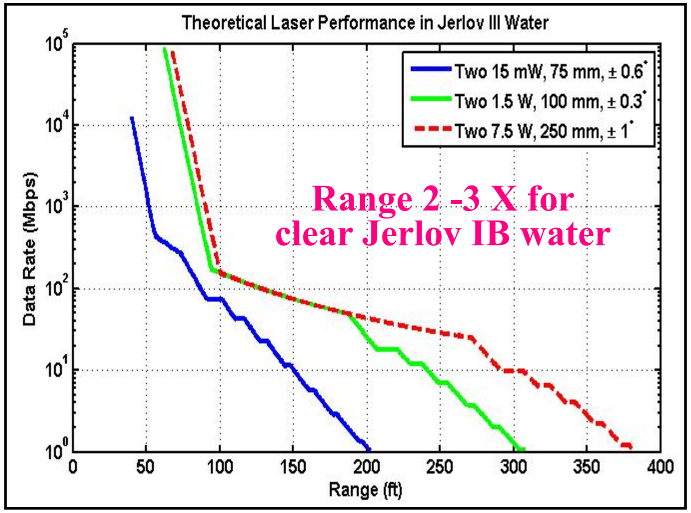
All-Underwater Optical Propagation: The Basics

532 nm (Green) Jerlov Water Parameter	Jerlov IB (m-1)	Jerlov II (m-1)	Jerlov III (m-1)
a (absorption)	0.060	0.076	0.104
b (scattering)	0.084	0.227	0.452
c (beam attenuation)	0.144	0.303	0.556
ω_0 (albedo)	0.58	0.75	0.81
K (diffuse attenuation)	0.064	0.083	0.114
c / K ratio	2.3	3.7	4.9
θ_{RMS} scatter angle (˚)	5.6	5.6	5.6



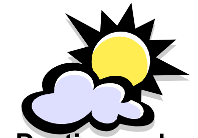
Three Distinct Propagation Regimes

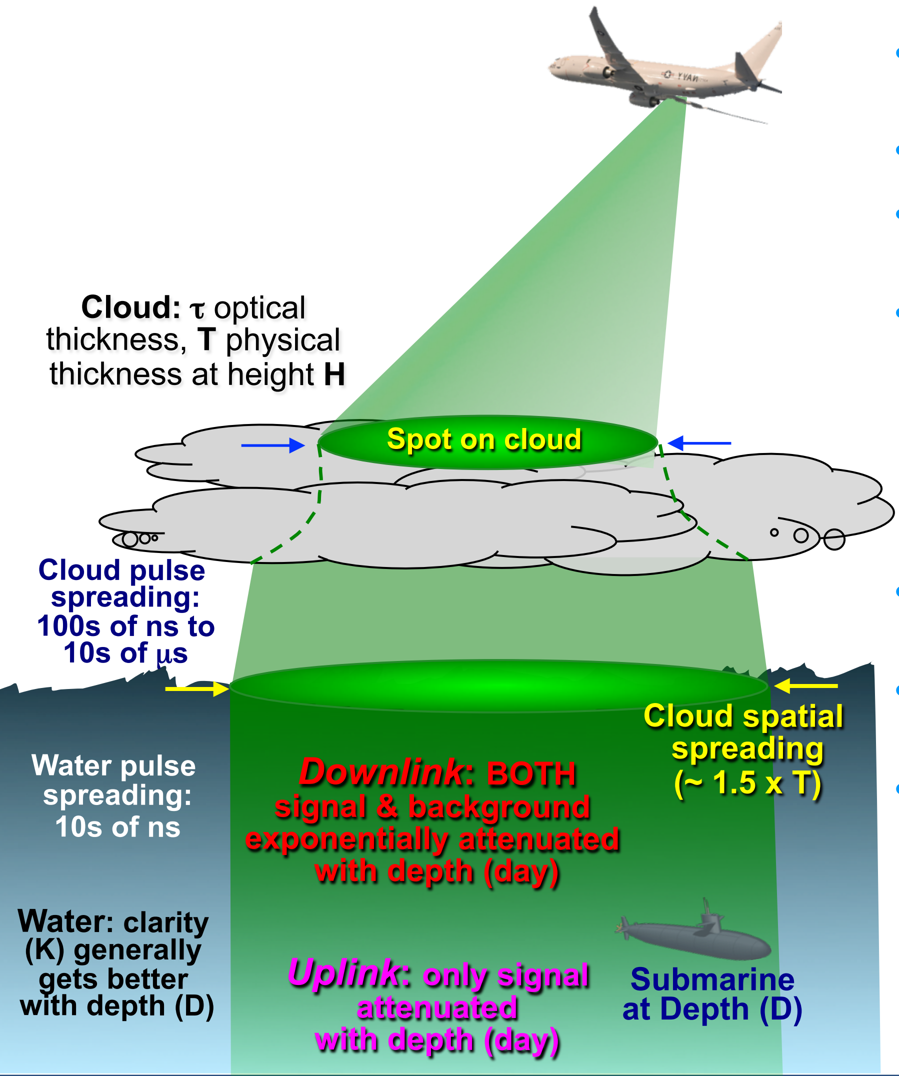
1. ***Fully Diffuse, Multiple Scattered Beam* (b * Z > ~ 20)**
   - ✓ Radiance is weak and diffuse (subtends 10's of degrees) & very large spatial spreading (reduces amount of photons collected by a small receiver aperture)
   - ✓ Requires large FOV to capture the diffuse, multiple scattered radiance
   - ✓ Low attenuation rate approaching e^{-aZ}, but very large pulse spreading
2. ***Multiple Forward Scattered (MFS) Beam* (~ 6 < b*Z < ~ 20)**
   - ✓ Radiance peaked in forward direction (increases as $(b*Z)^{1/2}$) with moderate spatial spreading (increases approximately as $(b*Z)^{3/2}$
   - ✓ Requires medium FOV to capture the MFS radiance (i.e., ~ 6 - 20°)
   - ✓ Low loss rate of e^{-KD} and moderate pulse spreading (e.g., < 4 ns at b*Z = 10)
3. ***Direct, Unscattered Beam* (b*Z < ~ 6)**
   - ✓ Very low radiance << 0.1° (transmitter aperture limited)
   - ✓ Requires narrow FOV to reject scattered light (i,e., *eliminates* pulse spreading)
   - ✓ High loss rate of e^{-cZ} ("c" is ~ 2 -5 X larger than K), but NO pulse spreading



All-underwater propagation regimes depends on range, transmitter beam divergence, receiver FOV and both optical scatter/absorption parameters of the ocean path

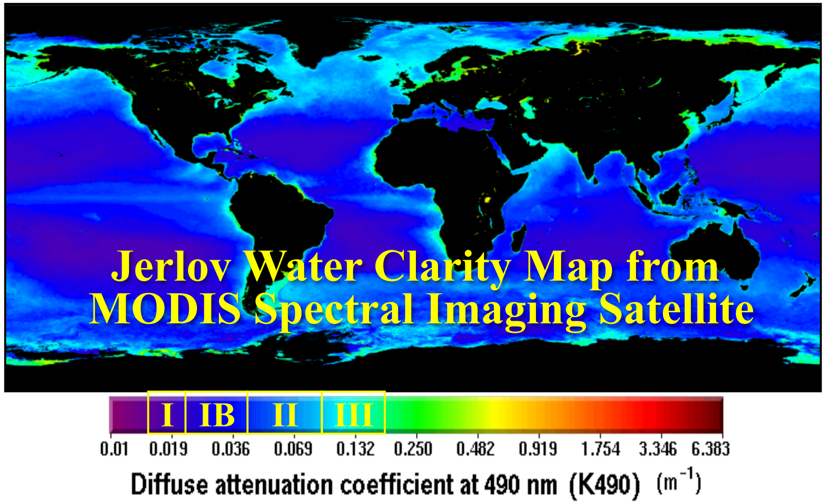
Propagation Channel Characteristics of a Through the Air-Water Interface OLC Channel

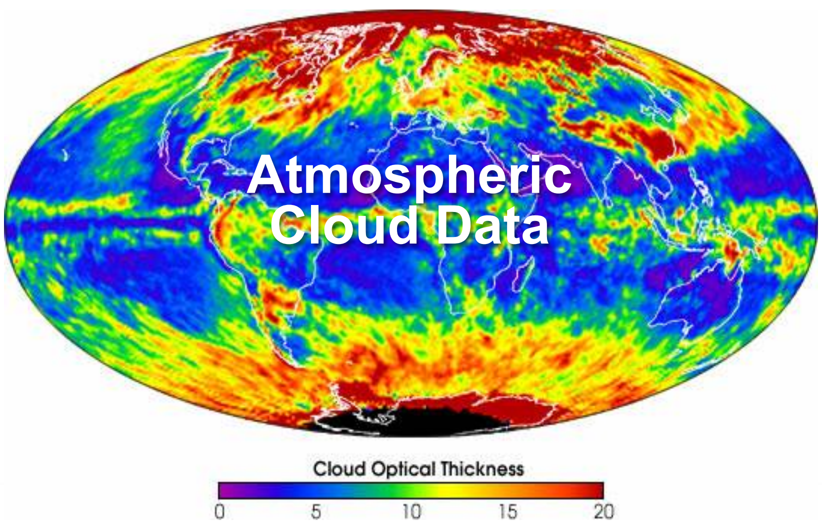




- Uplink & downlink are *NOT* reciprocal: daytime *downlink* SNR scales as e^{-KD} while *uplink* SNR scales as: e^{-2KD} / R^4
- Basically, everything *works great at night or clear*
- Uplink comm performance is reduced approx *linearly with the range* (i.e., increasing scan angle and/or higher altitude)
- Downlink data rate is nominally limited by
  - Day (cloudy or clear) is SNR limited (i.e., laser energy-per-pulse/ background); Night (cloudy) is cloud pulse-stretching limited
  - With Tx zoom, data rate is *nearly independent* of altitude/range
  - Because of water absorption (vs. scattering), downwelling radiance moves towards nadir vs. depth & limits to ± 19 °
- Anamorphic Tx zoom and Rx FOV correction vs. nadir angle can increase performance substantially for large angles
- Spatial spreading in clouds reduces received energy/pulse, increases required A/C Rx FOV and complicates scan strategy
- Water turbidity rapidly degrades SNR (i.e., depth & data rate)
  - "Green" littoral water is more turbid than open-ocean "blue" water and generally gets clearer (i.e., "bluer") with depth
  - Sea state is very much a second order effect and may help at large nadir angles (clear)
  - Multiple scattering in sea water (K & D) defines sub Rx FOV

UW OLC Performance Modeling Is Well Understood & Experimentally Verified

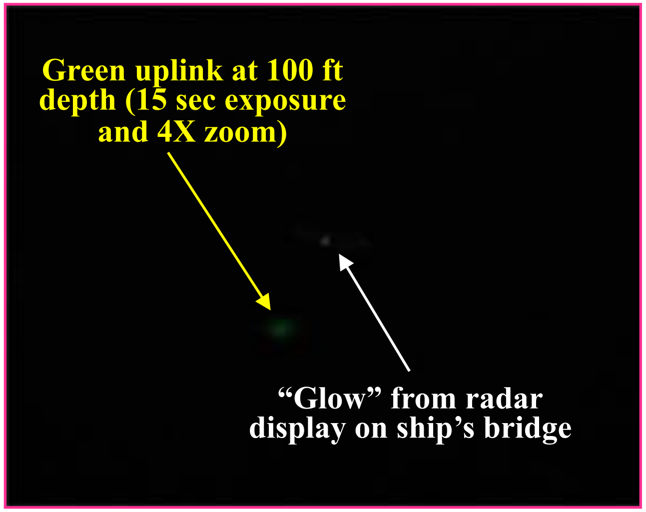




- The model has evolved from > 30 years of development by the Navy (e.g., SLC, λSat)
- Water and cloud data bases were developed using both satellite and ocean cruise/sub data
- Extensive aircraft to sub lasercomm experiments in the 70’s and 80’s validated the models
  - Sub depths varied over a very large range
  - From clear to turbid ocean water; from clear to thick cloud conditions
- Comms to USAF aircraft lasercomm receiver though 30,000 ft of Cumulonimbus clouds
- SpotCast CSD demos in several airborne experiments and in RIMPAC ’86 FLEETEX
- 2-way BeamCast comm demo between above water and UW terminals to Mbps
- The all-underwater HDR lasercomm tests conducted over a wide variety of water clarities and ranges (including fully-autonomous signal acquisition and reciprocal tracking at sea). Real-world tests at SCI agree within ± ~ 1.5 dB

Model predictions and measured results from sea-tests agree to better than ± 2 dB over a wide range of operating depths and environments

2004 SEADEEP Experiment Demonstrated Feasibility of Two-Way High Data Rate OLC

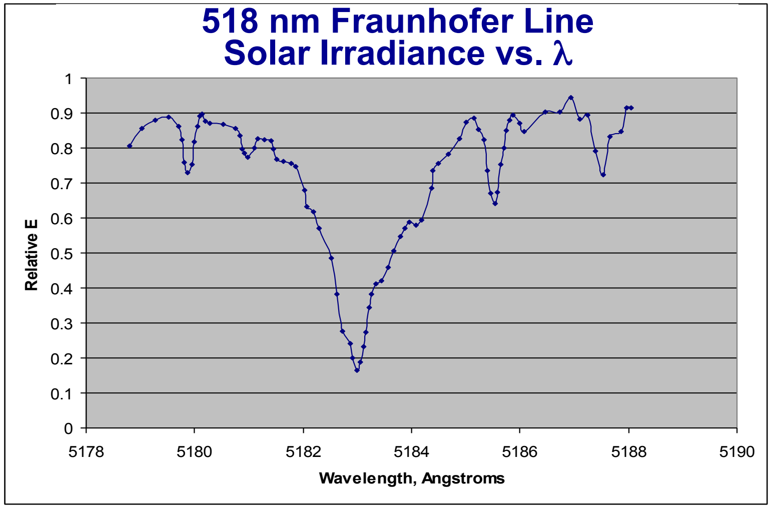


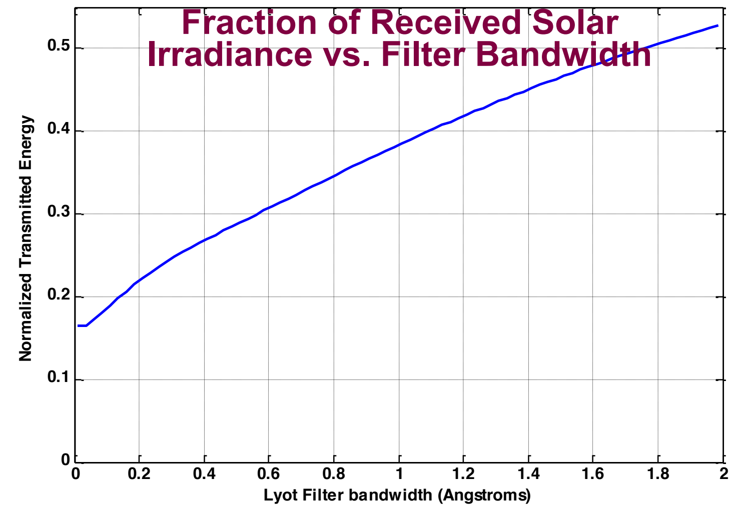
- Two-way laser comm experiment at San Clemente Island (SCI) in 2004 demonstrated the last remaining SLC physics issue: feasibility of high bandwidth (Mbps) BeamCast comms through air/water interface to depth in a real ocean environment (both up and down)
  - ✓ Due to limited funding, blue downlink laser and green uplink receiver mounted in van at SCI and green uplink fiber-coupled laser from ship to UW terminal with blue downlink receiver canister
  - ✓ Small COTS lasers (**0.15 W down**, **0.8 W up**) at representative airborne SLC geometry (*60° nadir angle, 3,000 ft range*) and turbid ocean water (K~ 0.11 m^{-1}, *Jerlov III)*
- Max data rate "demonstrated" (NOT max data rate *achievable*): *2 Mbps DOWN; 500 Kbps UP* to approximately 110 ft depth
- Excellent Low Probability of Detection (LPD): only a faint uplink spot visible (approximately as detectible as glow from radar display leaking out of the window of the surface support ship)

2-way data transfer at Mbps and *NO Vegas Laser Light Show . . . !*

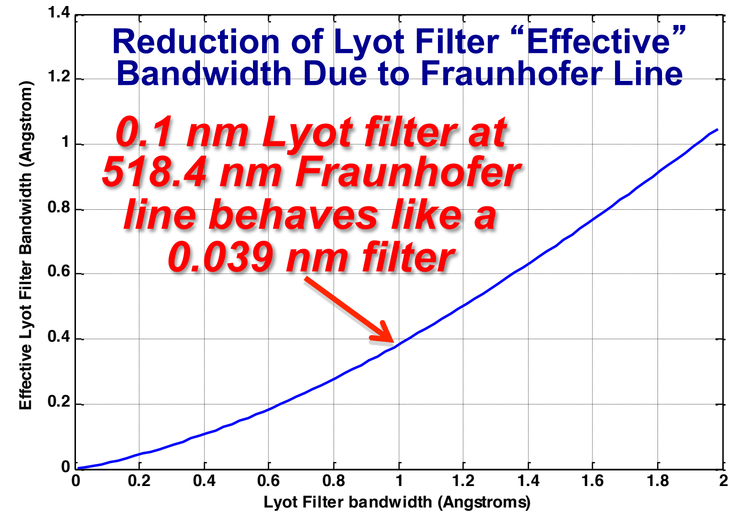
The Selection of a Laser and Narrowband Optical Filter On a Notional OLC Architecture

A Notional OLC Architecture Exploiting the Fraunhofer Line "Filter-Advantage"

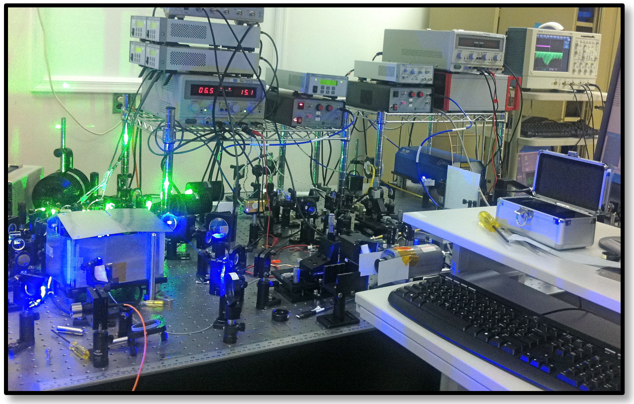




- Exploits fundamental characteristics of the UW OLC channel
  - "n" dB advantage (day) using the 518 nm Fraunhofer "dip"
  - 518 nm is a good compromise of color for ocean waters and better in the stressing littoral waters ("green" water)
- Can be matched to X2, Ytterbium fiber lasers (efficient, compact, reliable technology easily scaled to higher power)
- Conventional Lyot filters can match the Fraunhofer band
  - Compact, robust, field-tested Lyot filters (e.g., makes optimum use of available canister area & filter $\Delta\lambda_{ENBW} = \Delta\lambda_{sig}$)
  - Modest operating temperature (e.g., ~ 40°C)
  - High altitude airborne filters can reduce receiver FOV for much better bandwidth performance ($\Delta\lambda_{sig} \approx FOV^{-2}$)

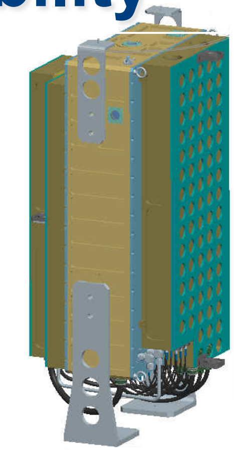


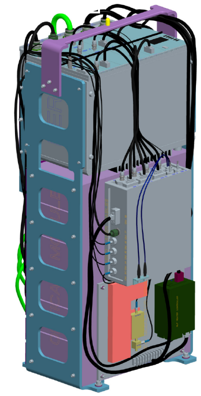
Examples of Laser Options and Their Impact on Both Operational and Fiscal Viability



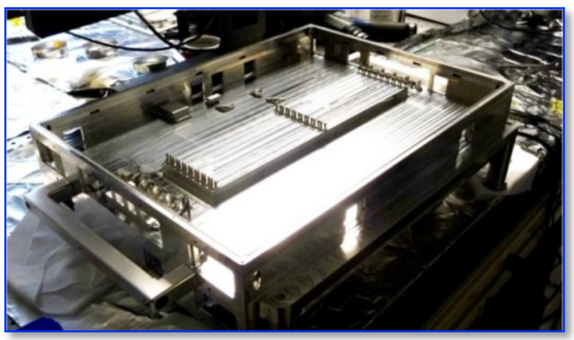
Frequency-Tripled/ OPO Nd:YAG Laser

This goes into that!

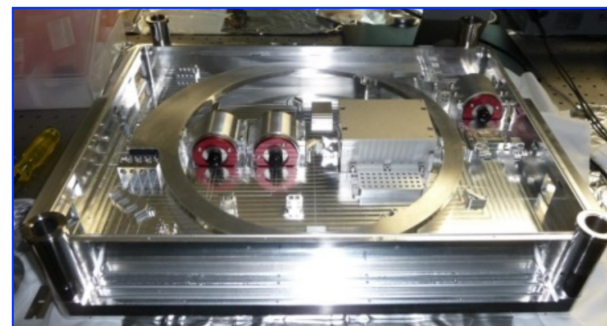




Frequency-Doubled Yb Fiber APLA Laser *



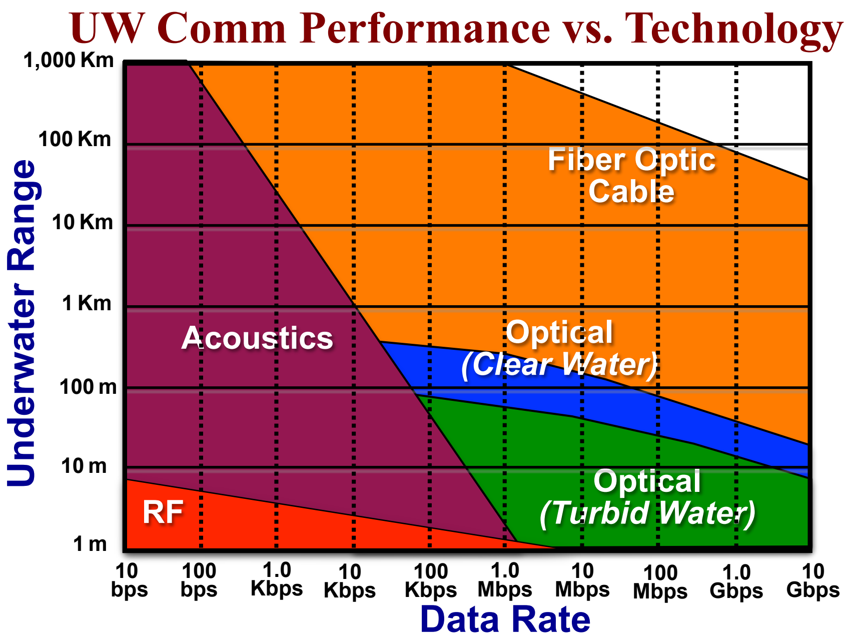
****Adaptive Pulsewidth Laser Architecture (APLA) dynamically matches laser PRF and PPM pulsewidth to instantaneous channel characteristics***



Yb APLA Fiber Laser Advantage

- > 4 dB SNR (day) operating at the 518 nm Fraunhofer "dip"
- Approximately 20 X wall plug efficiency and less than 1/20th cost
- ~ 160 X more compact (W/ft^3) & ~ 60 X more output-power/pound (W/lb)
- Laser PRF variable from KHz to MHz (e.g., 1,000 X max data rate)
- Qualifiable in "relevant environments"

The OLC Bottom Line



- ISR is critical to the Navy's mission
  - The collection of offboard ISR is only of use to the warfighter if it can be transferred with high fidelity and low latency(i.e., high bandwidth)
  - The "Unmanned-Imperative" (e.g., UAVs, UUVs), which is so critical to affordability, makes information transfer even more difficult
  - Minimizing platform operational limitations (e.g., speed, depth, tethers and cables) is key to operational utility
- Fundamental "physics" defines underwater comm range/data-rate performance

- Legacy systems (RF or acoustics) do **not** meet the requirements to connect the undersea environment either due to physics, lack of stealth, insufficient bandwidth and/or the ability to be jammed or otherwise denied
- Most importantly, *only OLC can transfer tactically-significant information through the air-water interface*
- While Comms at Speed and Depth (CSD) has been a persistent objective for the Submarine Fleet since the 1970's, CSD (e.g., SLC) has not become an operational capability for the Fleet (mostly due to both real and perceived cost)

Questions?