Discussion topics on underwater wireless communications for underwater networks: rates versus ranges, interoperability, and multimodality

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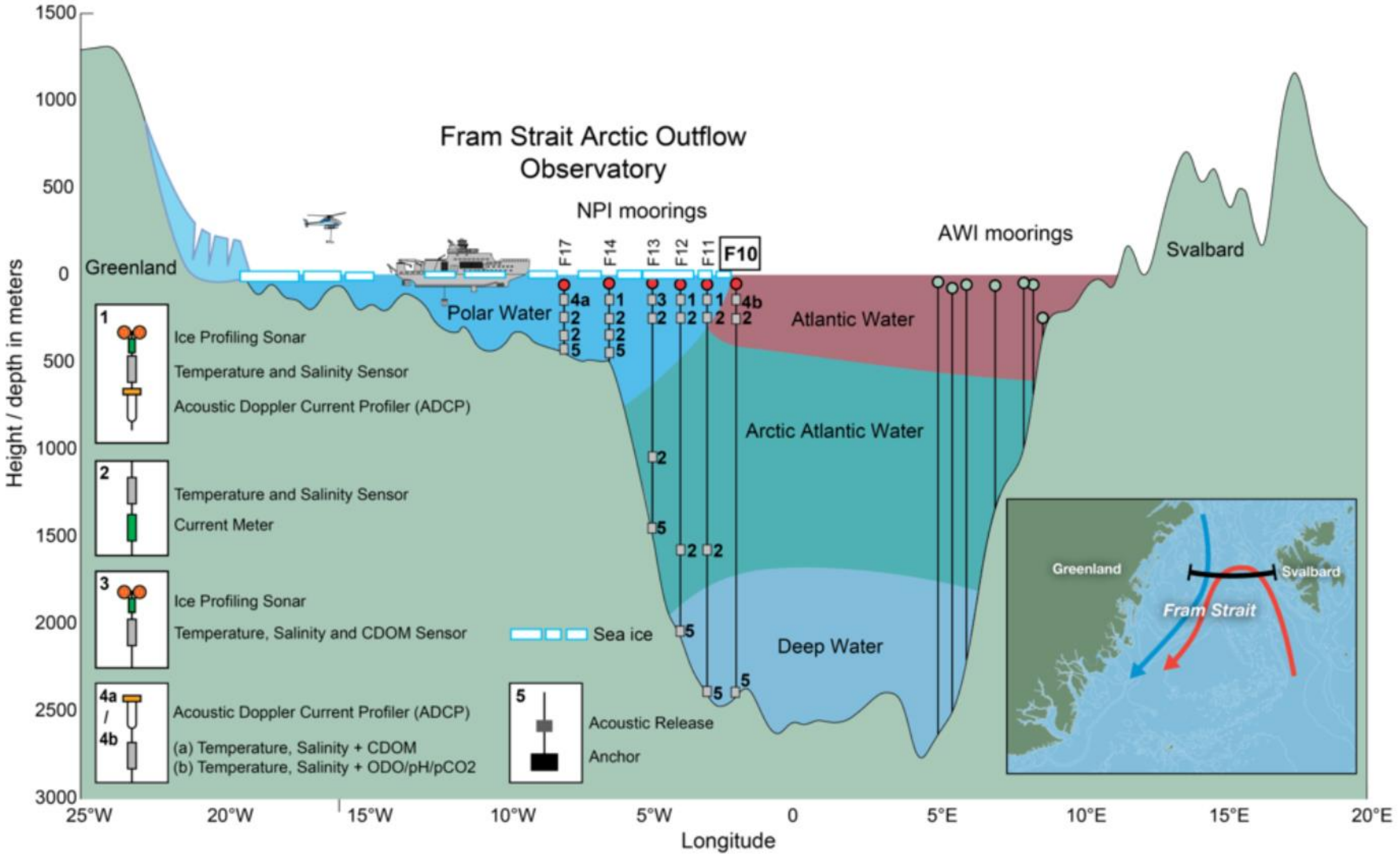
Underwater wireless communications

For underwater networks

Underwater stationary sensor networks (i.e., Eulerian ocean observations)



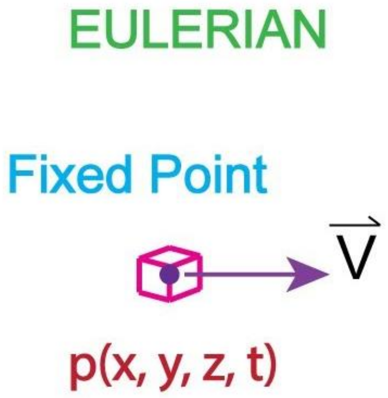
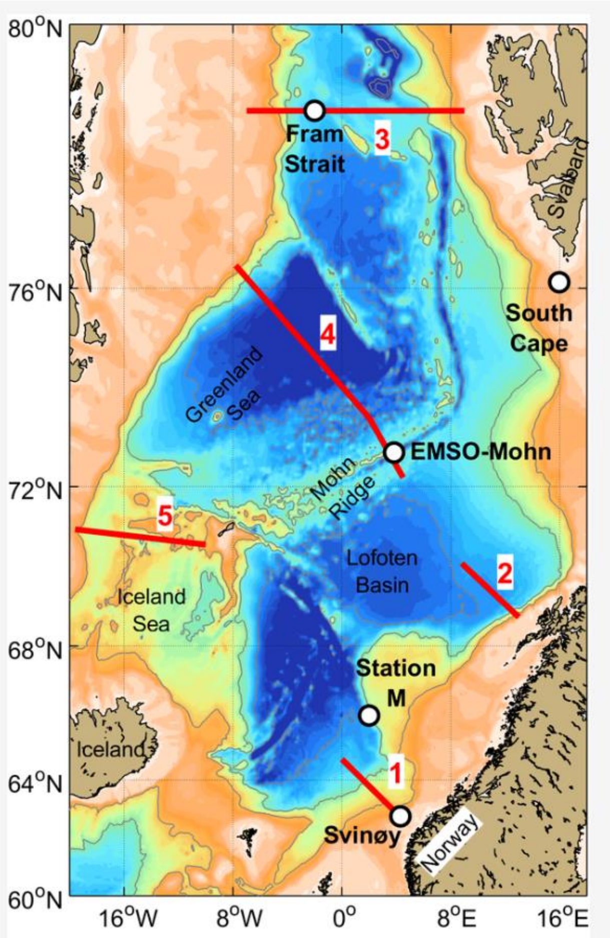
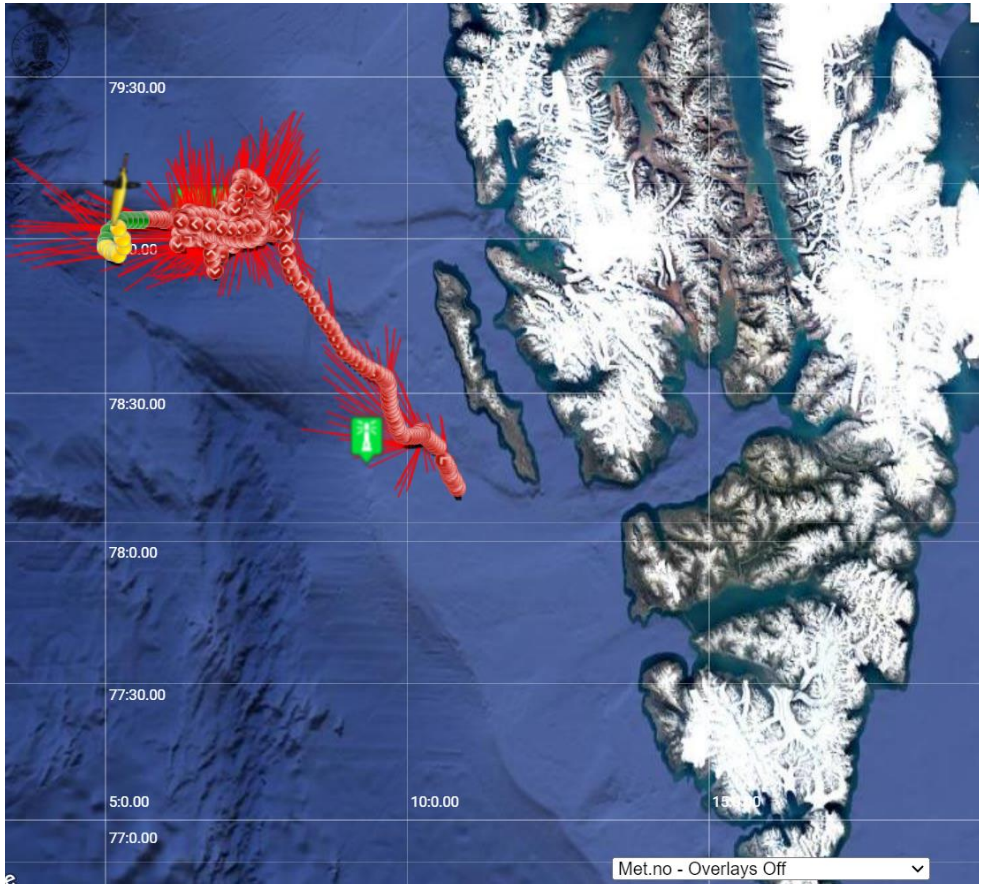
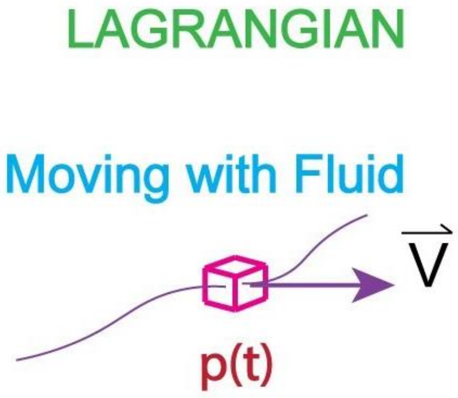


Photo: Laura de Steur, Norwegian Polar Institute. Fram Strait Arctic Outflow Observatory.

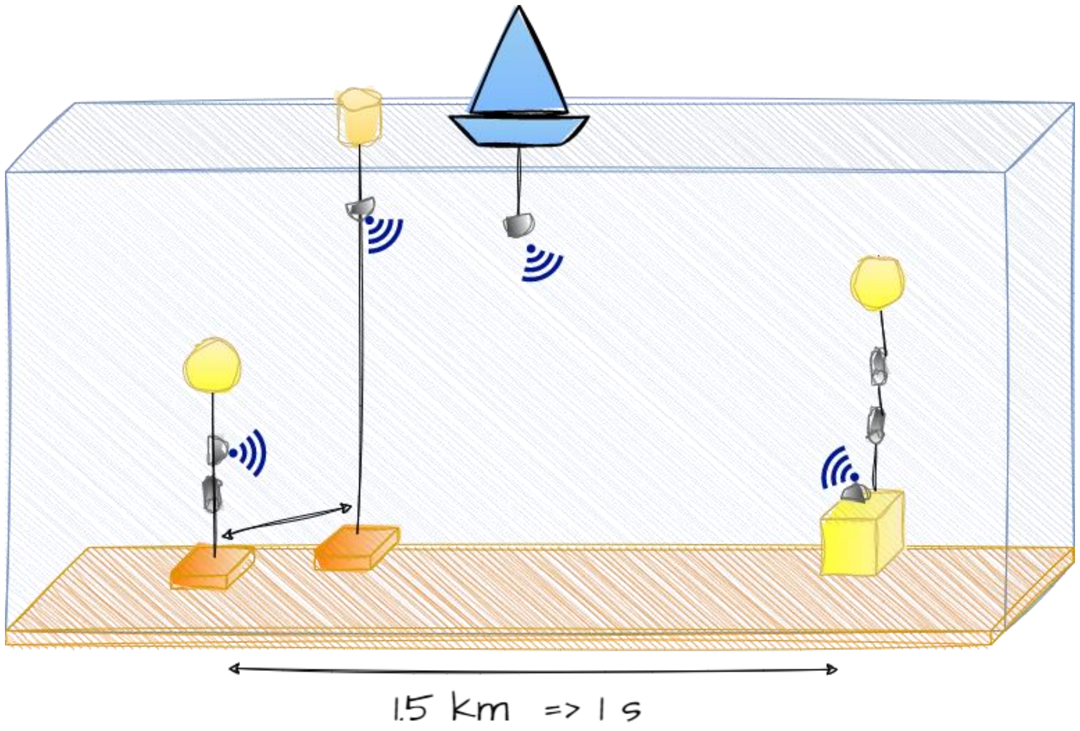
Underwater mobile sensor networks (i.e., Lagrangian ocean observations)

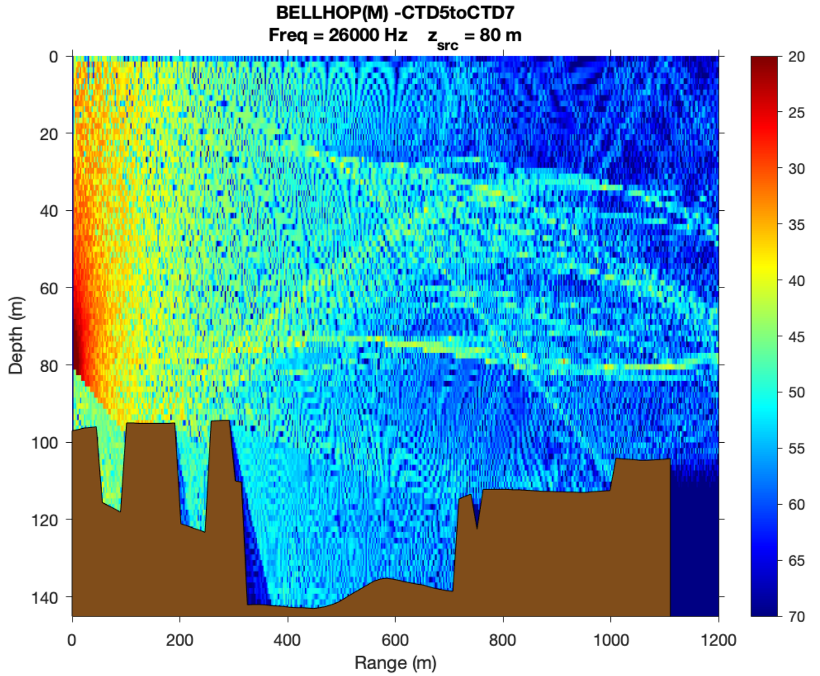


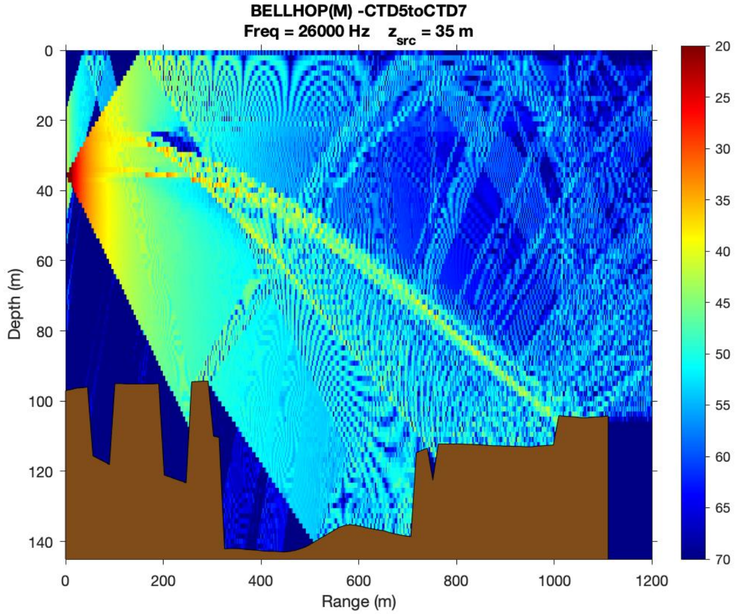




Underwater acoustic communications







- Underwater sound speed about 1500 m/s, dependent on physical and chemical properties of the water
- Typical values for the center frequency, Fc from 2 kHz up to 60 kHz
- B= Fc/2, ultra-wideband communication systems
- Applications are delay tolerant, low data rate, over long distances

Underwater free space optical communications

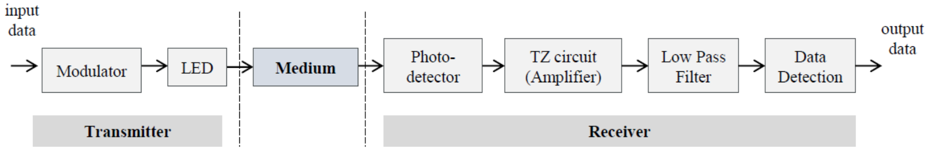
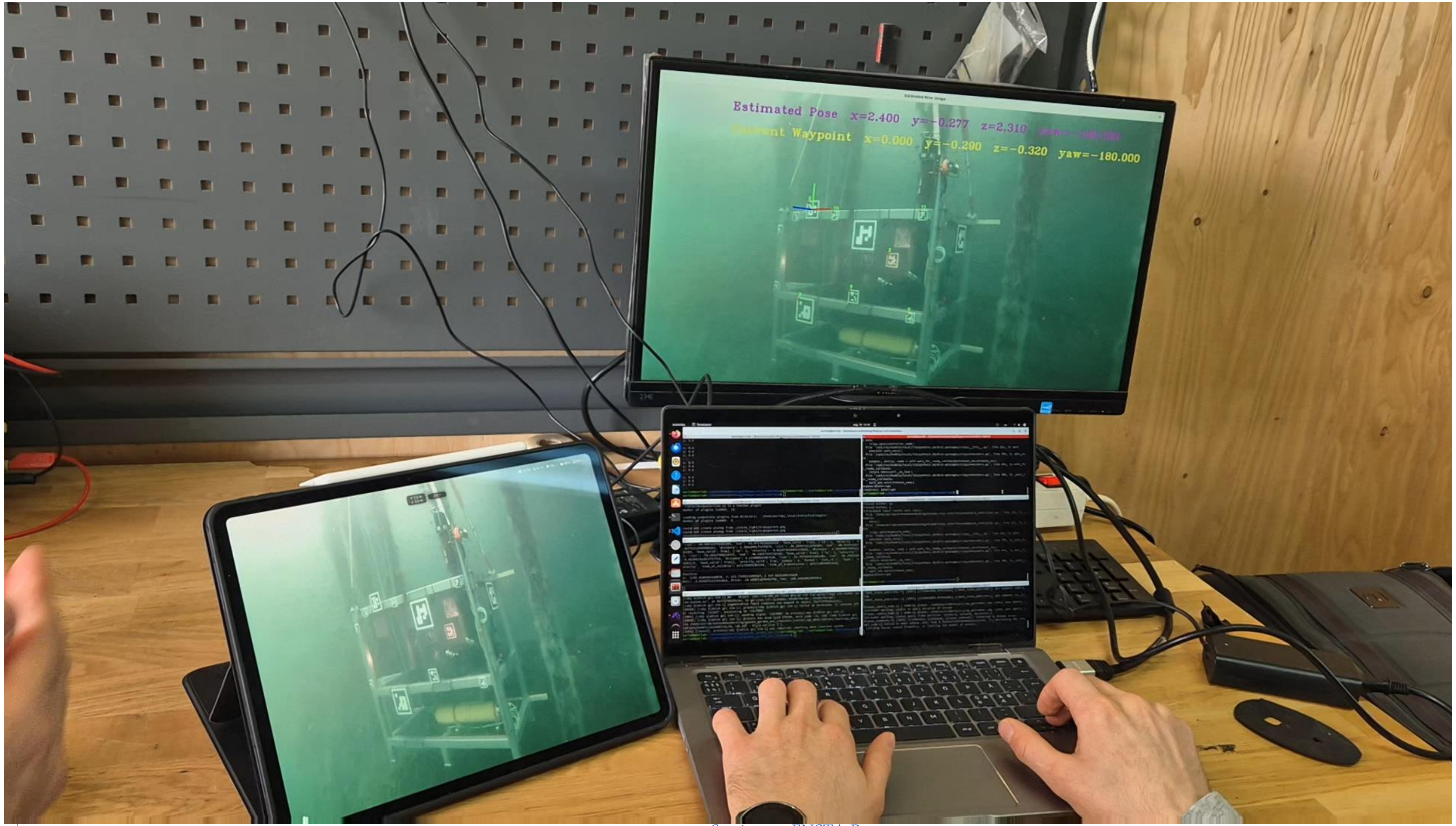


Fig. 1. End-to-End general Block Diagram of UWOC communication link.

- Point-to-point communication systems
- Underwater light speed about 2.25 10^8 m/s
- Depending on water depth
- Depending on water turbity
- Applications are high data rate (up to 10 Mbps)
- For short distances (up to 100 m)

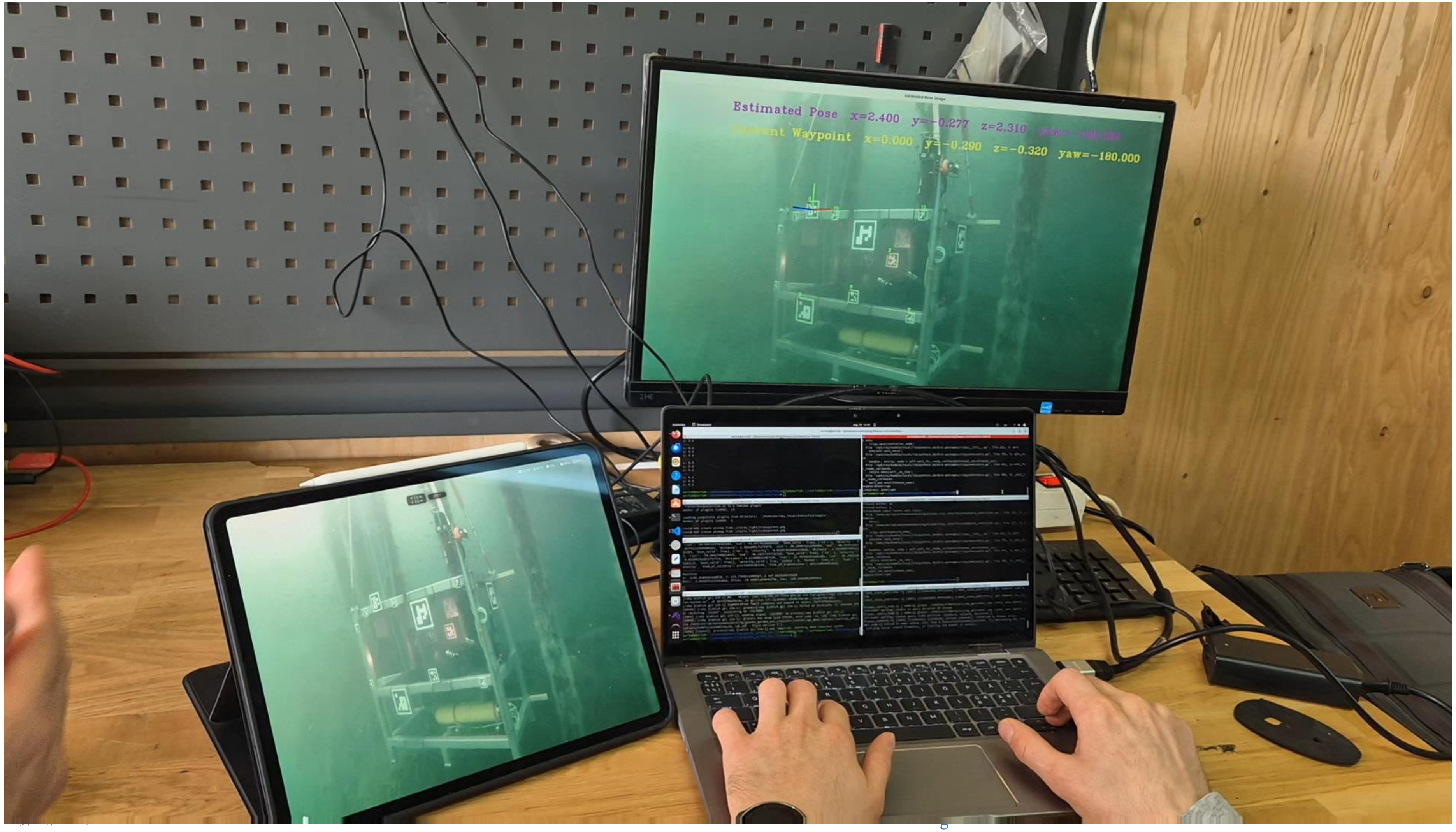
WiFi used for underwater communications in magnetic inductive plucks for wireless charging: automatic docking



Master Thesis

NTNU
Norwegian University of Science and Technology

WiFi used for underwater communications in magnetic inductive plucks for wireless charging



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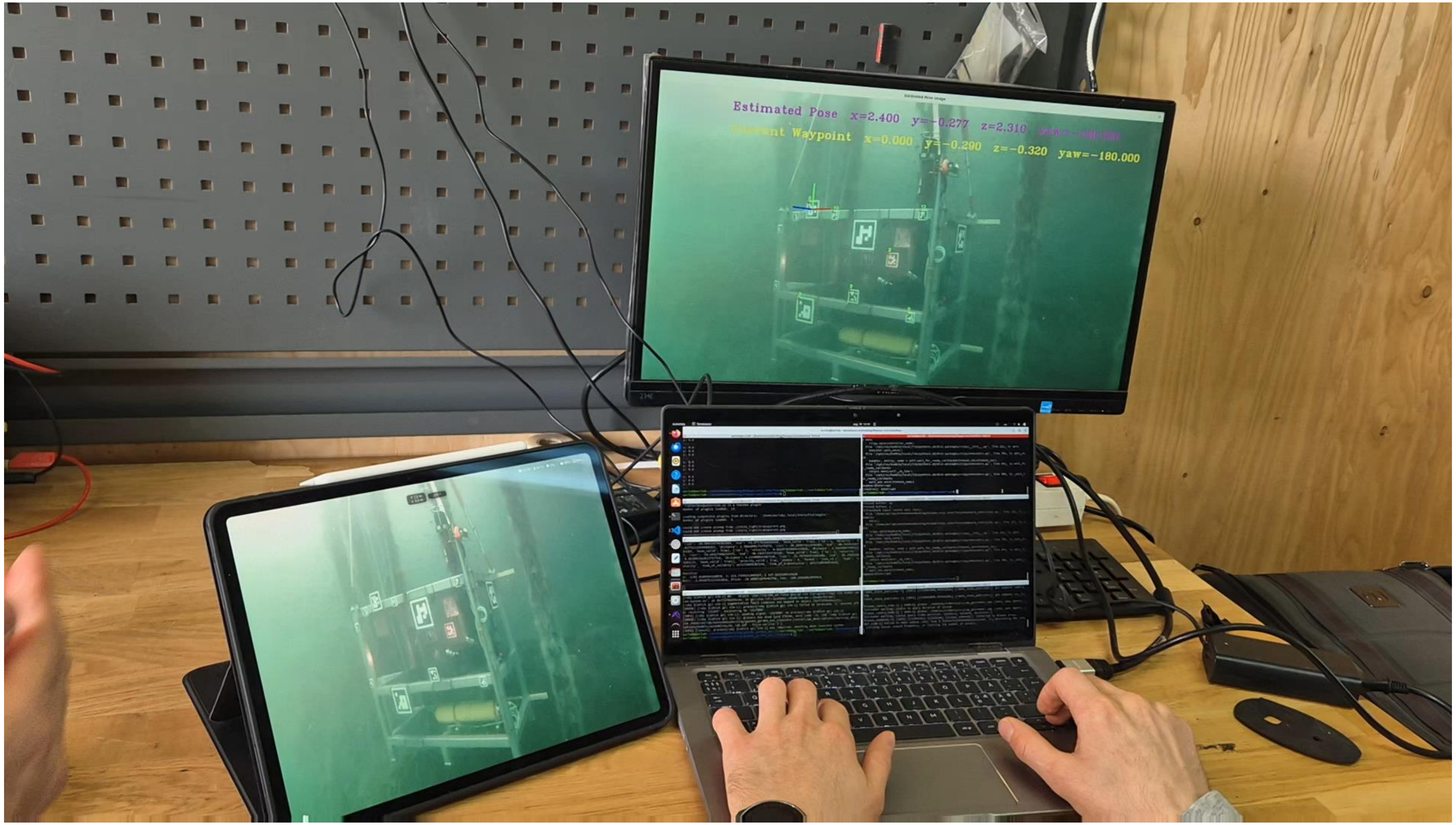

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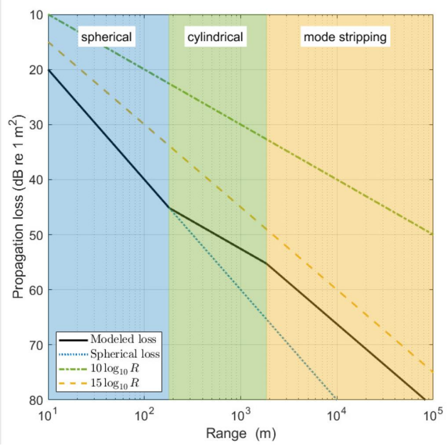
Rates versus ranges

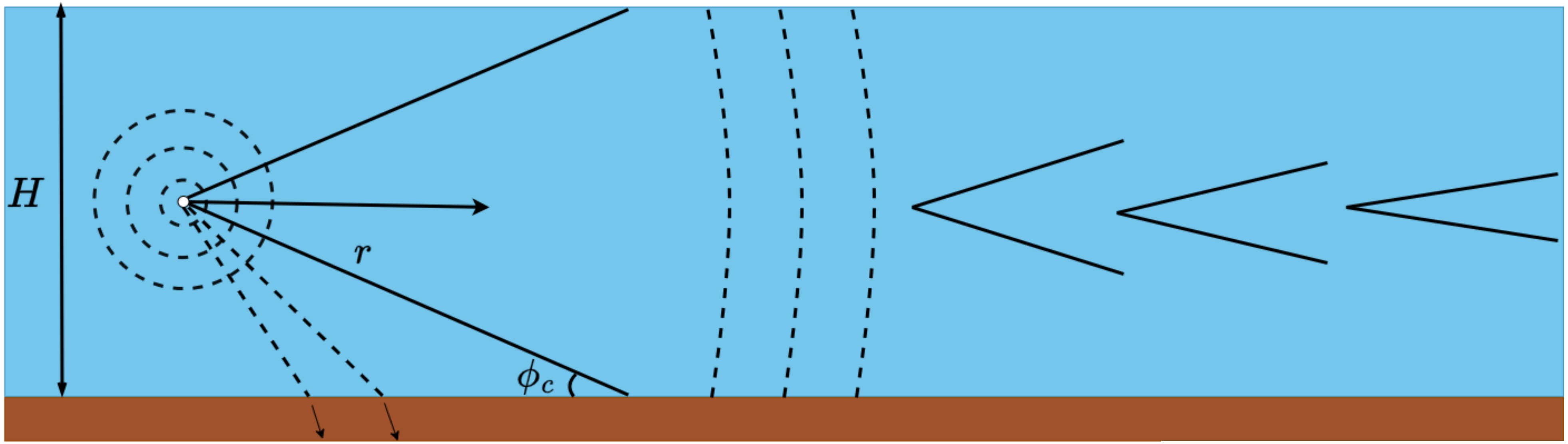
in underwater wireless communications

Underwater Acoustic Propagation Loss: absorption and geometrical spreading law



$$\mathrm{SNR} = \mathrm{SL} - \mathrm{NL} = L_\mathrm{S} - \mathrm{PL} - \mathrm{NL}\ ,$$

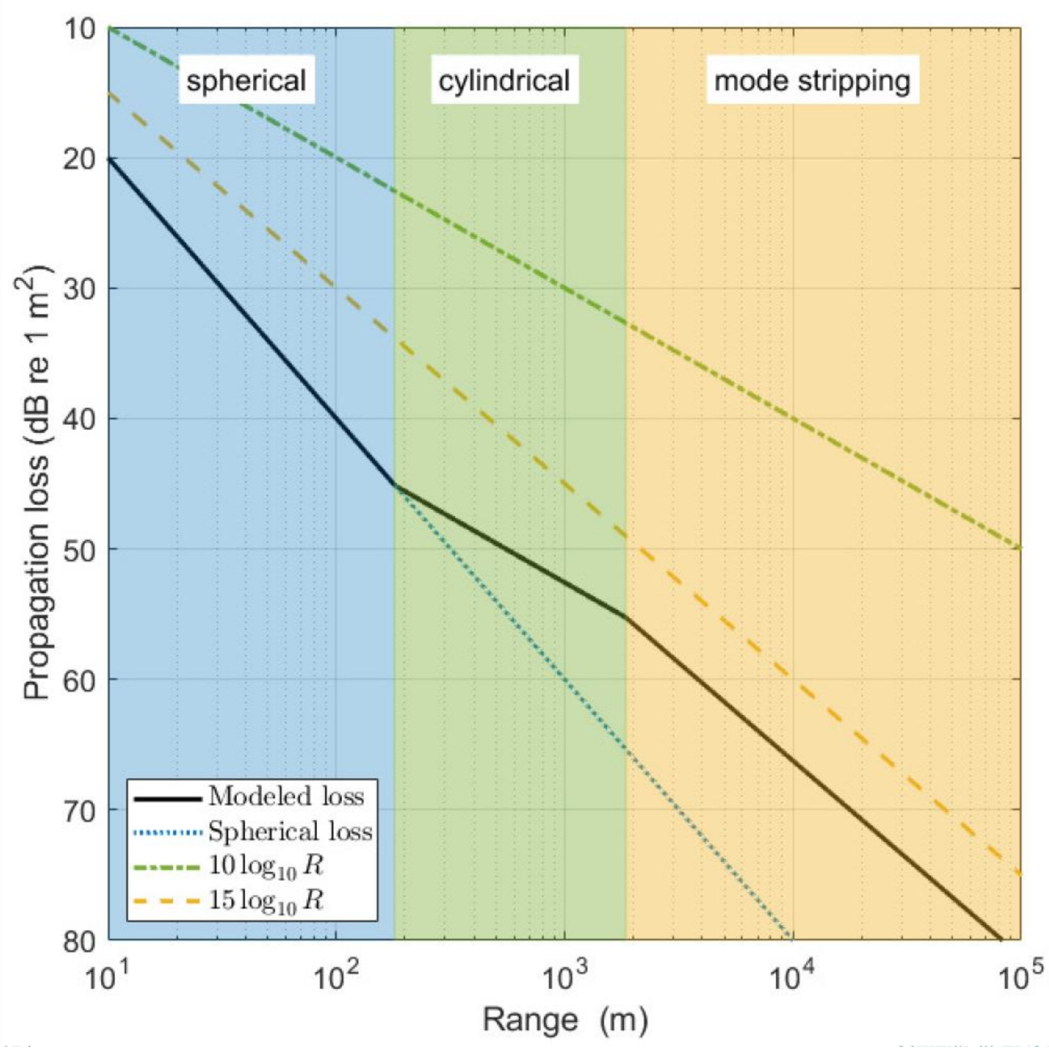
$$I = \frac{P}{4\pi r^2} \qquad I = \frac{P\sin\phi_c}{2\pi r H} \qquad I = \frac{P\sin\left(\sqrt{\frac{\pi H}{4\eta r}}\right)}{2\pi r H}$$

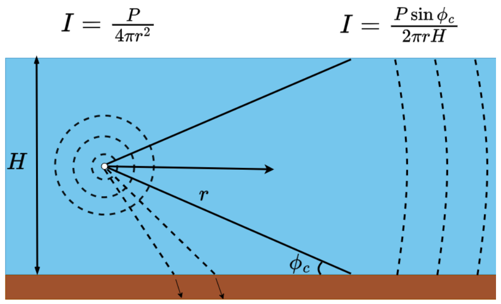


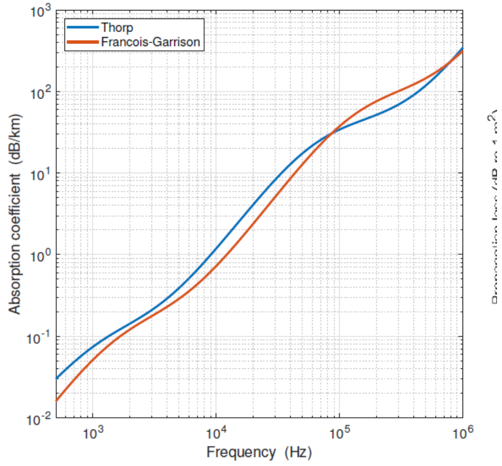
$$\mathrm{PL} = L_\mathrm{S} - \mathrm{SL} = 20\log_{10} R + a(f,\ldots)r\ . \qquad \mathrm{PL} = 10\log_{10}\frac{H}{2\sin\phi_c r_0} + 10\log_{10} R + a(f,\ldots)r\ . \qquad \mathrm{PL} \approx 5\log_{10}\left(\frac{\eta H}{\pi r_0}\right) + 15\log_{10} R + a(f,\ldots)r\ ,$$

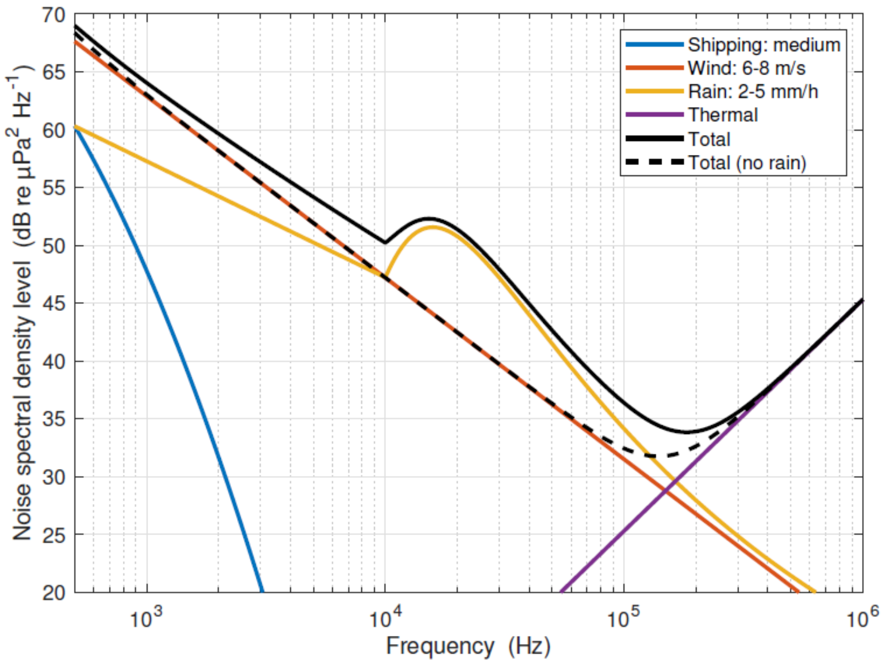
Underwater Acoustic Propagation

$$\mathrm{SNR} = \mathrm{SL} - \mathrm{NL} = L_S - \mathrm{PL} - \mathrm{NL} \,,$$



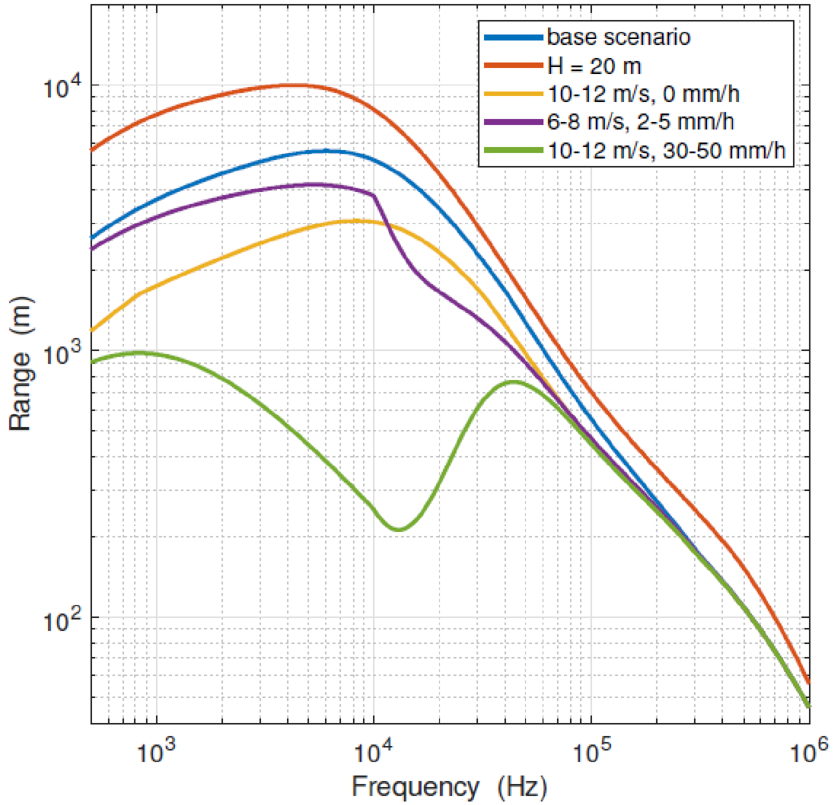






Rates vs ranges of underwater acoustic communications: results based on propagation and noise modelling

20 dB contours



SINR modeling in 2 transmitters and one receiver scenario

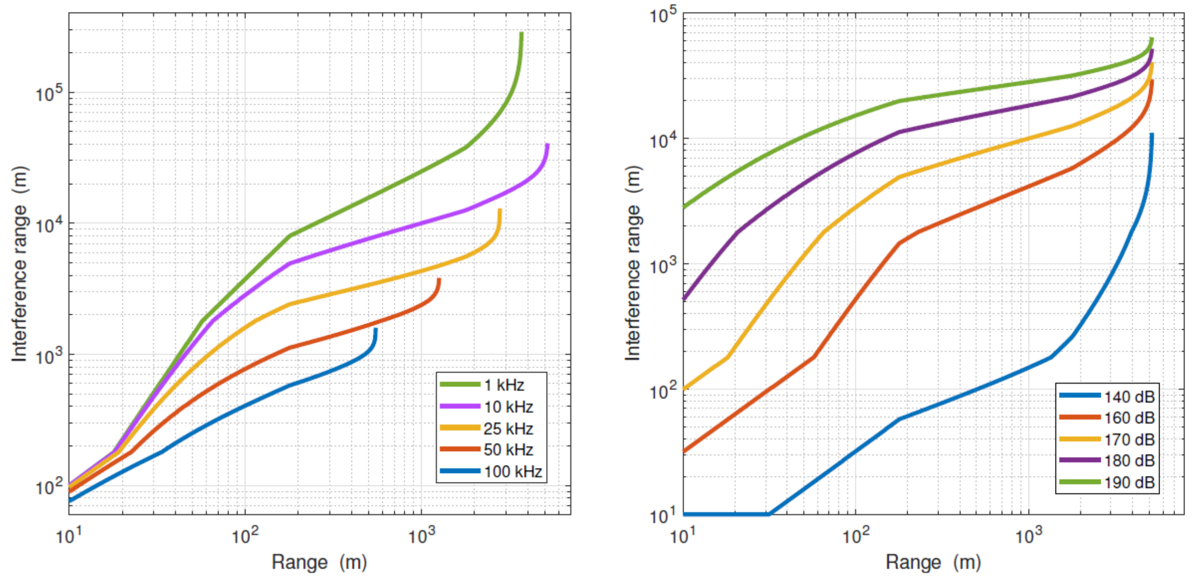
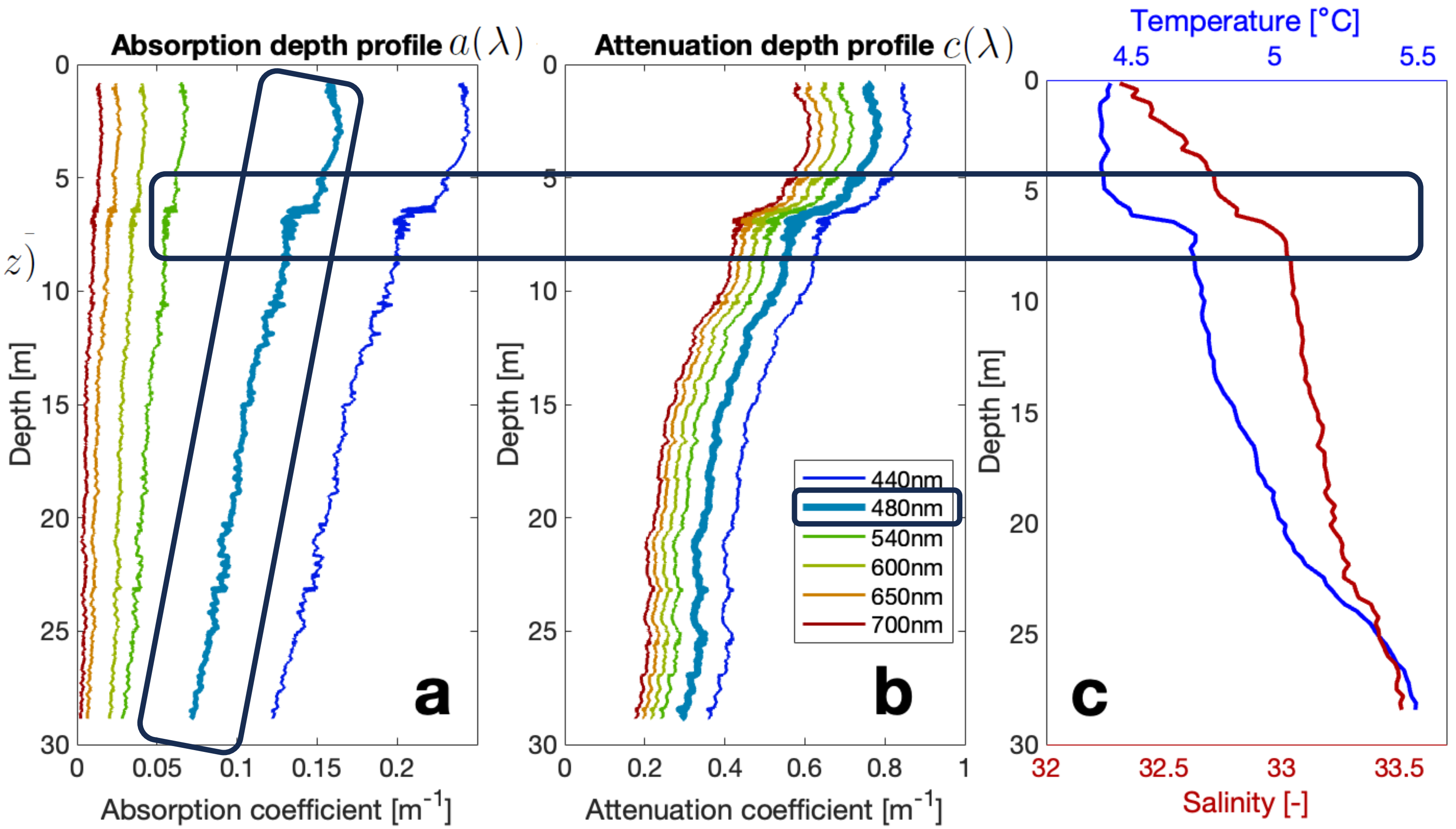


Figure 5: Left: Range relationship at different center frequencies for an interferer source level of 170 dB re μPa²m². Right: Range relationship at 10 kHz for different interferer source levels.

Depth profiles of underwater optical propagation and hydrological properties: measured light attenuation and absorption coefficients in water as a function of depth

Received intensity

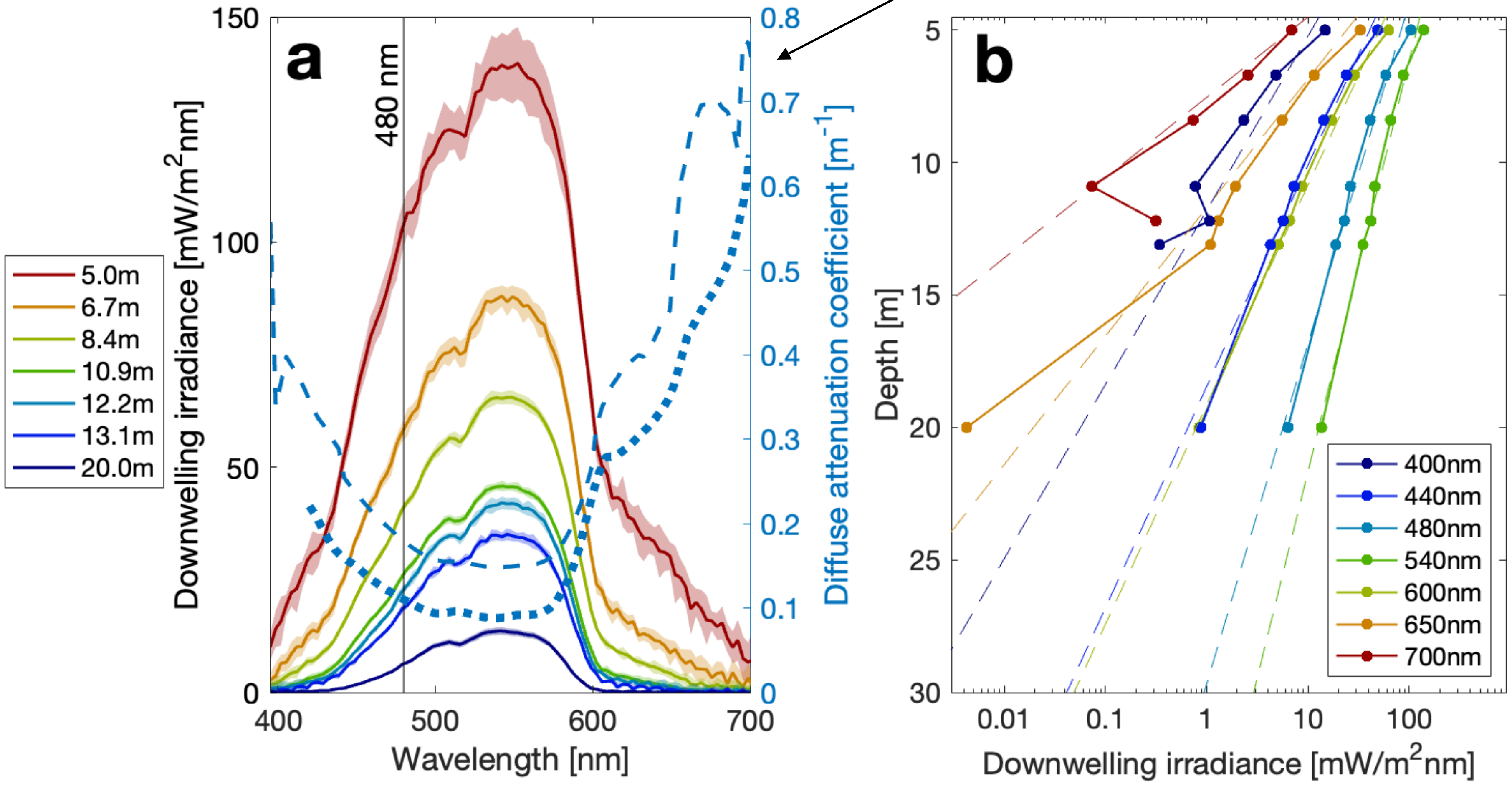
$$I(z) = I_0 L(\lambda, z)$$
$$L(\lambda, z) = \exp(-c(\lambda) z)$$
$$c(\lambda) = a(\lambda) + b(\lambda)$$



OOK 1s

Ambient light field at 0-30 m depth (i.e., background noise for the optical comm system): Irradiance and diffuse attenuation coefficient

$$K_d(\lambda) \approx [a_{\text{tot}}(\lambda) + b_{b,\text{tot}}(\lambda)] / \cos\theta.$$



OOK 0s

Water physical optical properties measurements

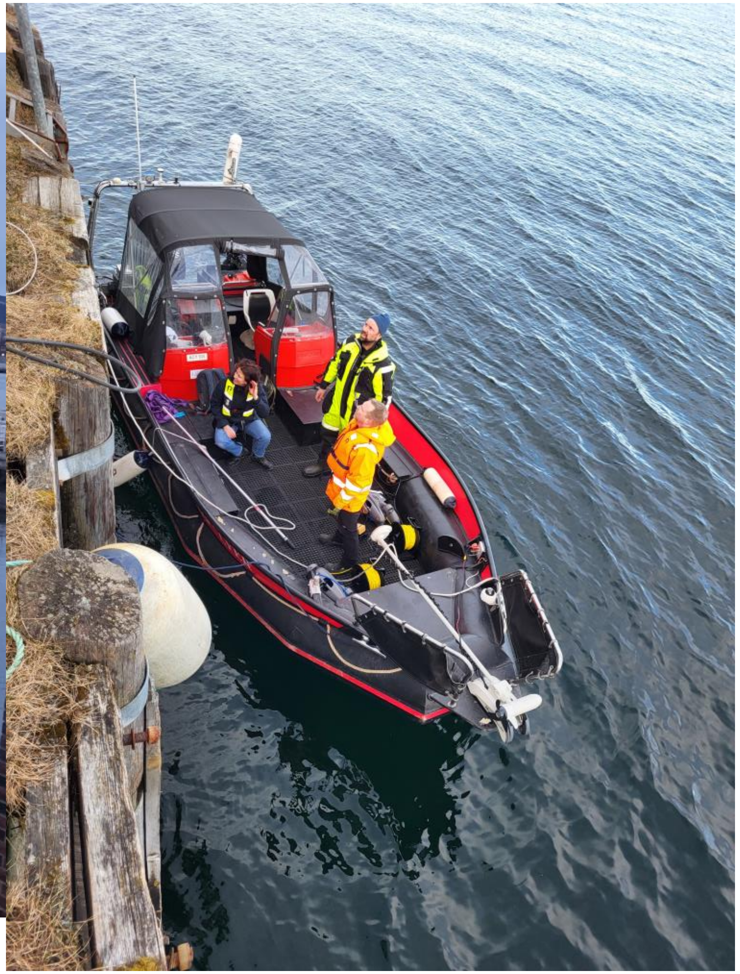
Ambient Light Field

Ramses ACC-VIS hyperspectral irradiance sensor
(TriOS Mess- und Datentechnik GmbH)

Optical Properties ,scattering and absorption

SeaBird Sci. ac-s, underwater light absorption and
attenuation sensor.

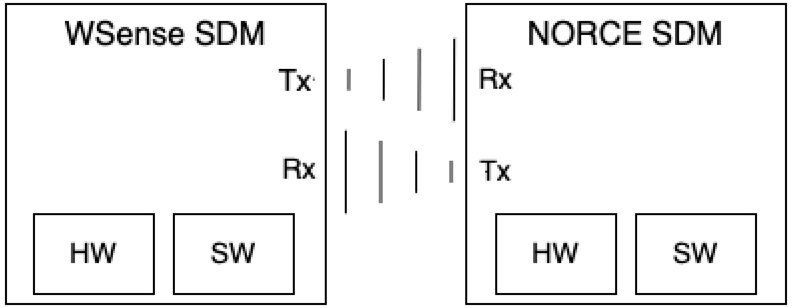
Ocean Lab facility at the Trondhjem Biological Station (TBS) NTNU



Rates vs ranges of FSO communications: effective rates measured in experimental research

Rate (kbps)	Distance (m)				
Depth (m)	15	20	25	30	35
60	2005	2150	1000	0	0
70	2005	2185	2155	695	0
80	2065	2000	2280	1935	0
90	2005	2215	2145	1565	0

Good connectivity from 10 m depth to 60 m depth with distances from 2 m up to 20 m. Files of 10 MBytes were transferred in 5 s over 30 m distance in vertical link in August 2024, between SEASAM (@60 m depth) and X3 drones (@90 m depth).



Physical Layer interoperability

Interoperability

in underwater wireless communications

JANUS Stanag 4748

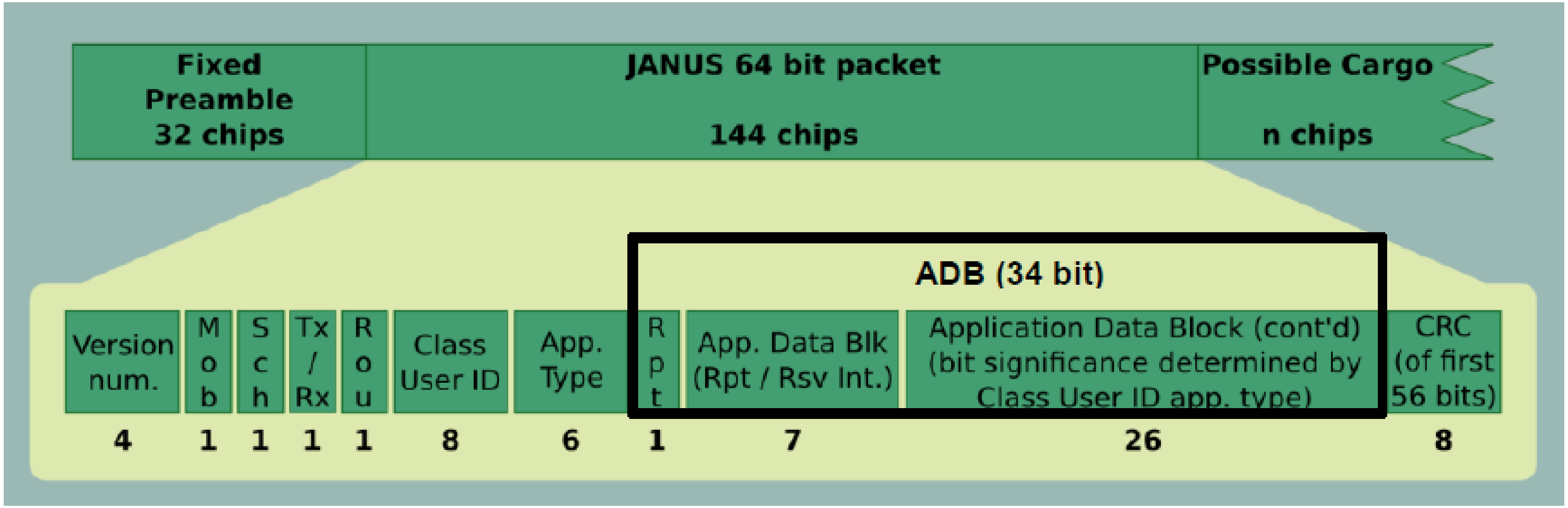
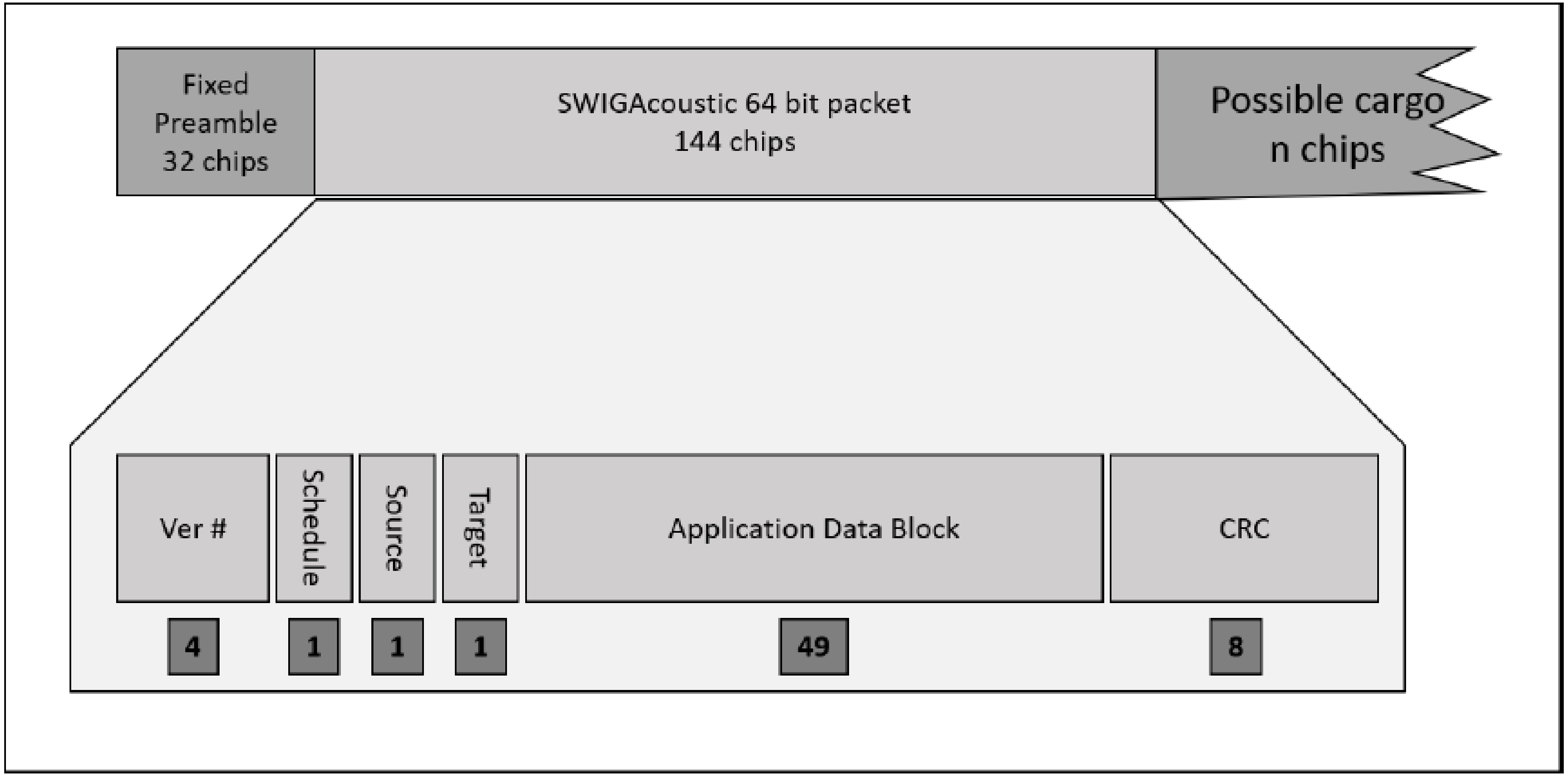


Figure II. The structure of a JANUS packet

SWiG Level 1


Fixed
Preamble
32 chips
SWIGAcoustic 64 bit packet
144 chips
Possible cargo
n chips
Ver #
Schedule
Source
Target
Application Data Block
CRC
4
1
1
1
49
8

Dual Channel Acoustic Protocol (DCAP)

Code	Fc (Hz)	BW (Hz)	Symbols/sec	User throughput (bps)
0	24000	6000	5000	4900
1	24900	5100	4250	4165
2	25600	4200	3500	3430
3	26500	3600	3000	2940
4	27500	2400	2000	1960
HSQPSK	26000	12000	10000	10000

Rate value code	FSw	BW	Cd	Symbol rate	Max bit rate
0	65 Hz	1690 Hz	0.015385 sec	65 sps	28 bps
1	130 Hz	3380 Hz	0.00769 sec	130 sps	57 bps
2	195 Hz	5070 Hz	0.005128 sec	195 sps	85 bps
3	260 Hz	6760 Hz	0.003486 sec	287 sps	126 bps
4	325 Hz	8450 Hz	0.0031 sec	323 sps	141 bps
5	390 Hz	10140 Hz	0.002564 sec	390 sps	171 bps
6	455 Hz	11830 Hz	0.0022 sec	455 sps	199 bps
7	520 Hz	13520 Hz	0.00192 sec	521 sps	228 bps

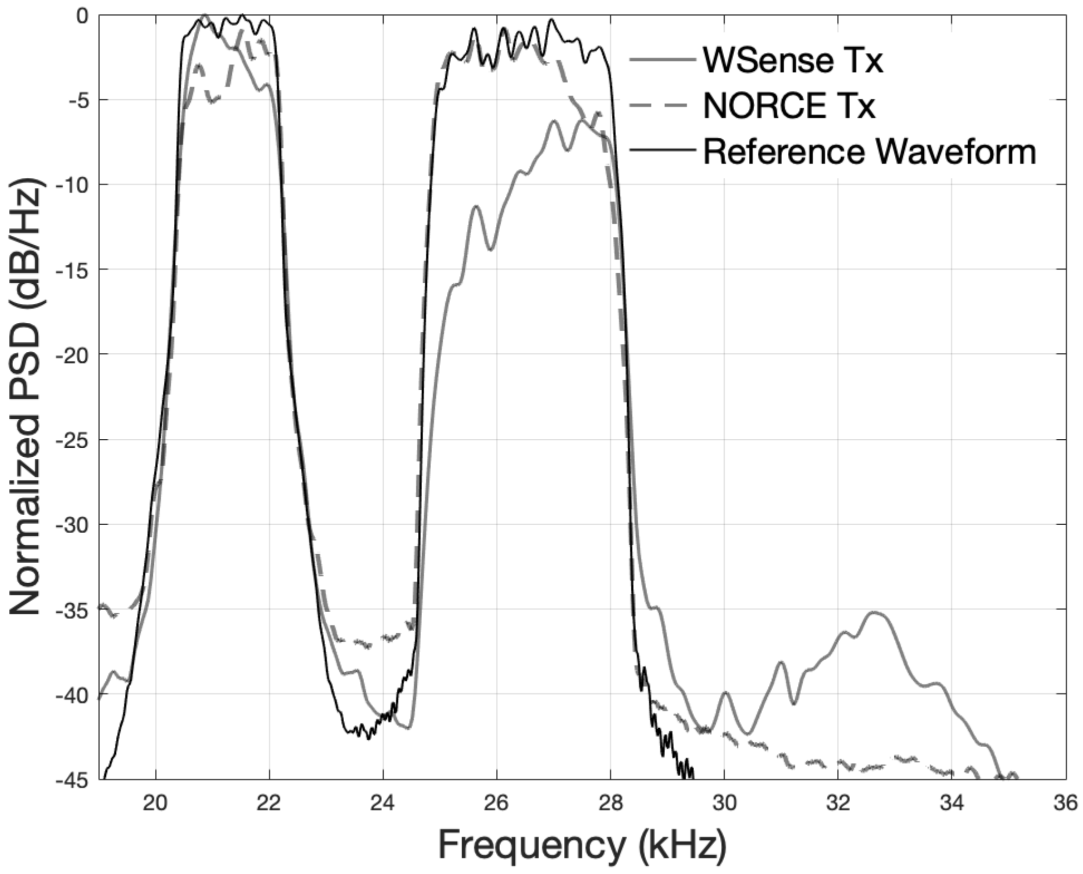
HDC Center Frequency (Hz)

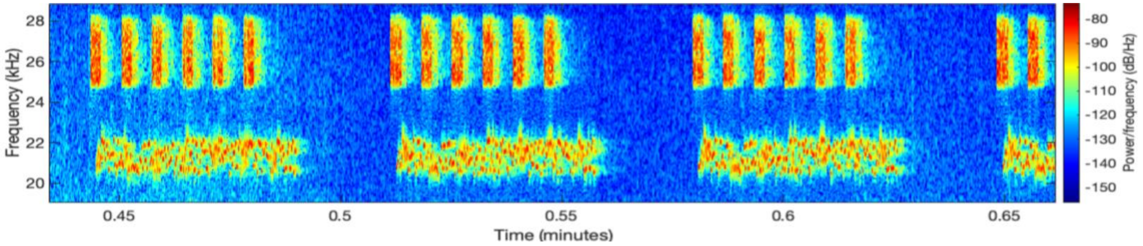
HDC BW (Hz)	24000	24900	25600	26500	27500
2000	FALSE	FALSE	FALSE	FALSE	TRUE
3000	FALSE	FALSE	FALSE	TRUE	FALSE
3500	FALSE	FALSE	TRUE	FALSE	FALSE
4250	FALSE	TRUE	FALSE	FALSE	FALSE
5000	TRUE	FALSE	FALSE	FALSE	FALSE

SMAC Center Frequency (Hz)

SMAC BW (Hz)	18795	19640	20485	21330	23465	24310	25155	26000
1960	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE
3380	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
5070	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
6760	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
8450	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE
10140	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
11830	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE
13520	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

Received Normalized Power Spectral Densities from two Software Defined Modems





Packet delivery rates

TABLE I: PDR over 6 m and 115 m links in both communication directions. These results are obtained by *post-processing* the recordings with the reference receiver software.

Transmitter	Channel & Modulation	Packet Delivery Ratio	
		at 6 m	at 115 m
WSense	SMAC-SAL1E	100%	100%
	HDC-QPSK 1	98.54%	0%
WSense	SMAC-SAL1E	100%	100%
	HDC-QPSK 2	98.58%	0%
WSense	SMAC-SAL1E	100%	100%
	HDC-QPSK 3	100%	0%
NORCE	SMAC-SAL1E	100%	100%
	HDC-QPSK 1	98.65%	3%
NORCE	SMAC-SAL1E	100%	100%
	HDC-QPSK 2	98.52%	6%
NORCE	SMAC-SAL1E	100%	100%
	HDC-QPSK 3	100%	65%

TABLE II: PDR at 6 m and at 115 m when the NORCE SDM transmitted to the WSense one. These results are obtained by the WSense receiving software implementation of DCAP.

Channel & Modulation	Packet Delivery Ratio		
	at 6 m	at 115 m - ST	at 115 m - H
SMAC-SAL1E	100%	100%	100%
HDC-QPSK 1	98.33%	0%	2.5%
SMAC-SAL1E	100%	100%	100%
HDC-QPSK 2	98.57%	0%	3%
SMAC-SAL1E	100%	100%	100%
HDC-QPSK 3	100%	1.25%	70%

Multimodality

in underwater wireless communications

UNDINA milestone: Three payloads integrated into the robot with the first implementation of the programmable protocol stack

High data rate (Mbps)

Control channel
and positioning

Recharge power (150 W)
upload-offload data (1Gbps)

UNDINA milestone: Three payloads integrated into the robot with the first implementation of the programmable protocol stack

High data rate (Mbps)

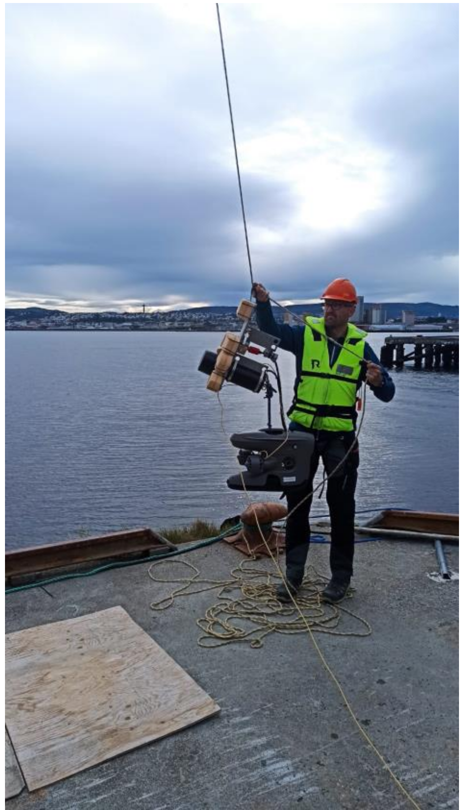
Recharge power (150 W)
upload-offload data (1Gbps)

Control channel and positioning

DELAIR MARINE

Functionalities that were verified and validated in August 2024

- Automatic docking by fusioning camera and DVL data.
- Positioning through a relay (without direct connectivity between USBL and drone to position).
- Fly over (with automatic data transfer through opical modem).
- Hybrid communication and positioning system (HoPS) validated with status messages sent by one drone while positioning all the drones in the water.
- Systematic tests of HoPS in open water in the fjord.



Conclusions

And open questions

Lessons learnt and perspectives

- X3 drones are an efficient and flexible platform to perform rate vs range and depth optical communication tests
- Optical modem performs satisfactorily for the use cases in UNDINA (horizontal and vertical close to sea bottom data transmissions from the drones to the benthic station).
- Run-off pollution increases attenuation at surface but will also reduce ambient light at depth.
- More systematic experiments are needed to better delimit the rate vs range and depths working regimes of the optical and acoustic communications.

References

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Thanks & Questions

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through the

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