INESCTEC
TECHNOLOGY & SCIENCE
ASSOCIATE LABORATORY

30 1985 THIRTY YEARS 2015

**FROM KNOWLEDGE GENERATION TO SCIENCE-BASED INNOVATION**

- RESEARCH AND TECHNOLOGICAL DEVELOPMENT
- TECHNOLOGY TRANSFER AND VALORISATION
- ADVANCED TRAINING
- CONSULTING
- PREINCUBATION OF TECHNOLOGY-BASED COMPANIES

# Underwater electromagnetic communication and power transfer technologies

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Wireless Battle of the Mesh v9, May 1 – May 7 2016, Porto – Portugal

# OUTLINE

- **Introduction**
- **Underwater RF propagation**
- **Software Defined Radio**
- **Auto Rate mechanisms**
- **Overview of research facilities**
- **Endure project**
  - Underwater radio
  - Underwater wireless power transfer
- **Underwater optical wireless**

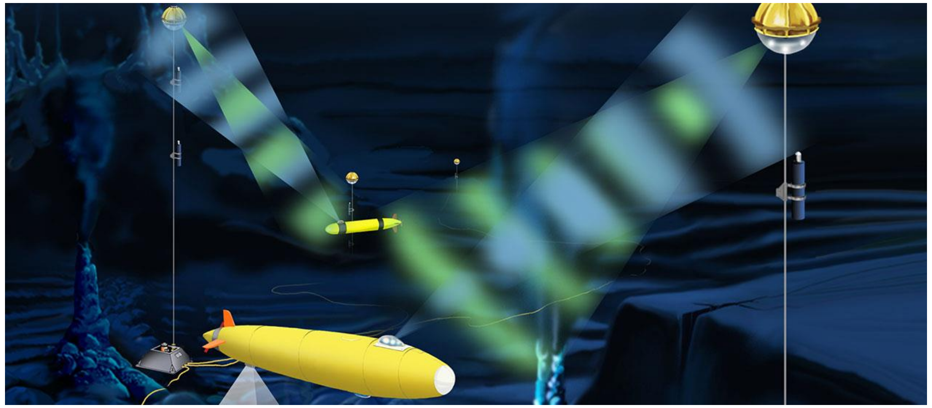
# INTRODUCTION

- **Wireless data transfer underwater is essential**
  - Data collection from Autonomous Underwater Vehicles (AUV)
  - Control of Remote Operated Vehicles (ROV)
  - Underwater Wireless Sensor Networks (UWSN)


- **Still a very challenging task!**

- **Acoustic communications**
  - Limited bandwidth
  - High delay
  - High power

- **Underwater visible light communications (UVLC)**
  - Higher throughputs
  - Require line-of-sight
  - Alignment is required



# INTRODUCTION

- **Radio Frequency (RF) based on IEEE 802.11 networks**
  - Broadband
  - Cost-effective
  - Non-line-of-sight
  - Short distance at 2.4 GHz (< 0.3m due to high attenuation)
- **IEEE 802.11 networks operating at VHF/UHF band**
  - Lower attenuation
  - Increased range
  - Compliant with IEEE 802.11af (TV white spaces) frequency range

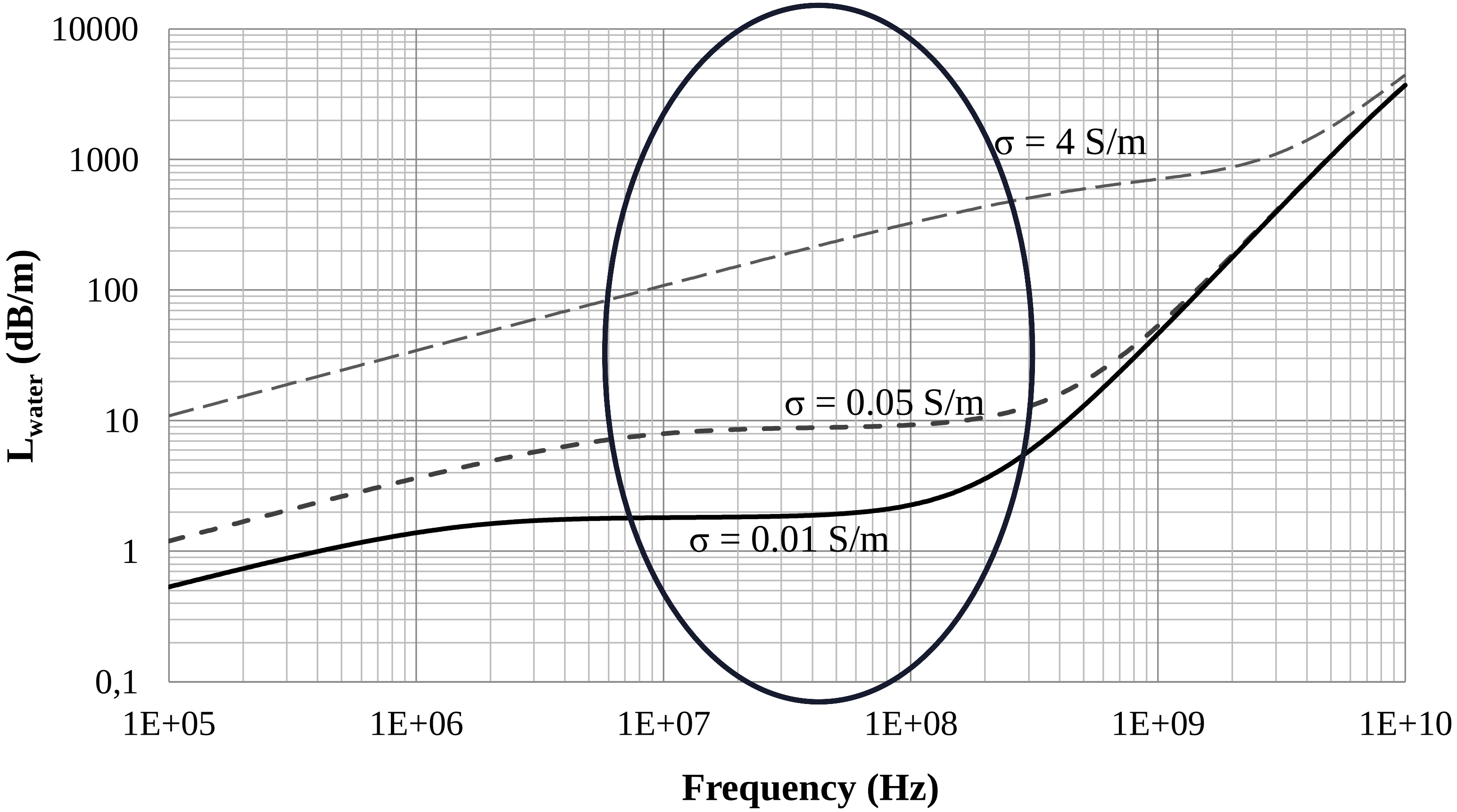
# OBJECTIVES

- **Study the performance of IEEE 802.11 networks in the 70-700 MHz range underwater using Software Defined Radio [1]**
  - In a large freshwater tank
  - In real world seawater conditions

- **Design of custom loop and dipole antennas for underwater environment [1]**

[1] Filipe Teixeira, José Santos, Luís Pessoa, Mário Pereira, Rui Campos, Manuel Ricardo, Evaluation of Underwater IEEE 802.11 Networks at VHF and UHF Frequency Bands using Software Defined Radios, in Proc. of WUWNet'15, Washington, USA, Oct. 2015.

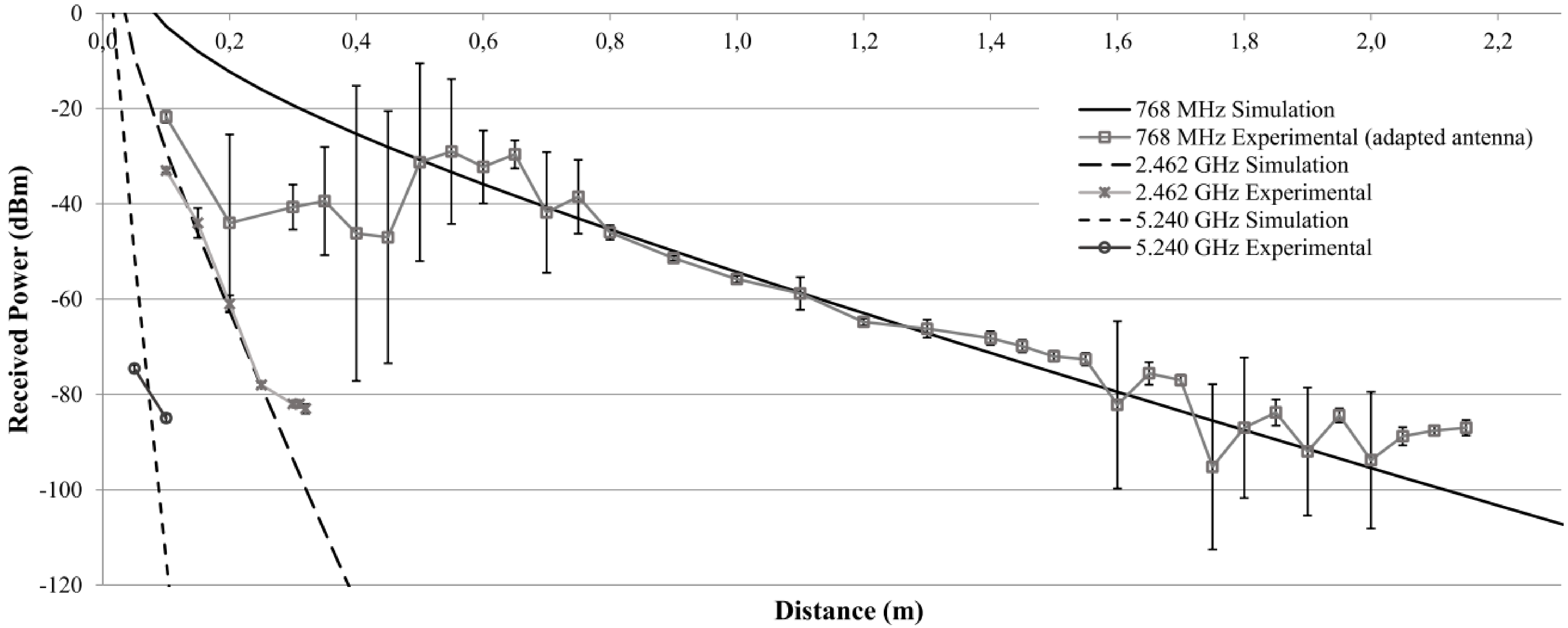
## RF is severely attenuated underwater [2]




## Move to 10-100MHz to decrease increase range

[2] F. Teixeira, P. Freitas, L. Pessoa, R. Campos, M. Ricardo, Evaluation of IEEE 802.11 Underwater Networks Operating at 700 MHz, 2.4 GHz and 5 GHz, in Proc. of WUWNet'14, Rome, Italy, Nov. 2014.

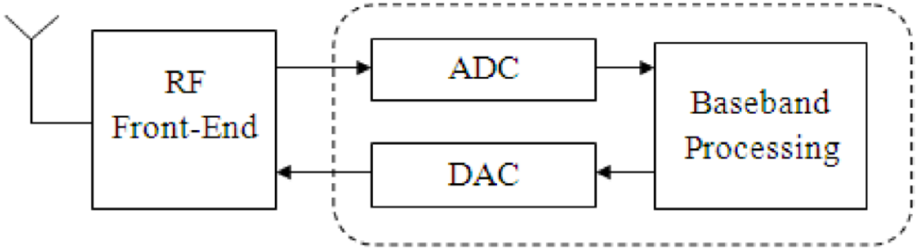
# UNDERWATER PROPAGATION MODELS




[1] F. Teixeira, P. Freitas, Luís Pessoa, R. Campos, M. Ricardo, Evaluation of IEEE 802.11 Underwater Networks Operating at 700 MHz, 2.4 GHz and 5 GHz, in Proc. of WUWNet'14, Rome, Italy, Nov. 2014.

## SOFTWARE DEFINED RADIO

- **All signal process done in software**




- **Open Source GNURadio SDK**

GNURadio
THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

- **Enable cost-effective – avoids proprietary solutions**

  **Used as a test platform**

- **Freedom to change PHY and MAC layers**

# SOFTWARE DEFINED RADIO

**Ettus USRP B210**

- 70 MHz to 6 GHz range
- 56 MHz maximum sampling BW
- USB 3.0 interface (data + power)

**gr-ieee802-11**

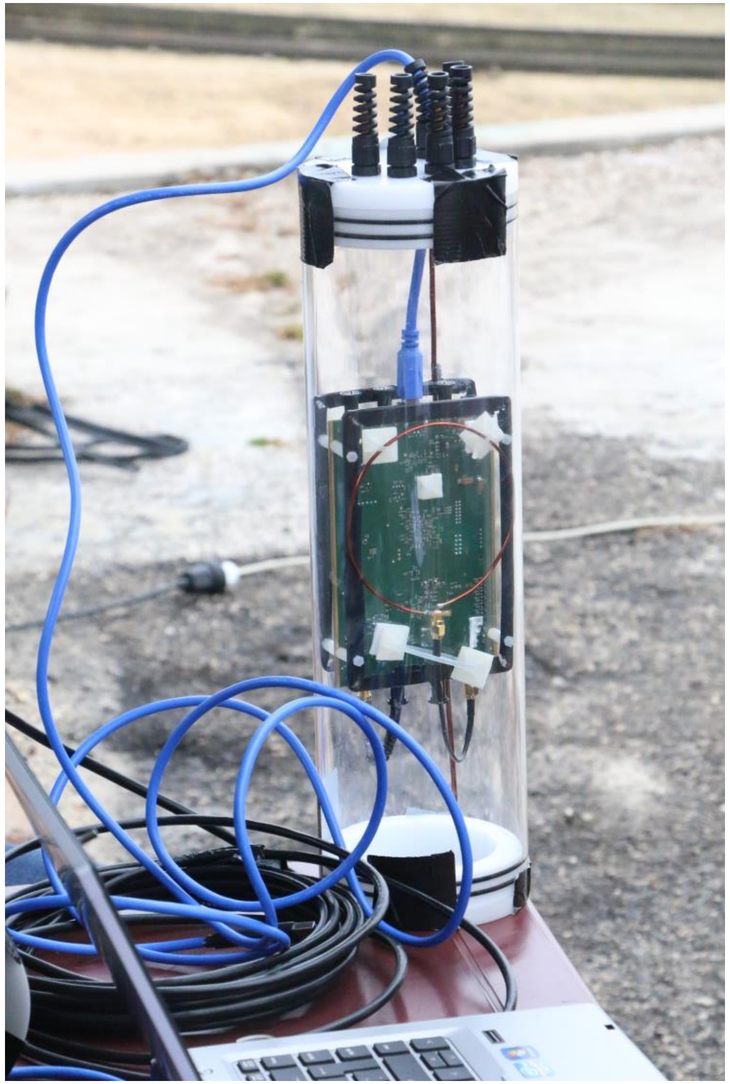
- Implements IEEE 802.11 a/g/p transceiver using GNURadio
- Adapted to work at VHF/UHF frequencies underwater

# EXPERIMENTAL SETUP

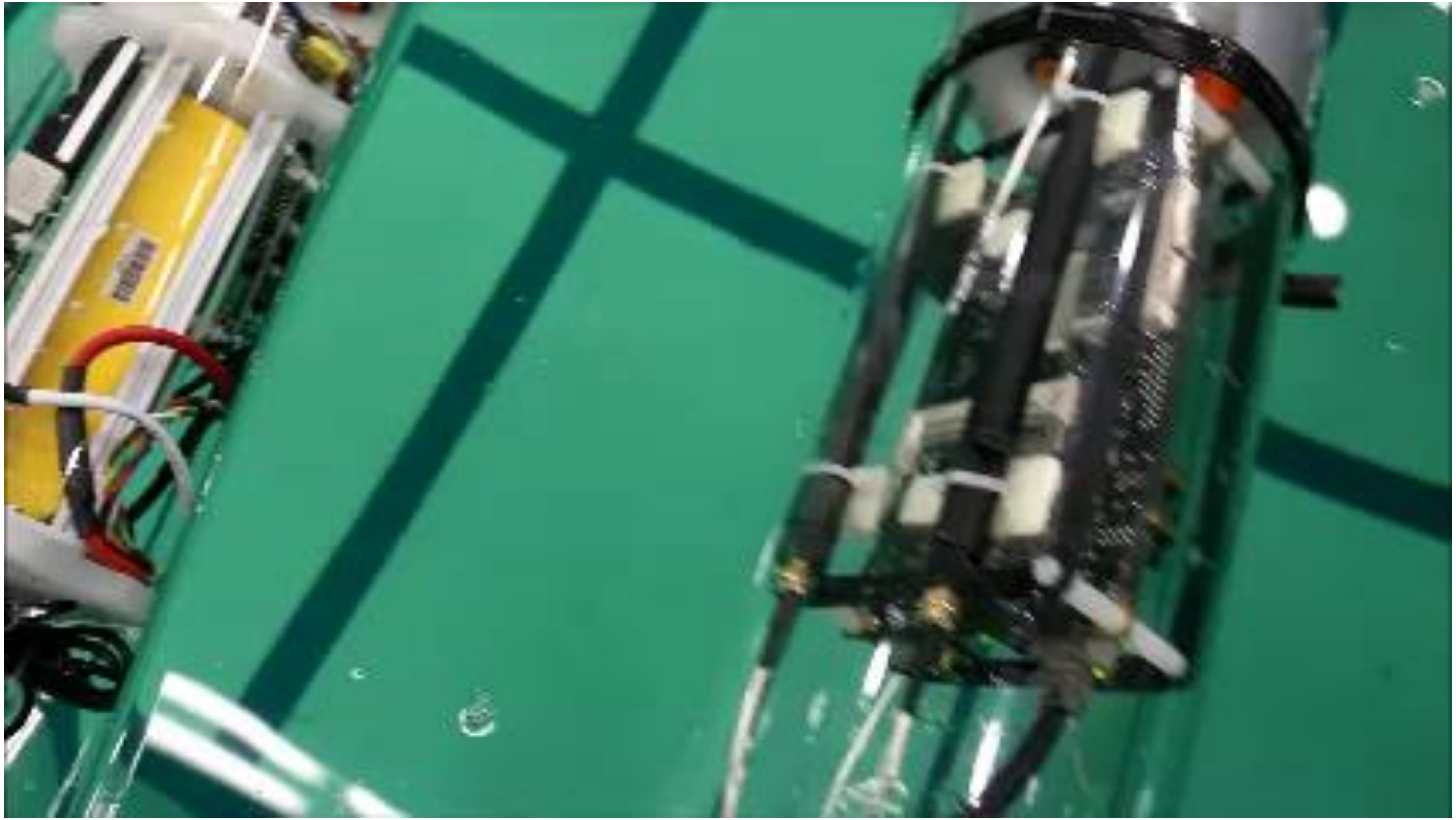
- **Ettus B210 SDR**
  - Inside an airtight acrylic cylinder
  - USB 3.0 connector to the surface
  - Connected to two laptops
  - No crosstalk between the USB3.0 cables
  - Transmitted power: **16 dBm**

- **Freshwater trial – INESC TEC**
  - 10 m x 6 m x 5.5 m (LxWxH) tank
  - Conductivity**: 0.0487 S/m** (25°C)

- **Sea trial**
  - Tagus estuary (Lisbon Naval Base)
  - Conductivity: **4.8 S/m** (25°C)



# EXPERIMENTAL SETUP



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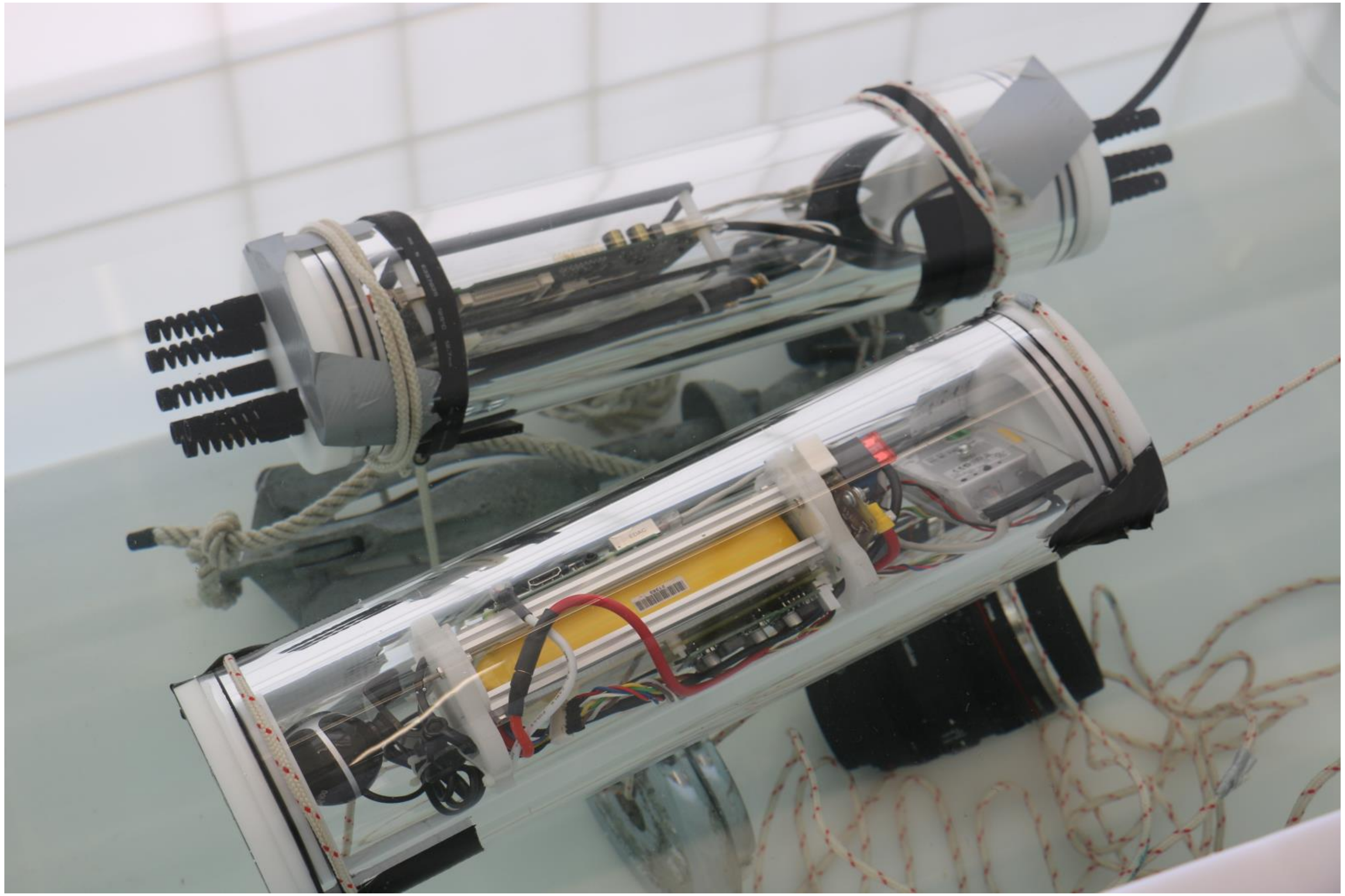

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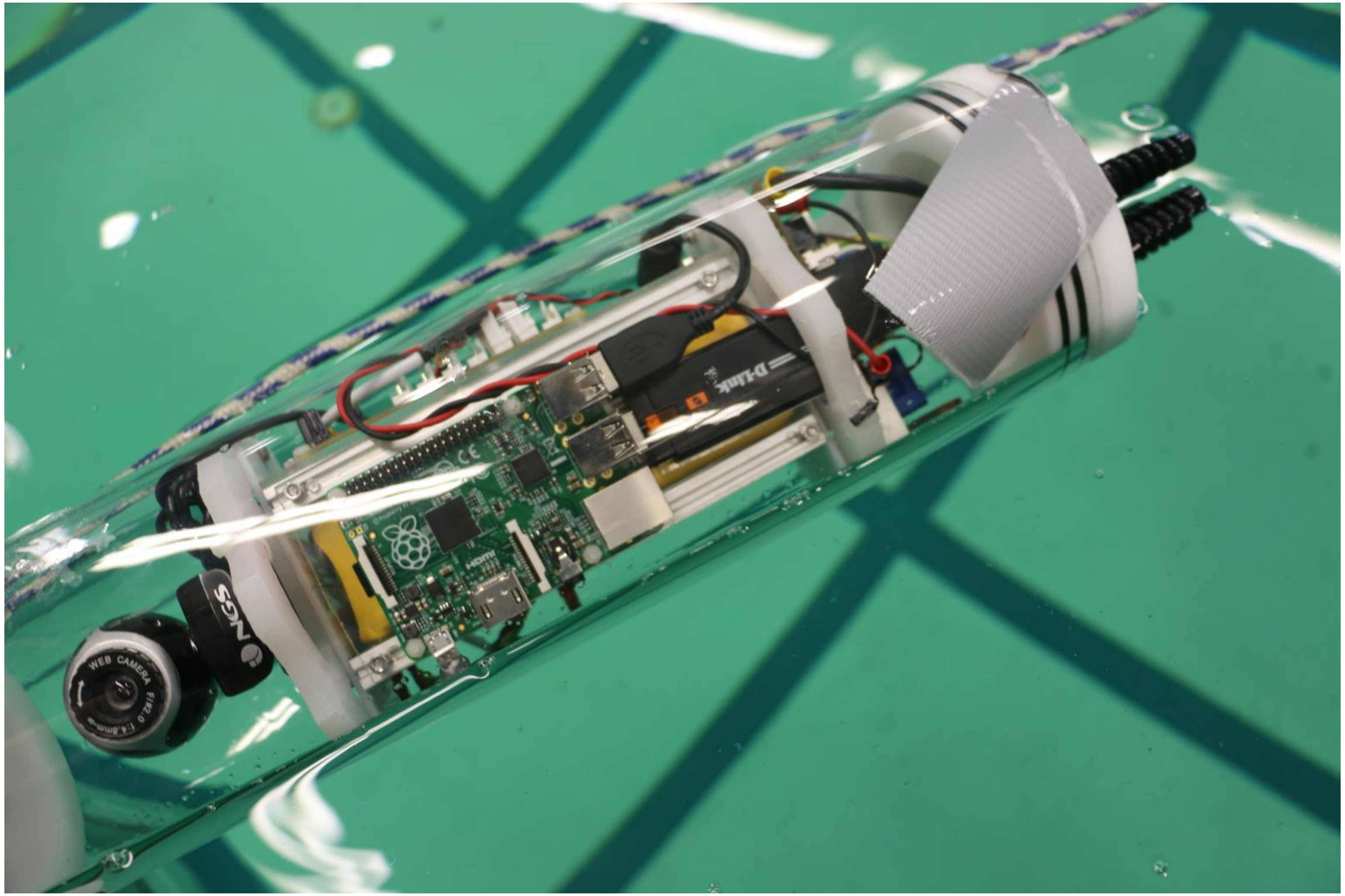
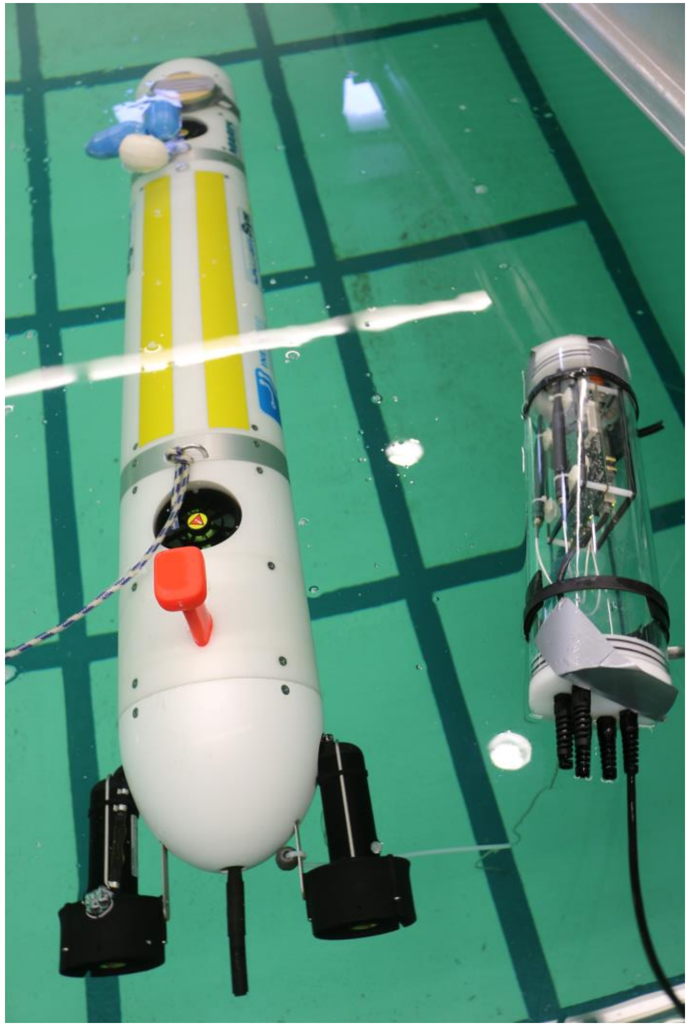
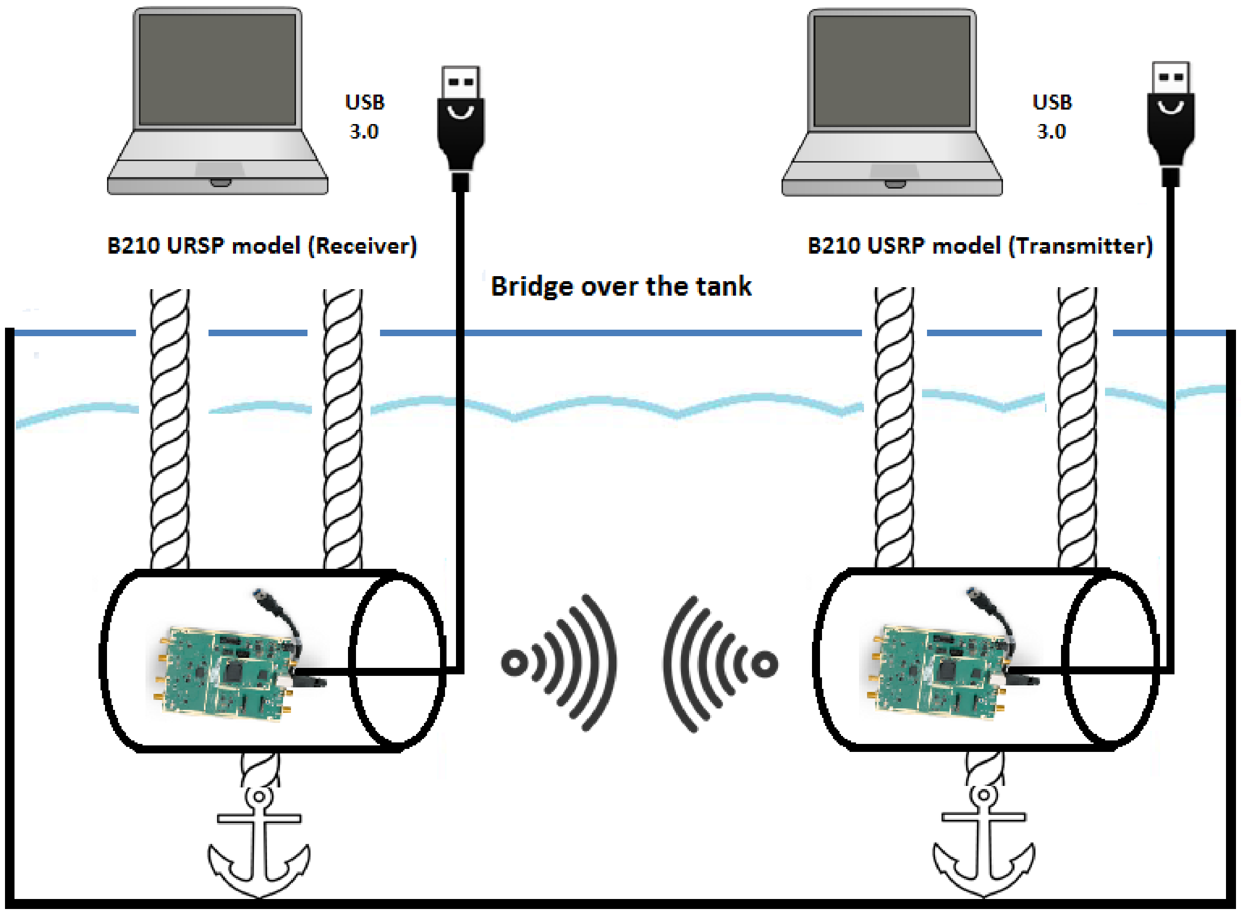


# EXPERIMENTAL SETUP

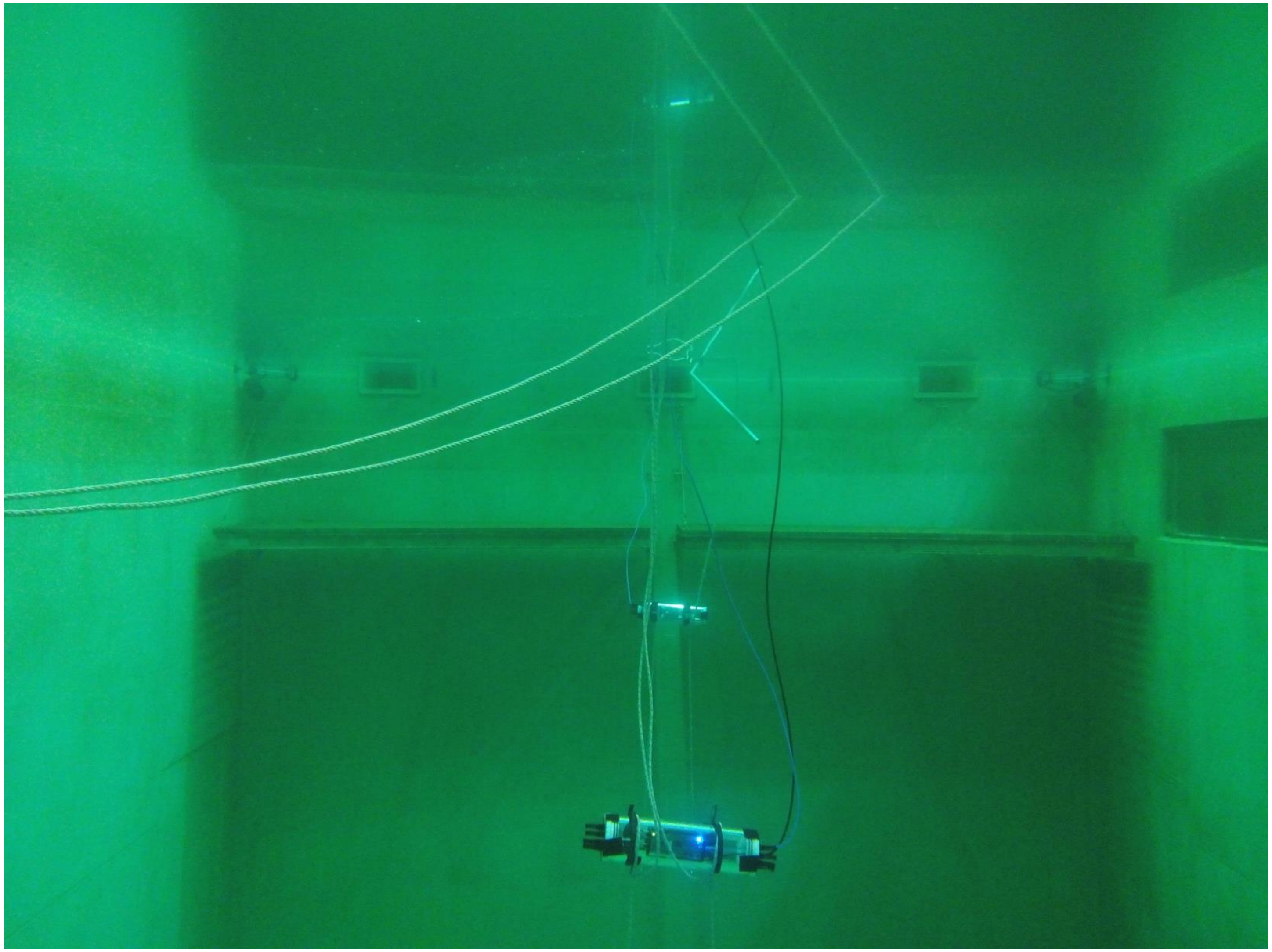
- **CUSTOM-DESIGNED ANTENNAS**
  - Inside the cylinder
  - Limited by the size constraints of the cylinder (12 cm diameter)
  - Loop antenna (freshwater)
    - LARGE LOOP (10 CM DIAMETER)
    - ONE WAVELENGTH PERIMETER (768 MHZ IN THE AIR)
    - 650 MHZ RESONANT FREQUENCY (UNDERWATER)
    - OTHER FREQUENCIES WITH HIGH S11 VALUES
  - Dipole antenna (seawater)
    - HALF-WAVELENGTH (30 CM)
    - 433 MHZ RESONANT FREQUENCY (IN THE AIR)
    - 350 MHZ RESONANT FREQUENCY (UNDERWATER)
    - OTHER FREQUENCIES WITH HIGH S11 VALUES
- **OTHER FREQUENCY BANDS OBSERVED UNDERWATER**
  - Independent of the relative positioning of the antennas
  - Indicate near-field coupling

# EVALUATION SETUP




Freshwater Tank - 10 m x 6 m x 5.5 m (LxWxH)

# EVALUATION SETUP



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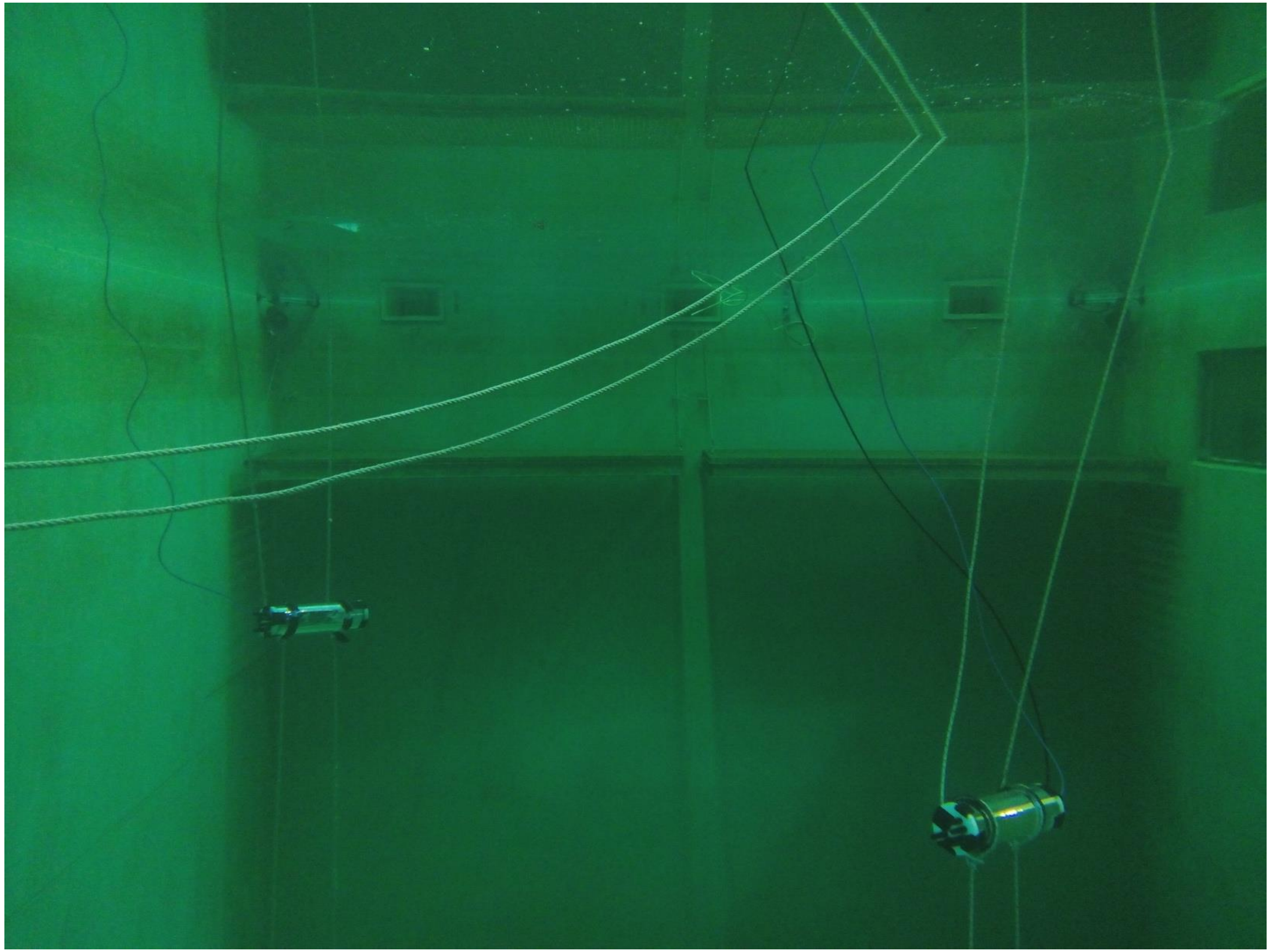

# EVALUATION SETUP

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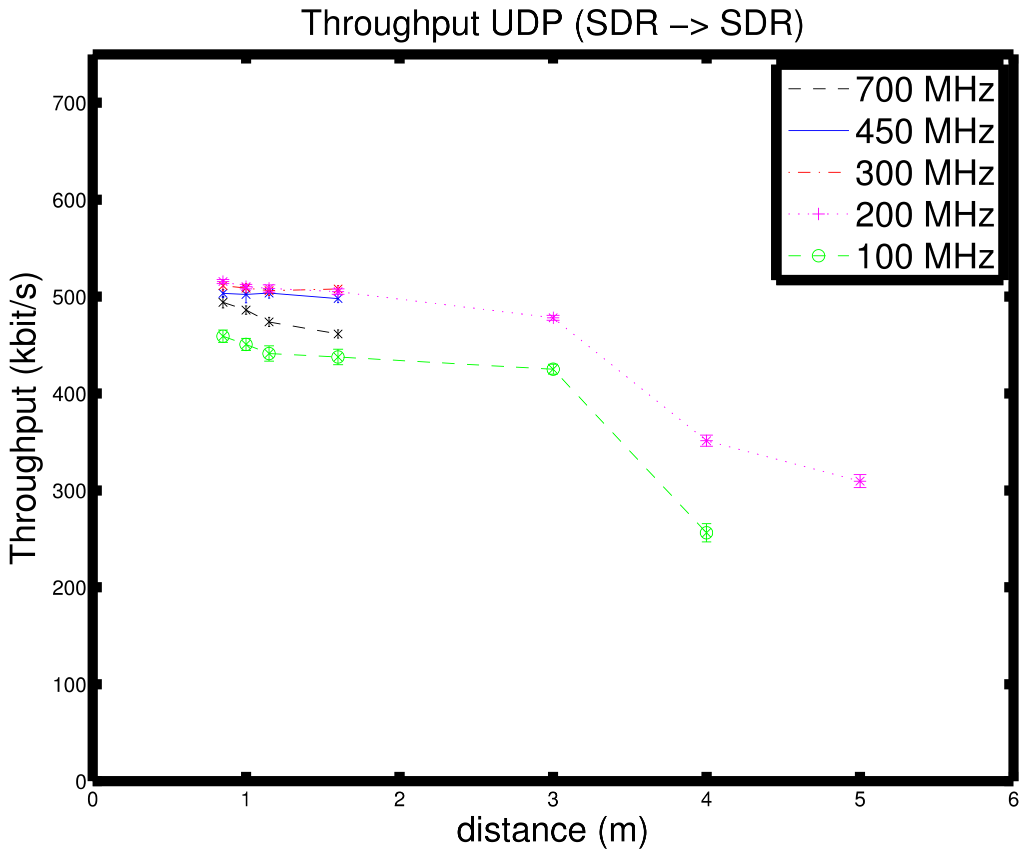
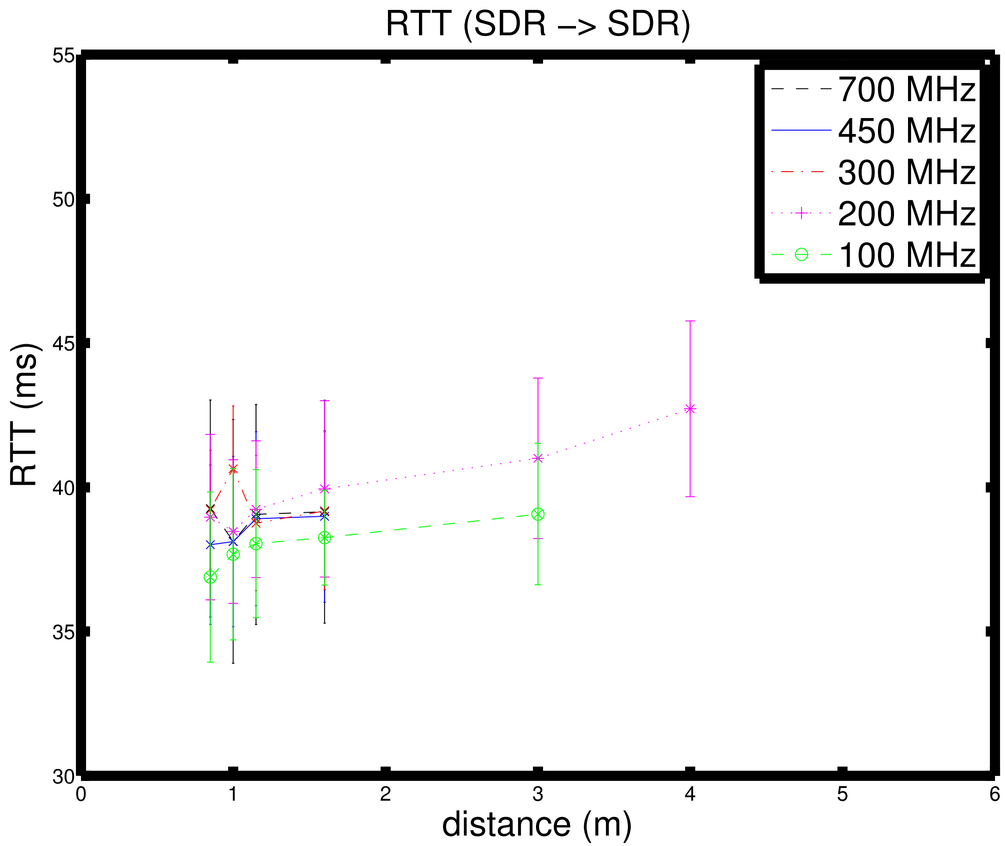
# EXPERIMENTAL RESULTS - FRESHWATER

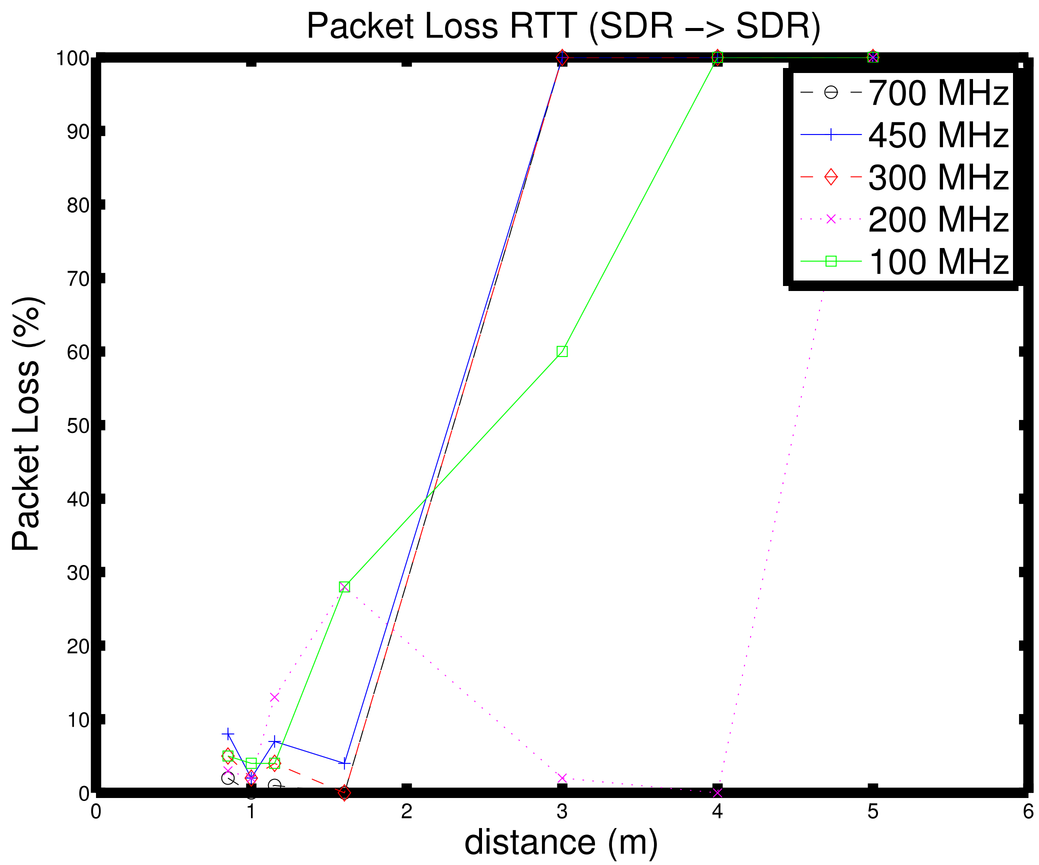



**DISTANCES UP TO 5M IN FRESHWATER AT 200 MHZ**
**CLOSE TO THE MAXIMUM THEORETICAL THROUGHPUT**
**250-550 KBIT/S UDP THROUGHPUT**
**DUE TO SDR-PC-SDR SIGNAL PROCESSING DELAY**

# EXPERIMENTAL RESULTS - FRESHWATER

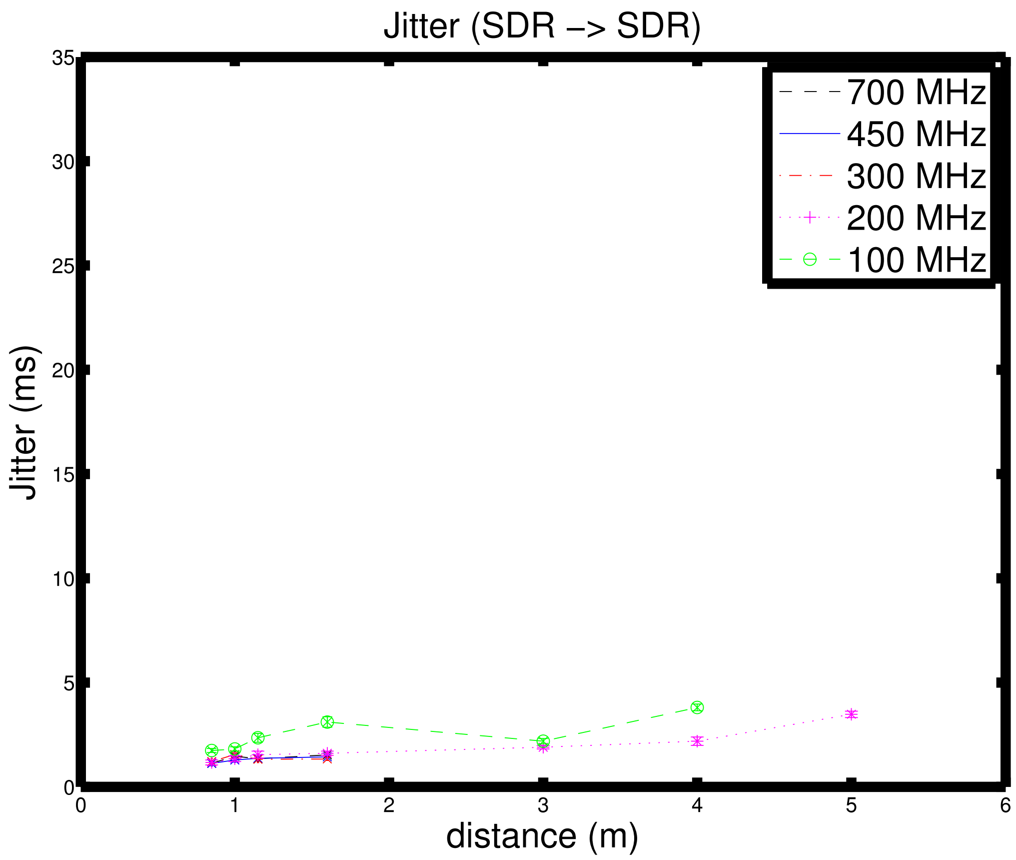



- RTT stable lower than 45 ms



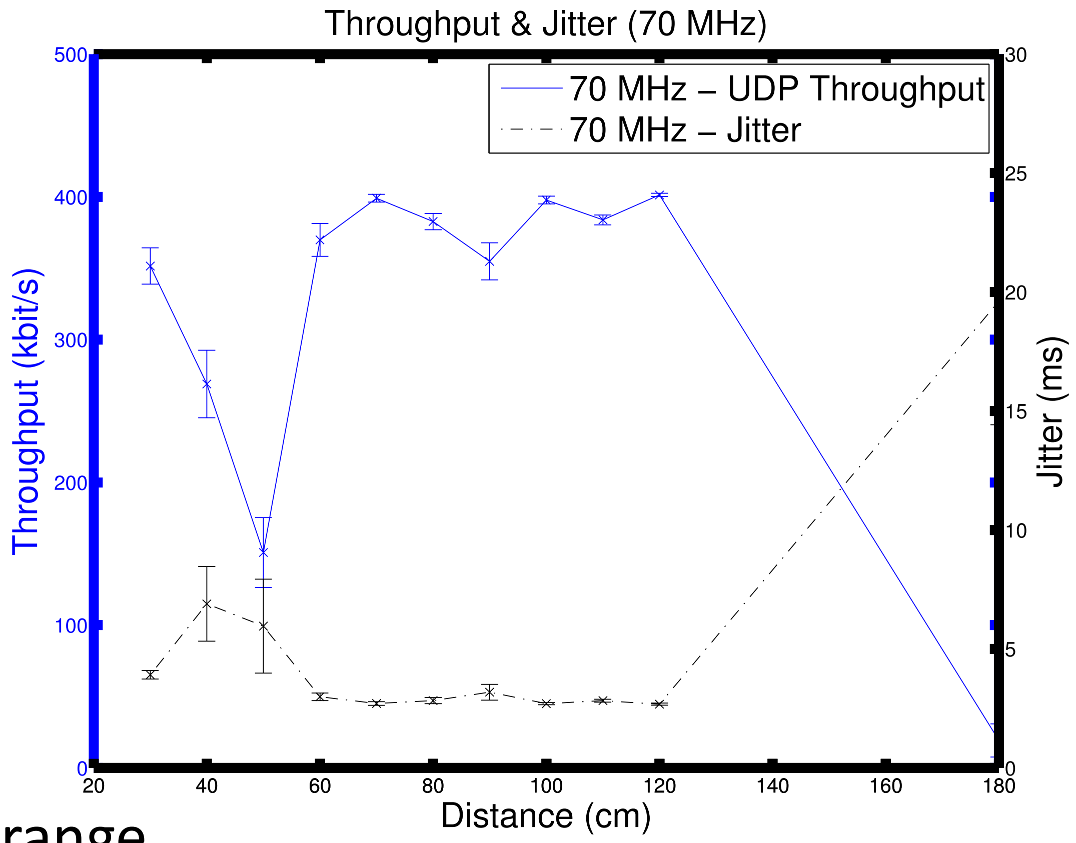

- Packet Loss Ratio lower than 10% up to 1.6 m
- No retransmissions

# EXPERIMENTAL RESULTS - FRESHWATER




- Under 3 ms for all tested frequencies

# EXPERIMENTAL RESULTS - SEAWATER




- 1.80 m range
- Throughput up to 400 kbit/s
- Jitter < 20 ms

# CONCLUSIONS – SOFTWARE DEFINED RADIO UNDERWATER

- **Increasing need for broadband underwater communications**
- **Radio Frequency – IEEE 802.11 networks**
  - Short-range
  - Cost-effective
  - Low power (<100 mW)
- **Lower frequencies required to overcome the underwater attenuation**
- **Software defined radio allows IEEE 802.11 networks to operate at 70-700 MHz underwater**
- **Increased range**
  - 5 m freshwater
  - 1.8 m seawater

# FUTURE WORK – SOFTWARE DEFINED RADIO UNDERWATER

- **Study the radiation pattern of antennas underwater**
- **SNR gain of antennas outside the cylinder**
- **10-70 MHz tests to improve range**
  - Down converter from 2.4 GHz to 10-70 MHz
  - Removes the SDR performance bottlenecks

# AUTO RATE ALGORITHMS UNDERWATER

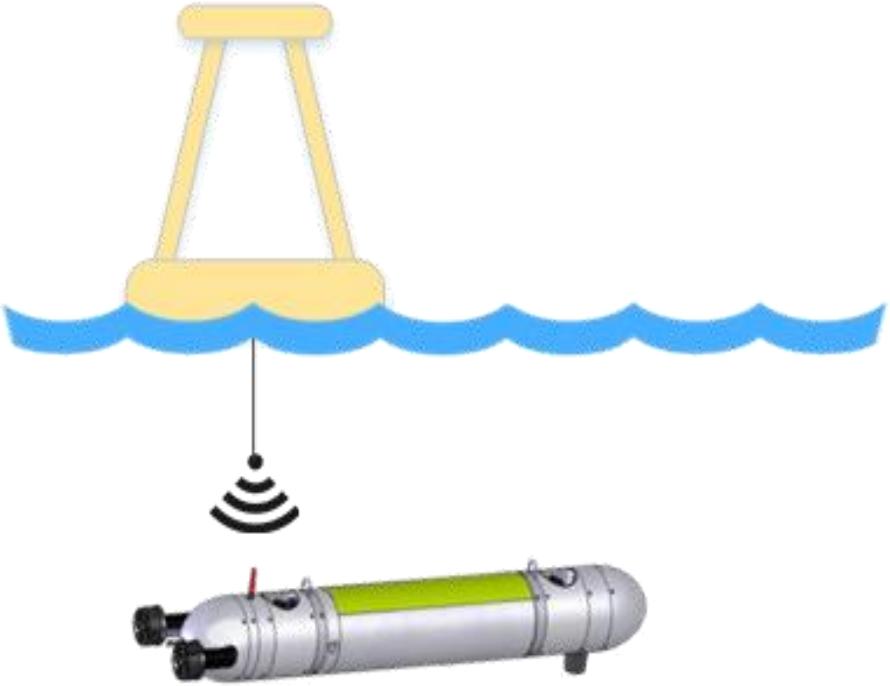
- **Radio Frequency (RF) based on IEEE 802.11 networks**
  - Broadband and cost-effective
  - Great signal changes with small distance change (high attenuation)
- **Rate adaptation algorithms**
  - Adapt the Modulation and Coding Scheme (MCS) according to the link quality
  - Designed for over-the-air environment
  - **May not work underwater due to sharp signal changes underwater – too slow to react**

**Performance evaluation of AARF, Minstrel, CARA, RRAA and Onoe rate adaptation algorithms underwater [3]**

[3] Filipe Teixeira, Rui Campos, Manuel Ricardo, IEEE 802.11 Rate Adaptation Algorithms in Underwater Environment, in Proc. of WUWNet'15, Washington, USA, Oct. 2015.

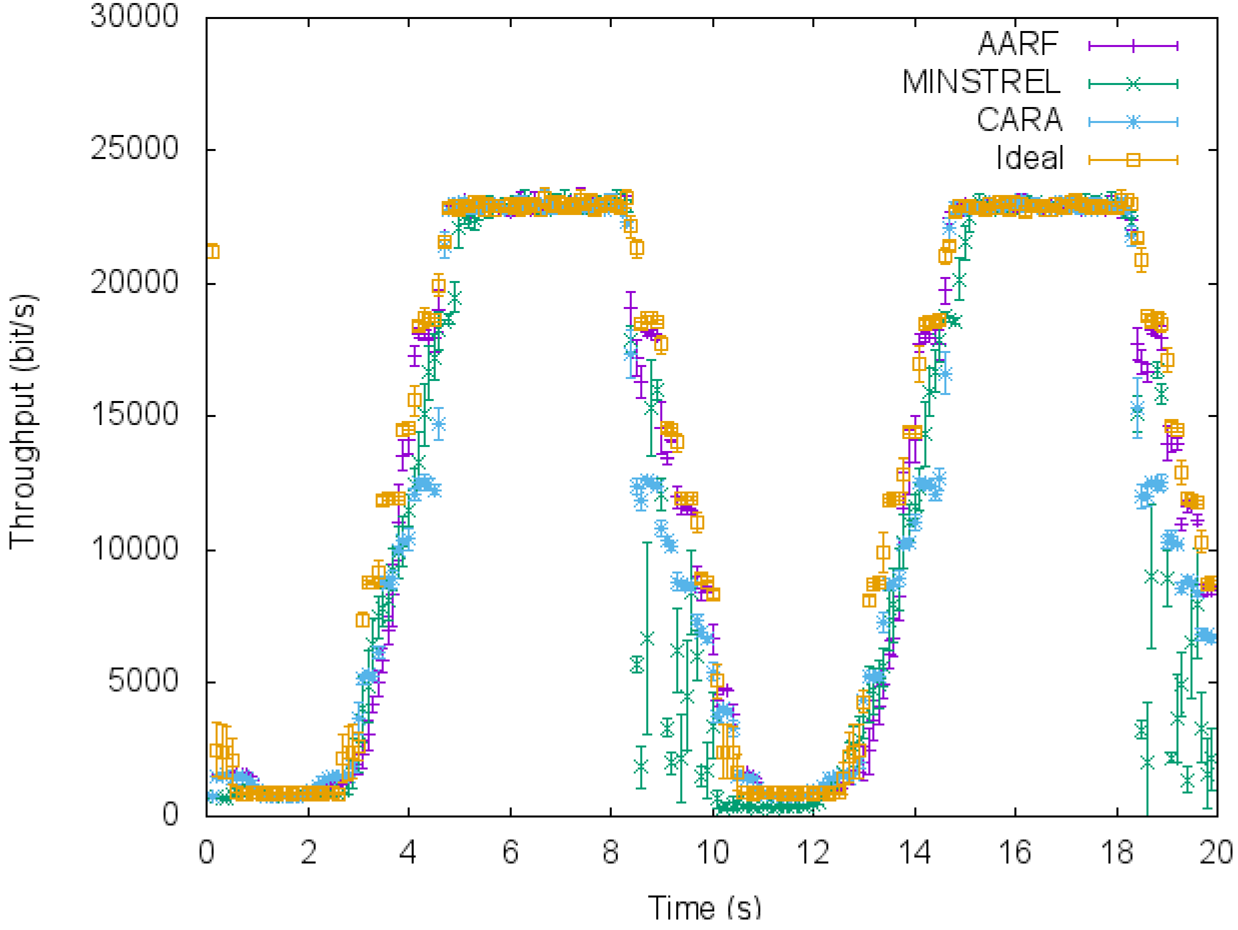
# EVALUATION METHODOLOGY

- Data transfer from Autonomous Underwater Vehicle (AUV)
  - Upload made through an **Underwater Access Point (UAP)**
- Three scenarios
  - AUV approaching the UAP
  - AUV leaving the UAP
  - UAP in a periodic movement
    - **Due to surface waves**
- ns-3 network simulator
  - 768 MHz carrier



# SIMULATION RESULTS

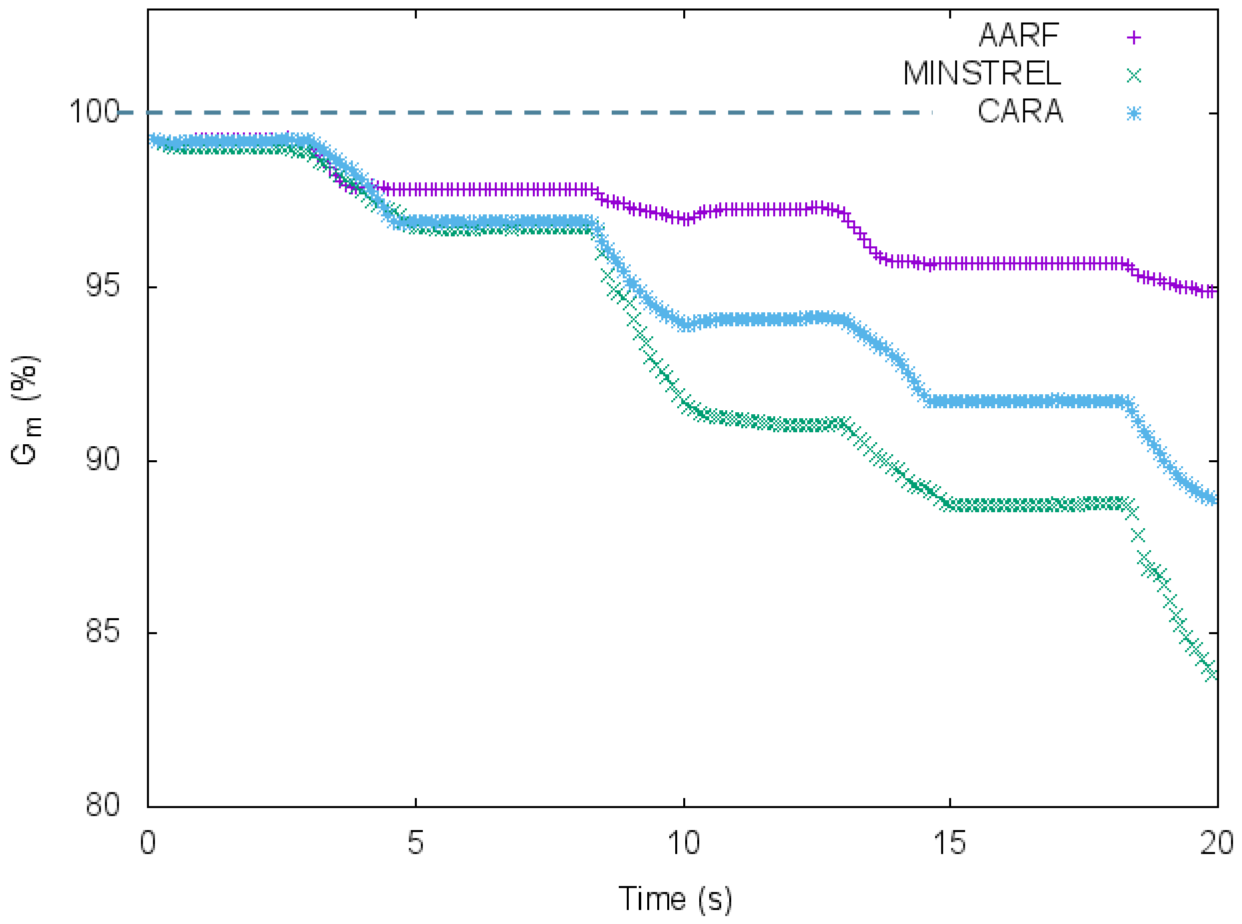
UDP Throughput – UAV with 10s wave period




- AARF closest to the ideal algorithm
- Minstrel is too slow to react to signal changes
- IDEAL = maximum fixed-rate throughput at each instant.

# SIMULATION RESULTS

Throughput gain over the ideal algorithm – 10s wave period




AARF able to achieve 94.5% of ideal throughput

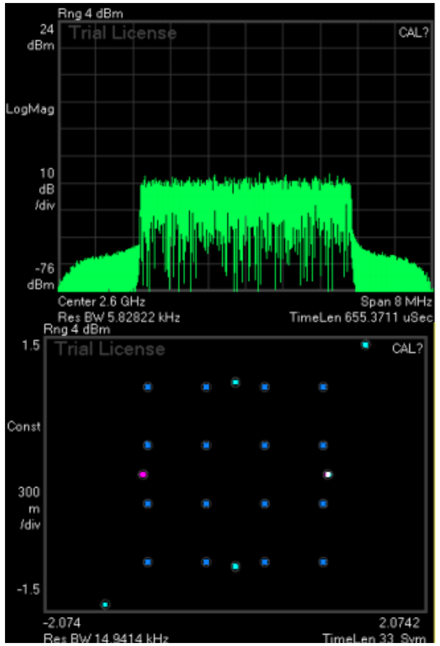
# CONCLUSIONS ON THE AUTO RATE ALGORITHMS UNDERWATER

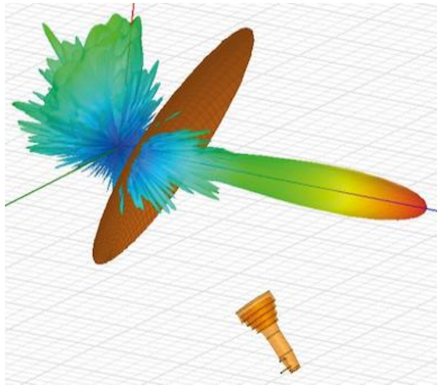
- **High attenuation of RF waves underwater**
  - Affects the decisions of rate adaptation algorithms
- **AARF showed the best results**
  - Per-frame decisions – faster to react to signal changes
  - Up to 94.5% gain
- **Minstrel**
  - Most used in ath5k/ath9k drivers (Linux OS)
  - Too slow to react to signal changes (outdated statistic info)
  - Up to 83.8% gain
- **RRAA and Onoe showed the worse results**

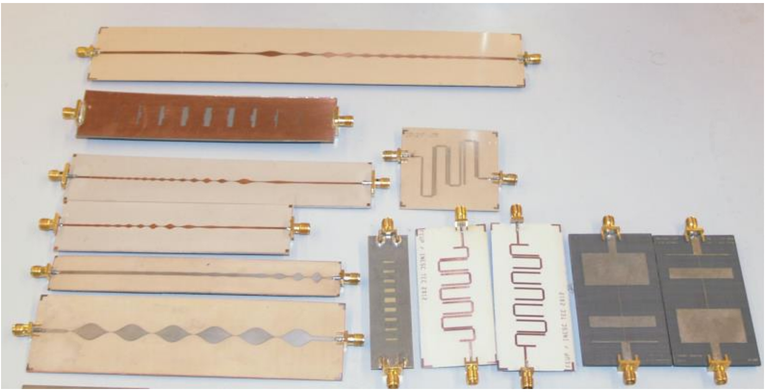
# MICROWAVE PHOTONICS LABORATORY

<u>Key equipment:</u>

- Vector signal generator 80 MHz BW
- Vector signal analyzer
- Vector network analyzer electrical/optical
- 20 GS/s Sampling Oscilloscope 2.5 GHz
- 13 Gbps PRBS and error detector
- Optical Spectrum Analyzer
- Electrical Spectrum Analyzer 50 GHz

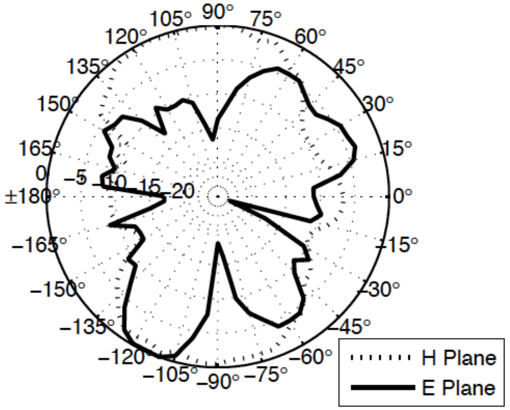


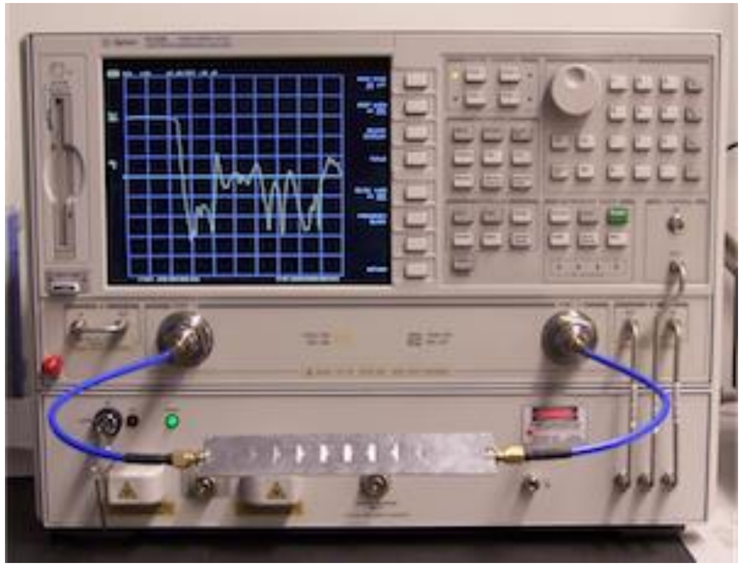





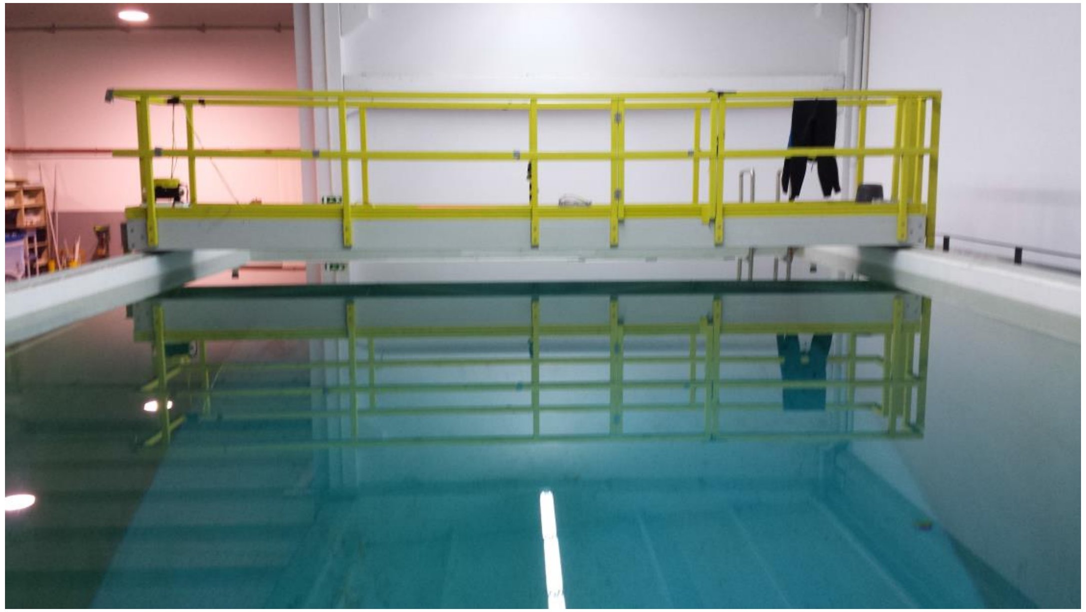
## Microwave devices and antennas

- Design assisted by HFSS and ADS
- Anechoic room characterization up to 40 GHz



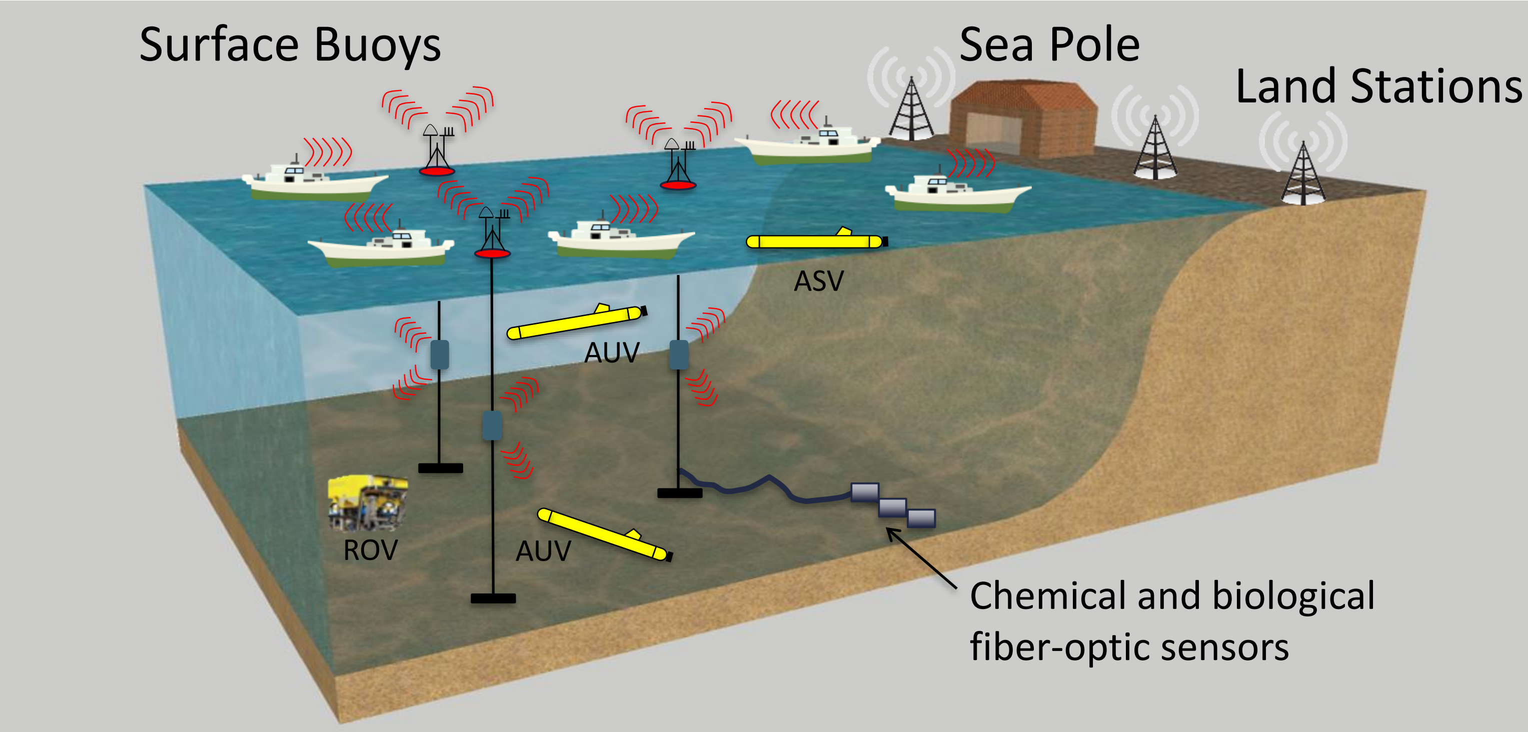
# TEST TANKS



**Located in Portugal, dedicated to support research, development, and test of multiple technologies:**

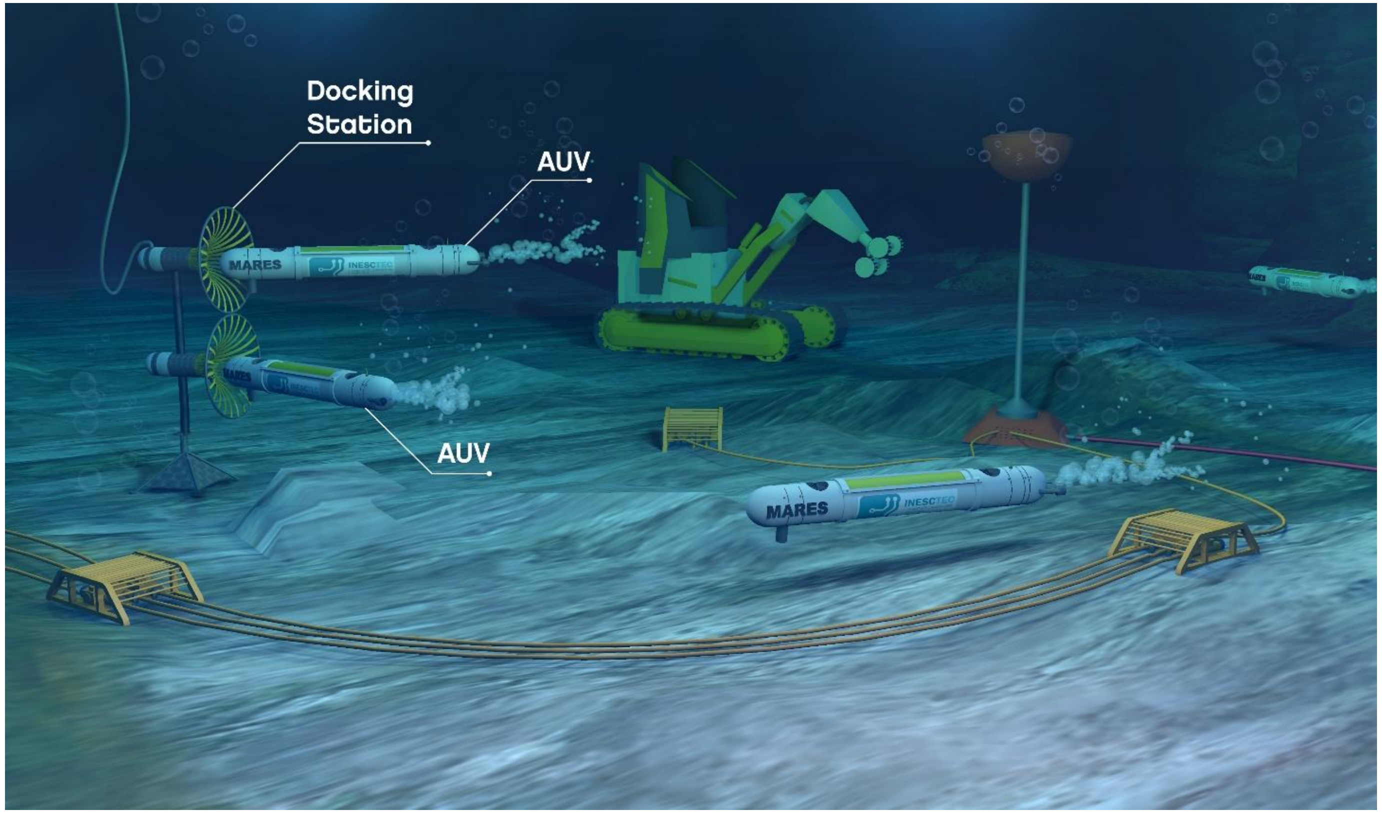
- Telecommunications,
- Marine robotics,
- Sensing

www.tec4sea.com



## ENDURE PROJECT

# MOTIVATION




**Increasing need to sense the underwater environment:**

- **Mobility requirements of robotic-based activities**
  - Real-time control and data harvesting from unmanned vehicles
  - Maintenance and surveillance operations
  - Applications in oil, gas and mining
- **Sensor networks for the assessment of:**
  - Impact of the exploitation of deep-sea raw material resources
  - Physical, biological and biogeochemical parameters (e.G. Climate change)

**Large and deep ocean -> Automation -> AUVs**

- Autonomous operation ✓
- Scalable ✓
- Limited autonomy ✗

**Need for solutions enabling the operation of multiple AUVs in remote oceanic locations, with time unlimited missions**

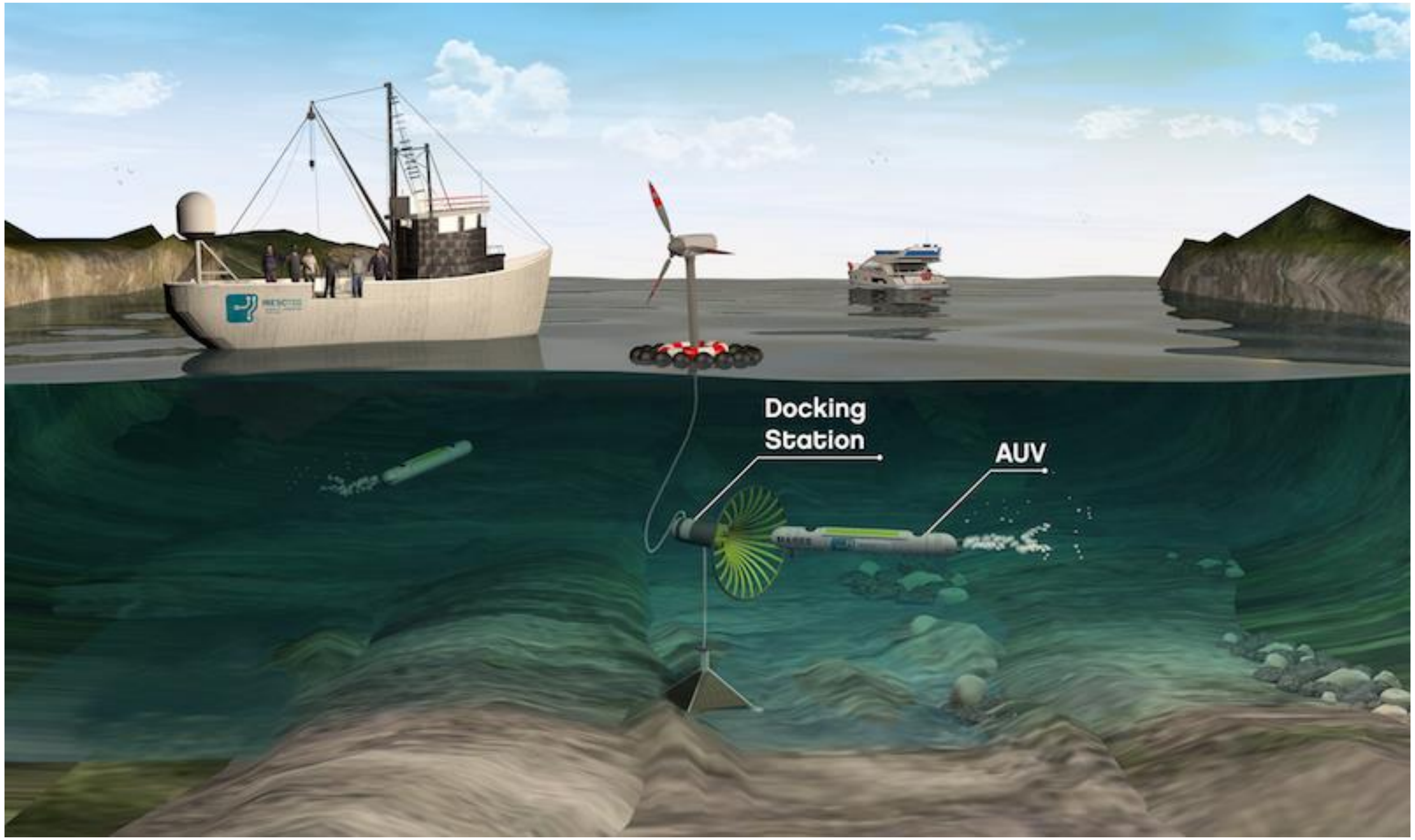
# ENDURE PROJECT OBJECTIVES

**Develop and demonstrate a cost-effective solution for recharging autonomous underwater vehicles used in remote oceanic areas:**

- Docking manoeuvre, based on a novel vision based AUV positioning subsystem.
- Wi-fi based high-bandwidth short range communication subsystem, for fast data downloading.
- Wireless battery recharging subsystem, capable of tolerating misalignments.

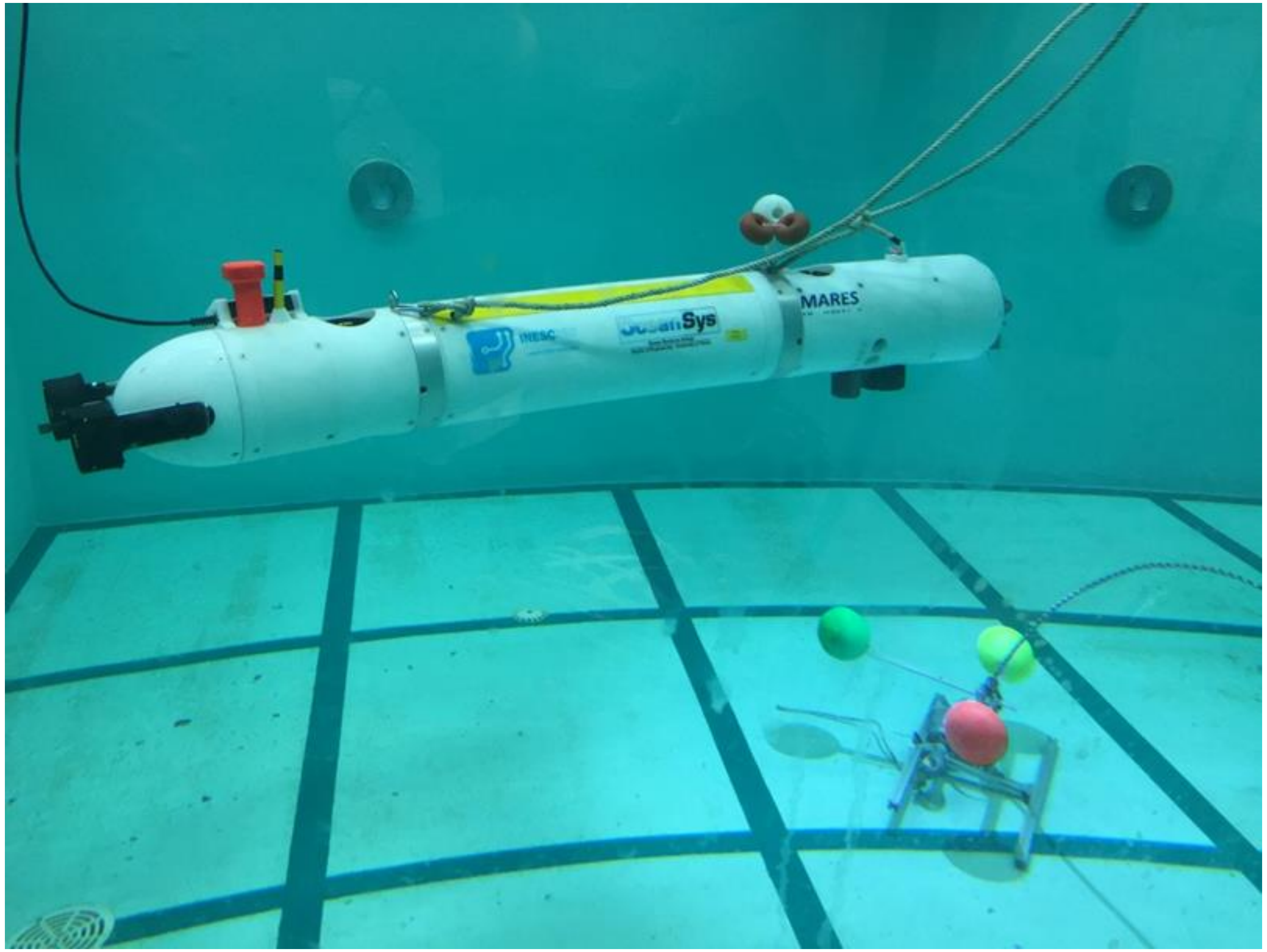
**Exploitation and impact assessment measures**

# ENDURE PROJECT DEMONSTRATION



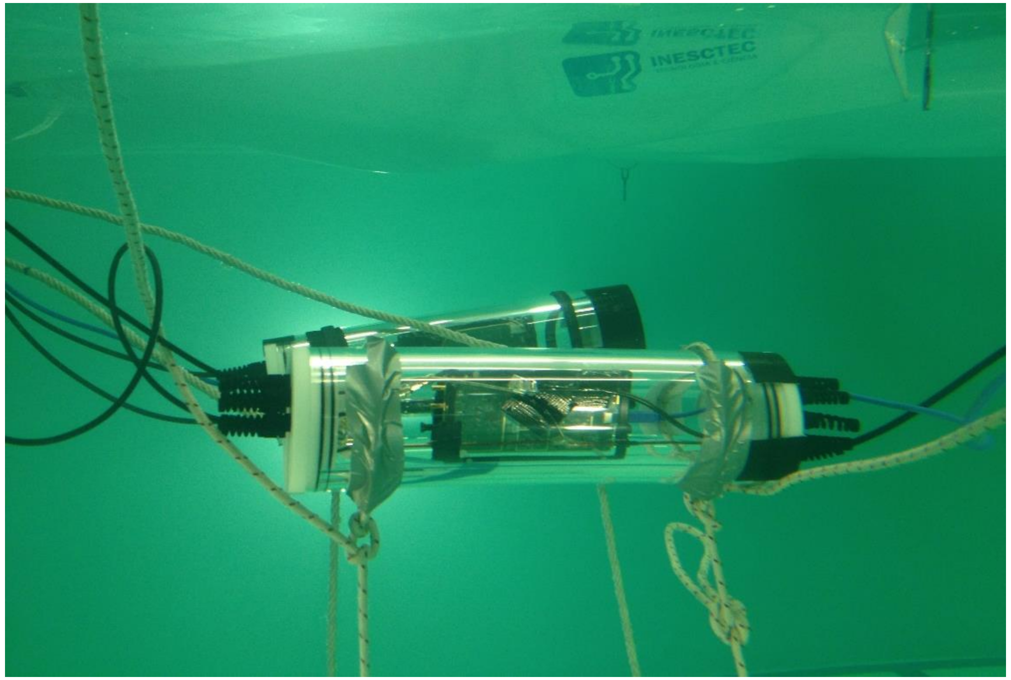

- **Based on a moored surface platform**
- **The AUV to be used is MARES, a highly flexible small-scale AUV developed by INESC TEC**
- **Demonstration targeted for a low depth costal ocean area in Portugal**

# DOCKING MANEUVRE



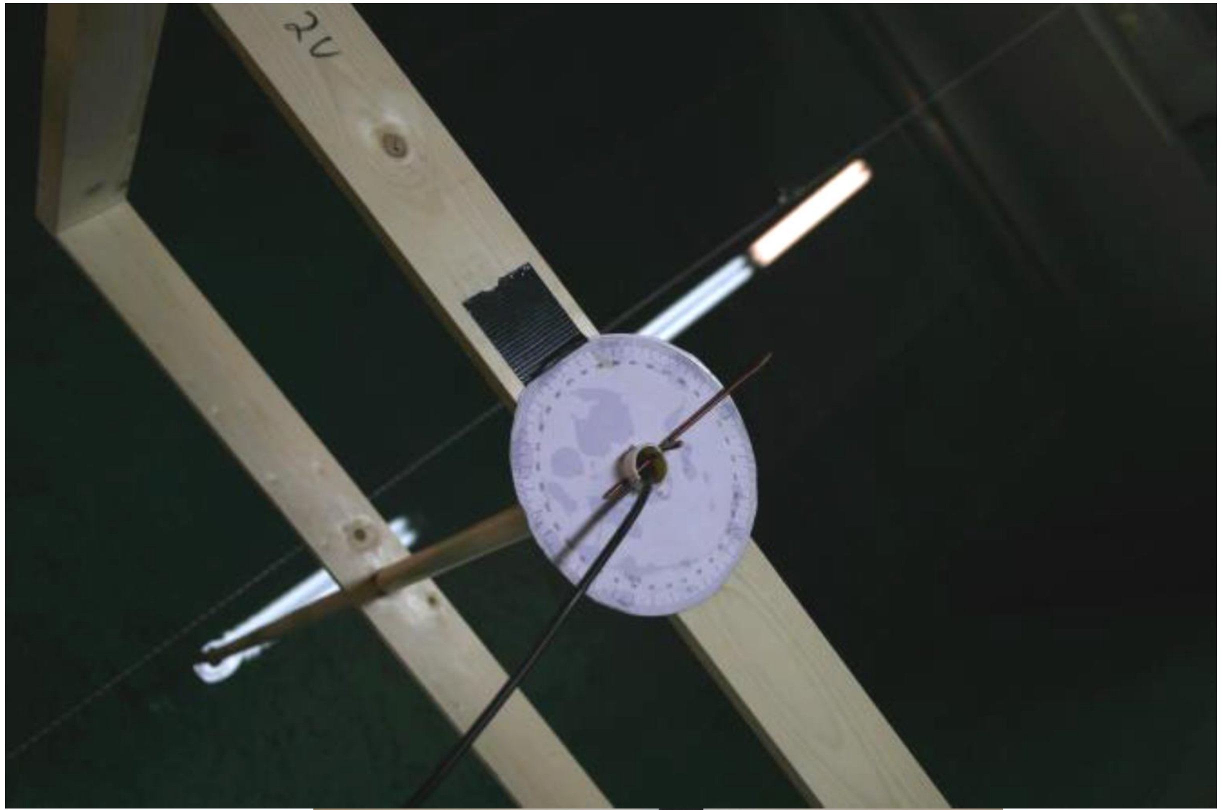

- **Based on a novel vision based AUV positioning subsystem.**

# SHORT RANGE COMMUNICATIONS




- **Propagation of RF waves in seawater is well suited for short-range broadband communications**
  - *A 100 MHz carrier suffers a 30 dB attenuation for each 10 cm of propagation*
- **Based on Wi-Fi radios using sub-GHz frequencies**

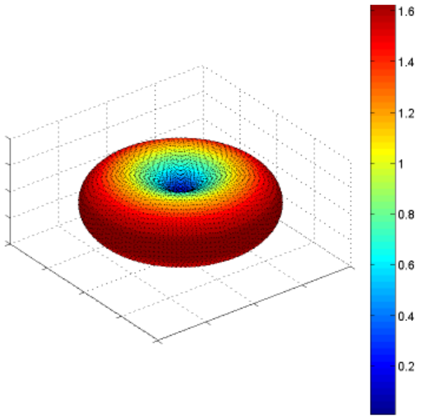
# SHORT RANGE COMMUNICATIONS



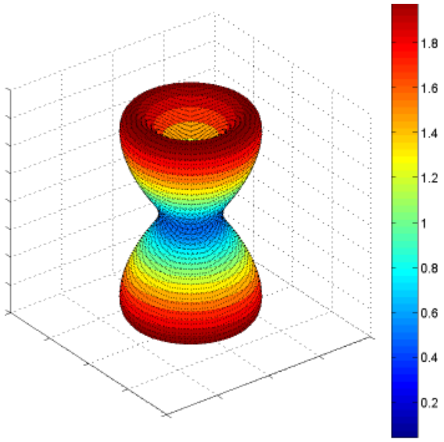
# SHORT RANGE COMMUNICATIONS

- **In seawater radiation pattern changes significantly, due to water conductivity**
- **Must be taken into account at the design stage**

**Dipole radiation pattern**

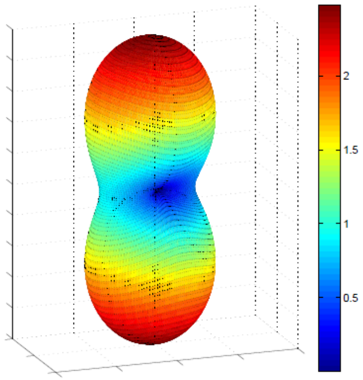



Fresh water

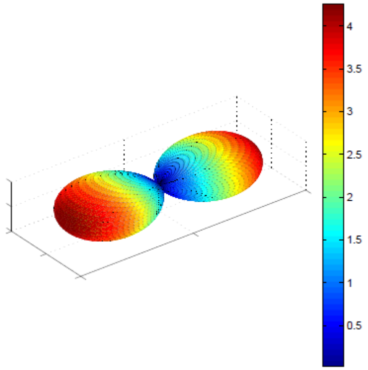



Sea water

**Loop radiation pattern**




Fresh water




Sea water

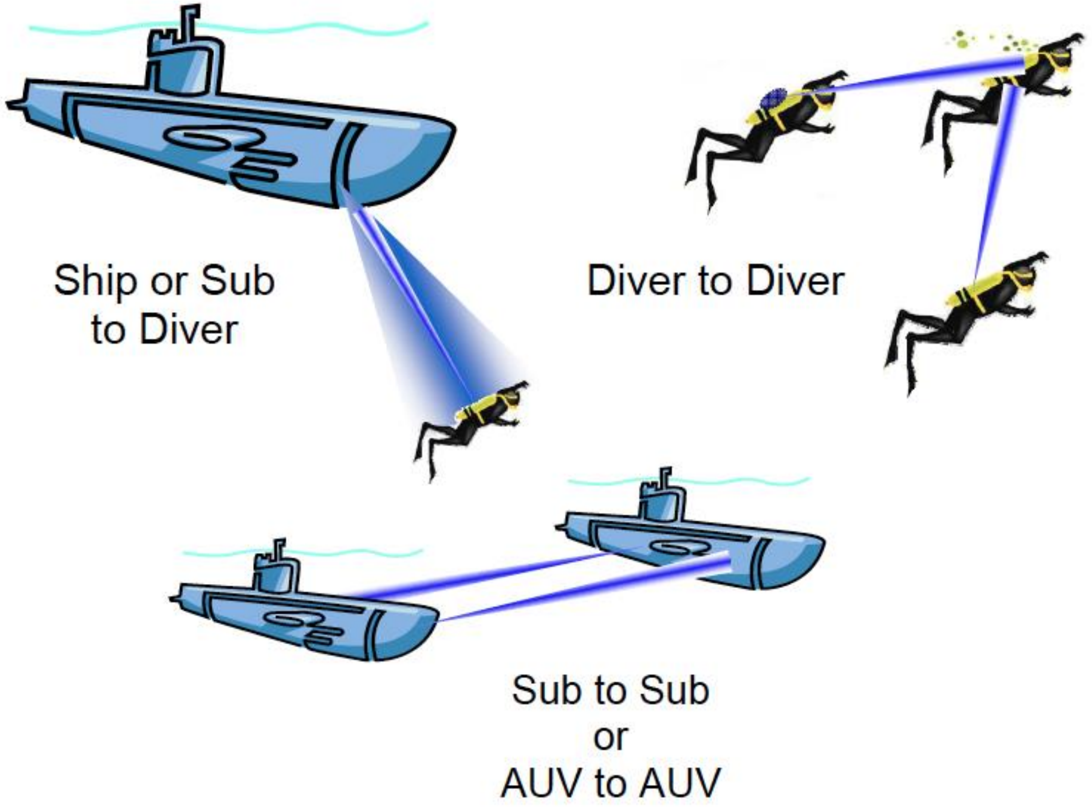
# UNDERWATER OPTICAL WIRELESS

- **Advantages**
  - Potentially significant range 100m-200m
  - Throughputs in the order of several Mbit/s
  - High propagation speed (low latency)
  - Low power consumption
  - Possibly leveraged by advances in terrestrial optical wireless

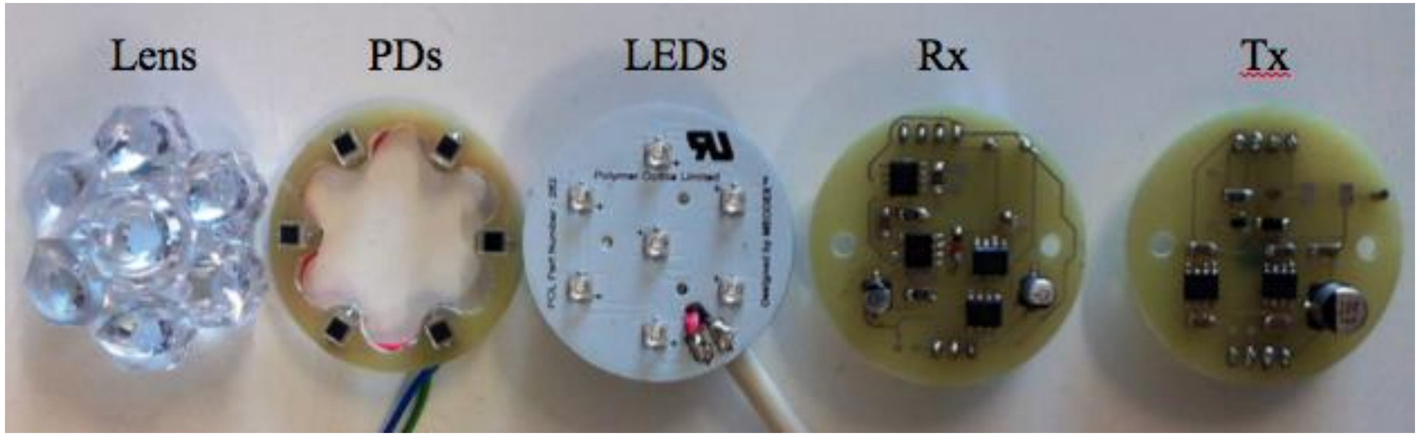
- **Disadvantages**
  - Requirement of line-of-sight
  - Shorter range than acoustics

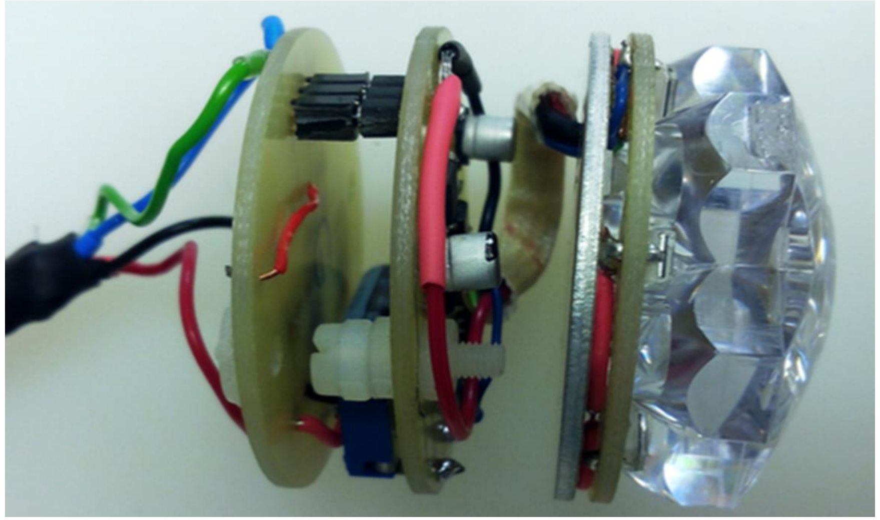
- **Initial interest in the 70's**

- **Renewed interest since 2004:**
  - Focus on links between underwater platforms
  - Autonomous data collection nodes
  - Un-maned vehicle technology
  - Increased need for submarine stealth
  - 100m range with Mbit/s speeds becomes attractive
  - Recent advances in low-cost light sources



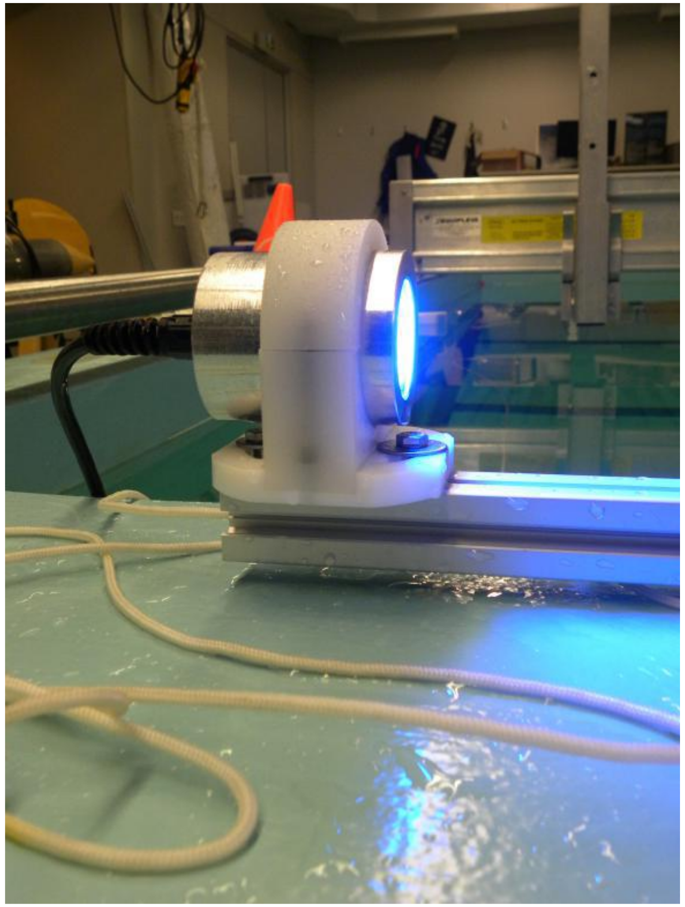
- **Modular implementation**
- **Conductive casing (Aluminium) for thermal dissipation**

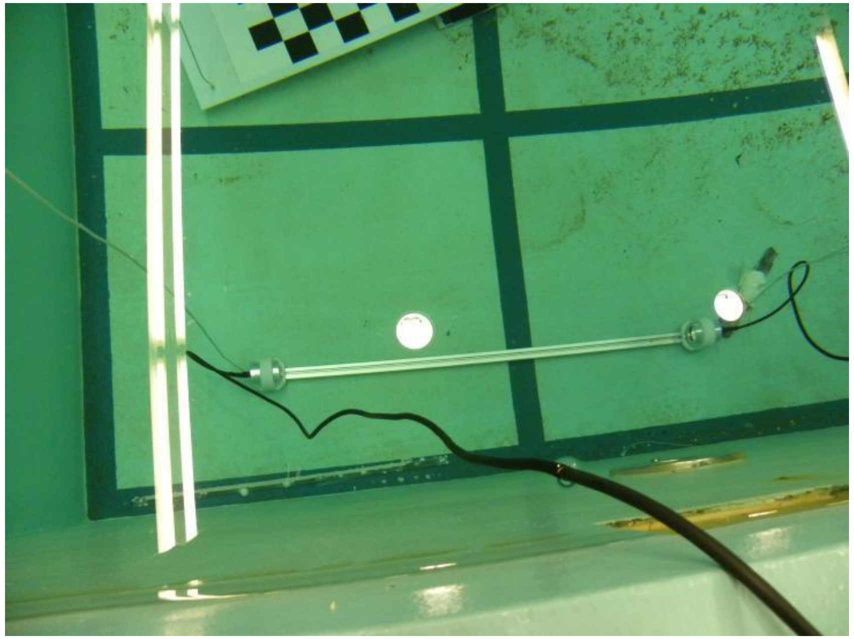


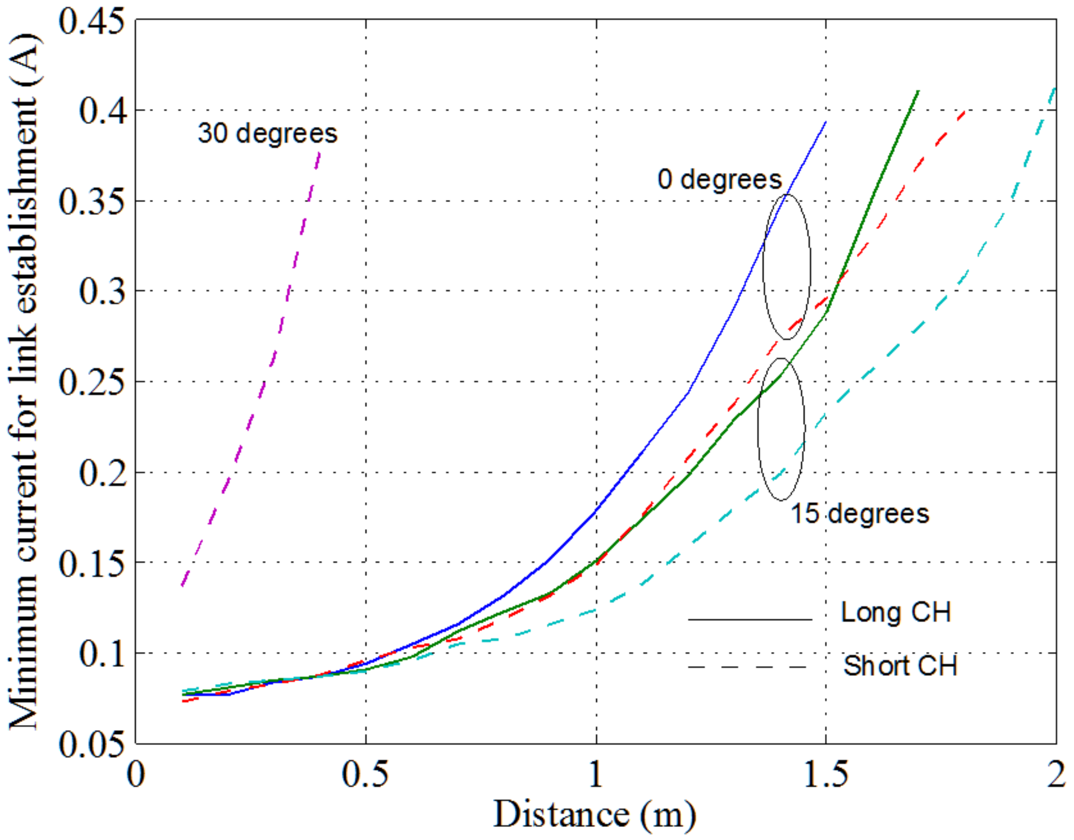
# UNDERWATER OPTICAL WIRELESS

- **3 Mbit/s Datarate**
- **Prototypes mounted on an aluminium profile**
- **Misalignment testing between TX and RX**

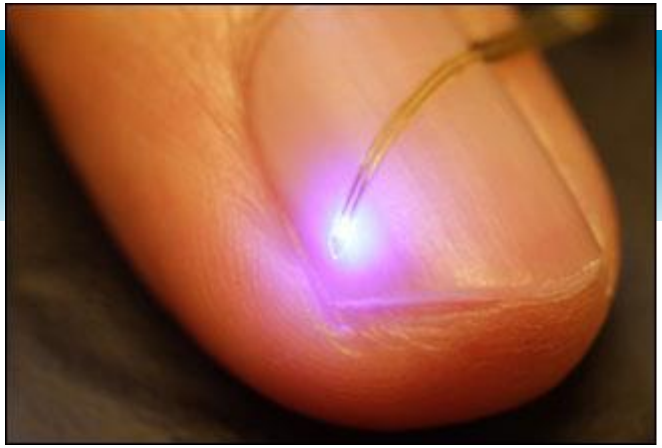




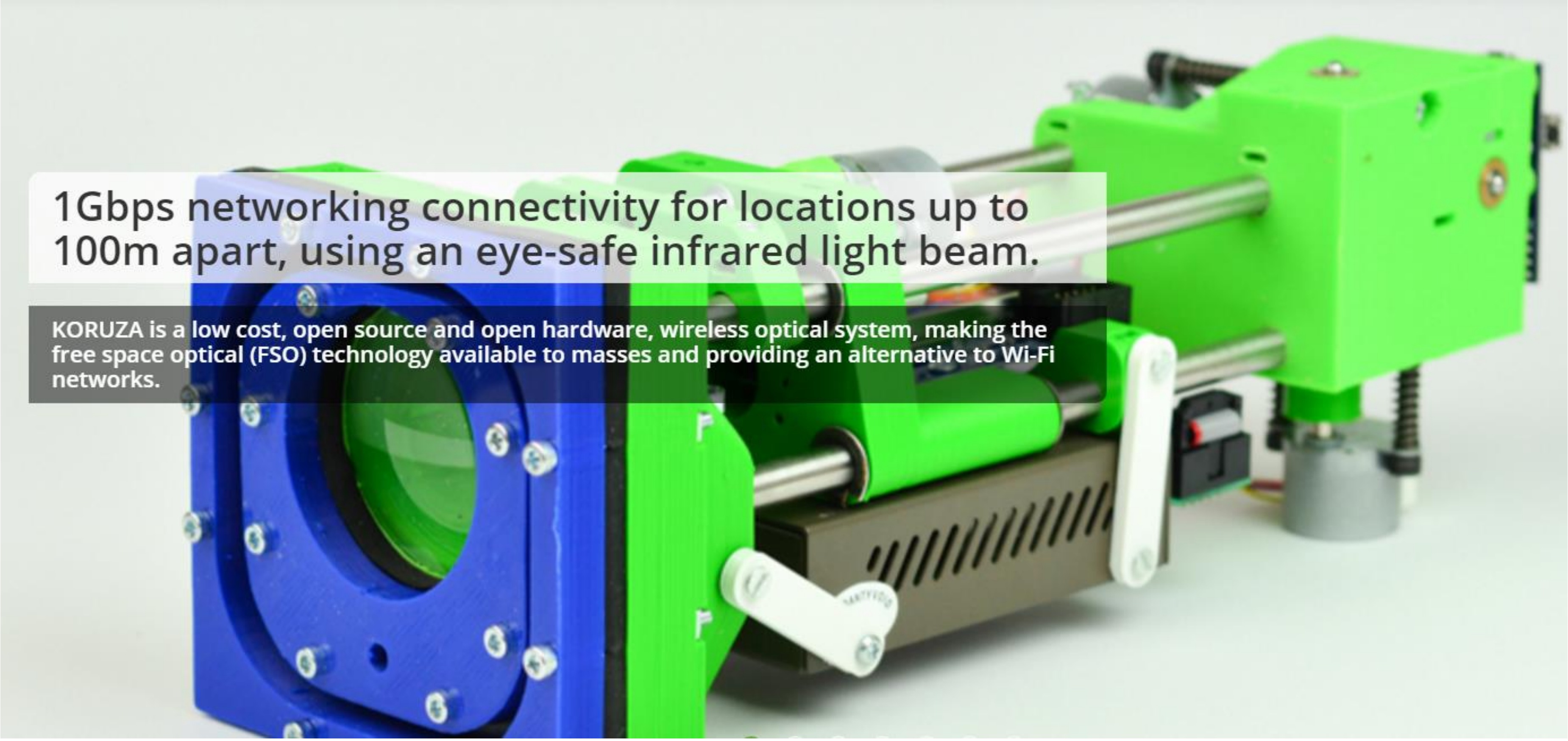
- **Experimental results**



# UNDERWATER OPTICAL WIRELESS



- **Research directions**
  - Micro-LEDs (100’s Mbit/s) … not yet underwater
  - Infrared SFP modules (1Gbit/s) … not yet underwater



# Thank you for your attention!

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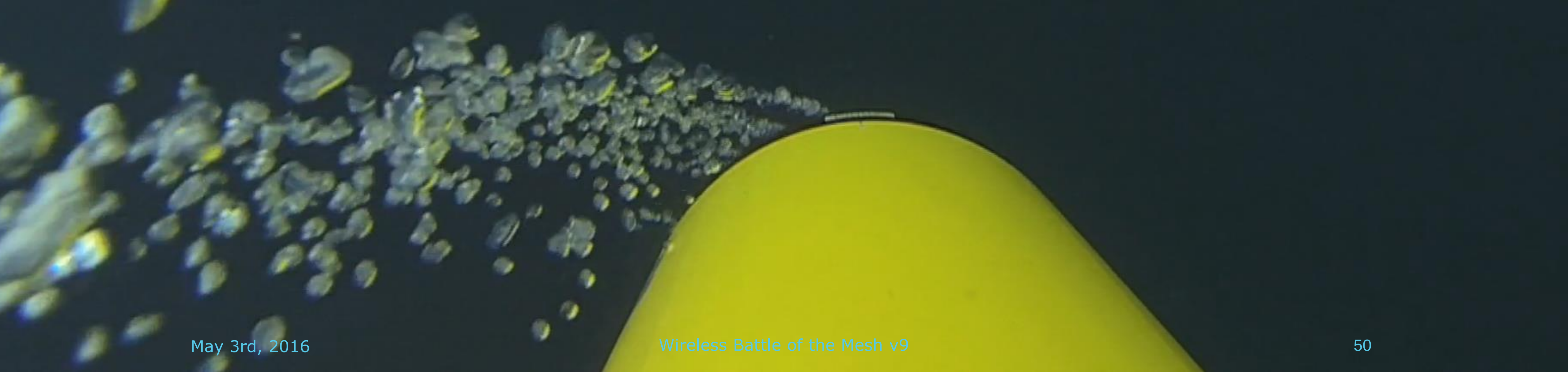

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FROM KNOWLEDGE GENERATION
TO SCIENCE-BASED INNOVATION

- RESEARCH AND TECHNOLOGICAL DEVELOPMENT
- TECHNOLOGY TRANSFER AND VALORISATION
- ADVANCED TRAINING
- CONSULTING
- PREINCUBATION OF TECHNOLOGY-BASED COMPANIES

# Underwater electromagnetic communication and power transfer technologies

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