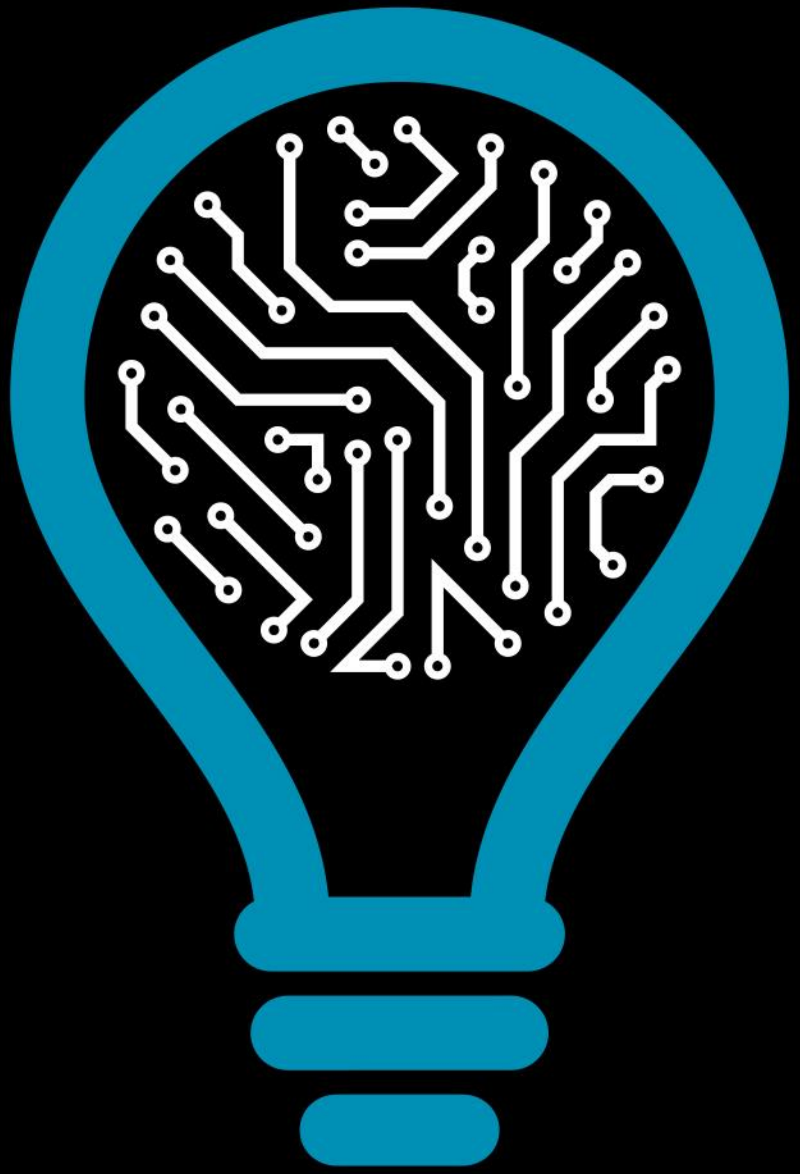
Underwater localization of acoustic sources – principles and approaches

Bruno Ferreira

Center for Robotics and Autonomous Systems, INESC TEC

Breaking the Surface,
Biograd Na Moru, Croatia
Sept. 29th, 2022



INESCTEC
INSTITUTE FOR SYSTEMS
AND COMPUTER ENGINEERING,
TECHNOLOGY AND SCIENCE

Outline

1. **Overview of most common principles in acoustic localization**
2. Source localization – glider search
3. BTS localization challenge

Beacon based localization - the basics

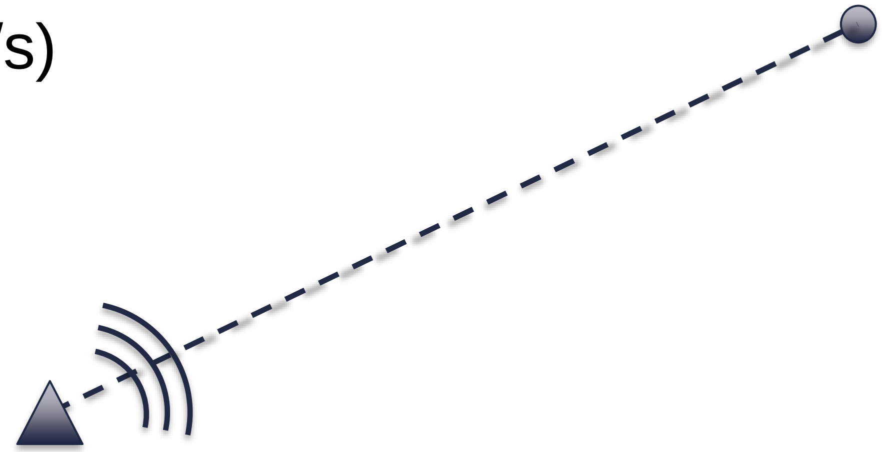
Beacon - an emitter transmitting a known signal

Receiver - an acoustic sensor listening to signals

Time-of-arrival - the instant of time that the known signal has been detected

Common assumptions on sound propagation:

- Constant velocity ($c \approx 1500$ m/s)
- Propagates spherically



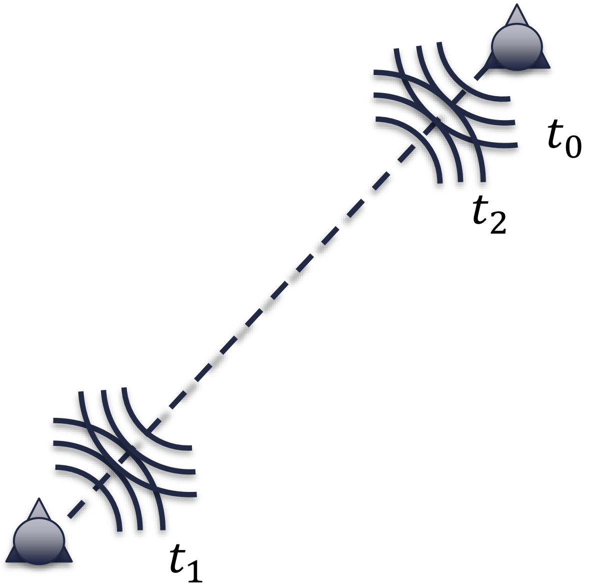
Pseudo-ranging

One-way travel time (OWTT) (synchronous):

- **Transmission time:** $\boldsymbol{t_0}$
- **Range:** $\boldsymbol{r = c \cdot (t_a - t_0)}$
- Only requires **one emitter**

Two-way travel time (TWTT):

- Requires **emission** and **reception** at two nodes
  1. B1 emits at $\boldsymbol{t_0}$
  2. B2 receives and replies back at $\boldsymbol{t_1 = t_0 + \frac{r}{c} + \Delta}$
  3. B1 receives at $\boldsymbol{t_2 = t_0 + 2\frac{r}{c} + \Delta}$
- Range estimated at B1: $r = \left(\frac{t_2 - t_0 - \Delta}{2}\right) \cdot c$



INESCTEC

2022 25.09. - 2.10. Biograd na Moru, Croatia
BREAKING THE SURFACE
14th International Interdisciplinary Field Workshop of Maritime Robotics and Applications

Bearing

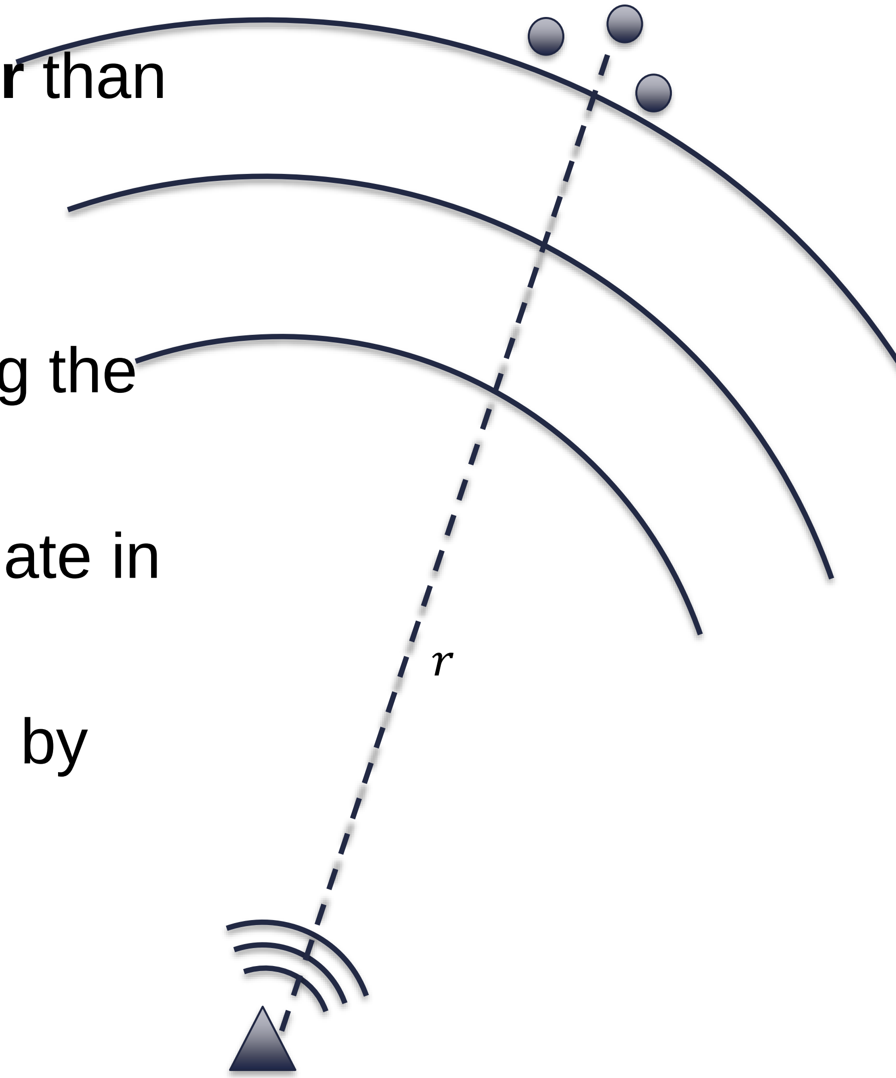
Distance between receivers is much **smaller** than slant range $\boldsymbol{r}$

- The wave is approximately planar

Time-differences-of-arrival enable estimating the direction-of-arrival (bearing)

- 4 sensors are needed to fully disambiguate in 3D

A **relative position estimate** can be obtained by combining **bearing with pseudo-range**



Bearing

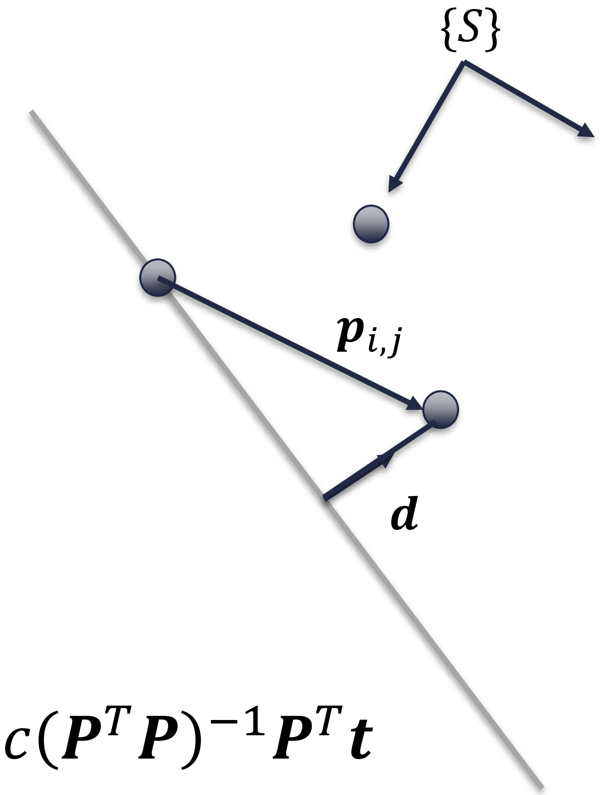
TDoA between receivers i and j

$$t_{i,j} = \frac{1}{c}\boldsymbol{d} \cdot \boldsymbol{p}_{i,j}, \qquad i \neq j$$

Writing in matrix form

$$\underbrace{\begin{bmatrix} \boldsymbol{p}_{1,2}^T \\ \boldsymbol{p}_{1,3}^T \\ \vdots \\ \boldsymbol{p}_{N-1,N}^T \end{bmatrix}}_{\boldsymbol{P}} \cdot \boldsymbol{d} = c \underbrace{\begin{bmatrix} t_{1,2} \\ t_{1,3} \\ \vdots \\ t_{N-1,N} \end{bmatrix}}_{\boldsymbol{t}}$$

$$\boldsymbol{d} = c(\boldsymbol{P}^T\boldsymbol{P})^{-1}\boldsymbol{P}^T\boldsymbol{t}$$



Multi-lateration – long baseline

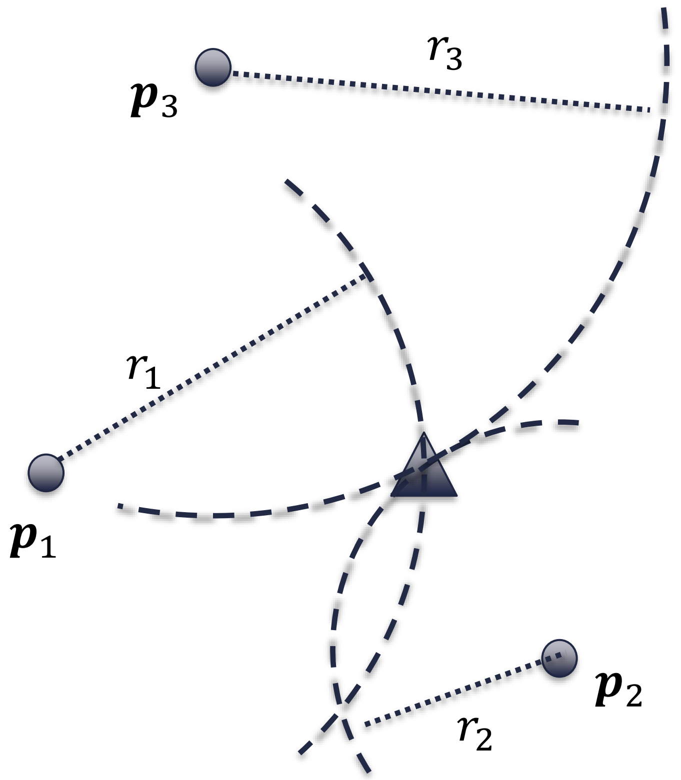
Position estimate given by the **intersection** of spheres with radii r_i and centers $\boldsymbol{p}_i$

When **multiple receivers (tracking)** are available

- 2 receivers: ambiguity
- **3 non-colinear** receivers are needed to **disambiguate** in 2D
- **In 3D, 4 receivers** are needed to **fully disambiguate** the position

The **inverted configuration (self-localization)** is also possible

- Beacon -> receiver
- Receiver -> beacon



Multi-lateration – synthetic baseline

Assumptions

- The **emitter is static**
- The **receiver** is **mobile** and can measure **pseudo-range**

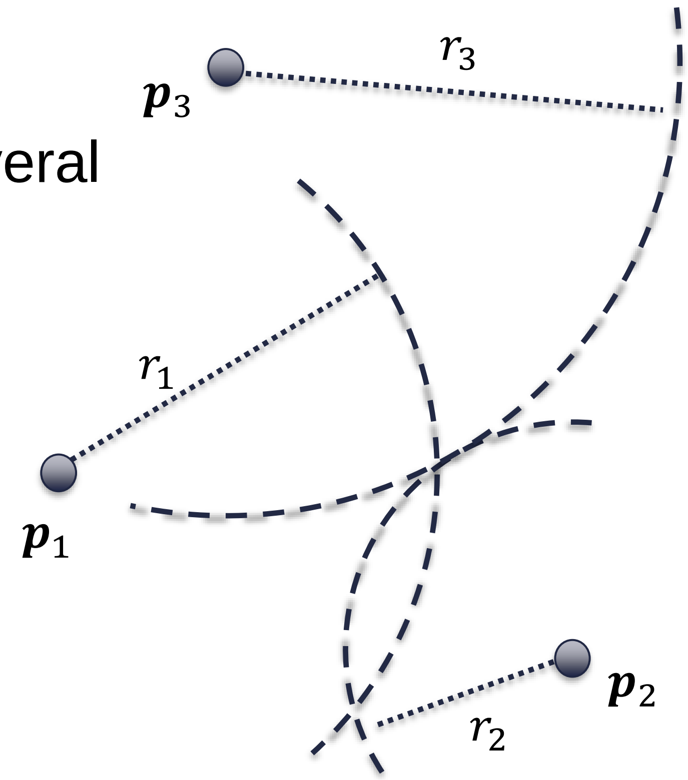
Principle: receiver measures pseudo-ranges at several locations

Advantages

- Minimalistic deployment of receivers

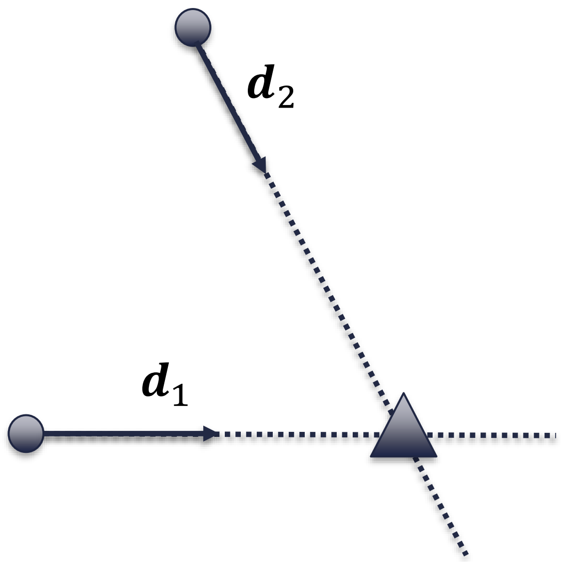
Disadvantages

- Unsuitable for mobile emitter
- (receivers must move much faster than the emitter)



Range-free localization – triangulation

Measure bearing at multiple locations and compute the **intersection** of lines passing through $\boldsymbol{p}_i$ with direction $\boldsymbol{d}_i$.

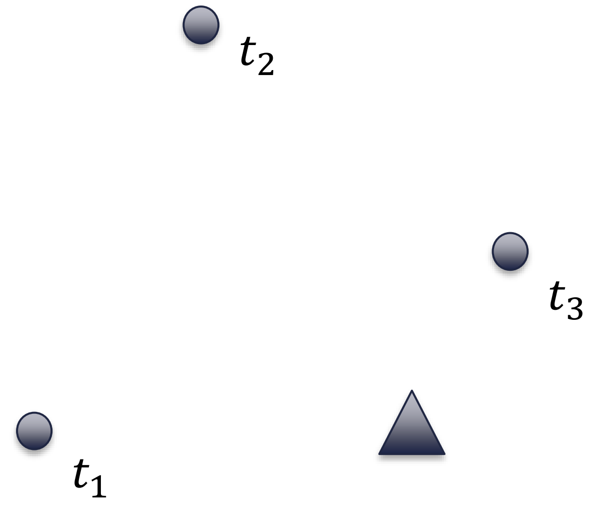


Range-free localization – ToA-only

Measure ToA, t_i, at several locations, $\boldsymbol{p}_i$

$$t_i = \frac{||\boldsymbol{p}_i - \boldsymbol{p}_T||}{c} + t_0$$

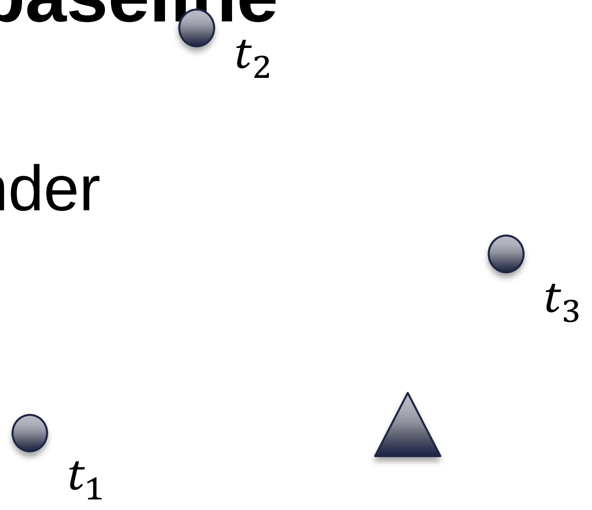
with $\boldsymbol{p}_T$ and t_0 being **unknown**.



With $\boldsymbol{N} > \boldsymbol{4}$ **measurements** (in 3D), we can estimate the emitter position employing a least-square error approach

$$\{\hat{\boldsymbol{p}}_T, \hat{t}_0\} = \boldsymbol{argmin}_{\{\boldsymbol{p}_T, t_0\}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{N}} \left((t_i - t_0) - \frac{||\boldsymbol{p}_i - \boldsymbol{p}_T||}{c} \right)^2$$

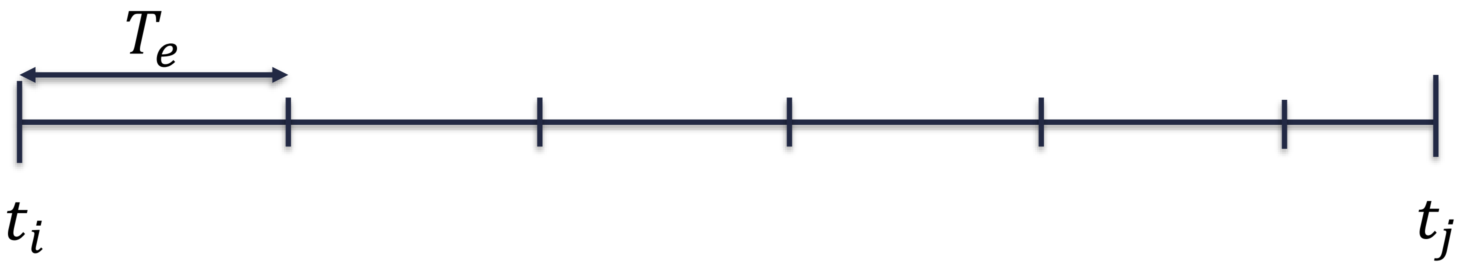
Range-free localization – ToA-only synthetic baseline



The **synthetic baseline** approach can be employed under the **assumption of periodic emission**, with period T_e

$$t_i = \frac{||\boldsymbol{p}_i - \boldsymbol{p}_T||}{c} + t_0 + N_e T_e$$

If T_e is known, then $N_e = floor\left(\frac{t_j - t_i}{T_e}\right)$ is the number of integer periods that fit between t_i and t_j



$$\frac{||\boldsymbol{p}_i - \boldsymbol{p}_T||}{c} < T_e$$

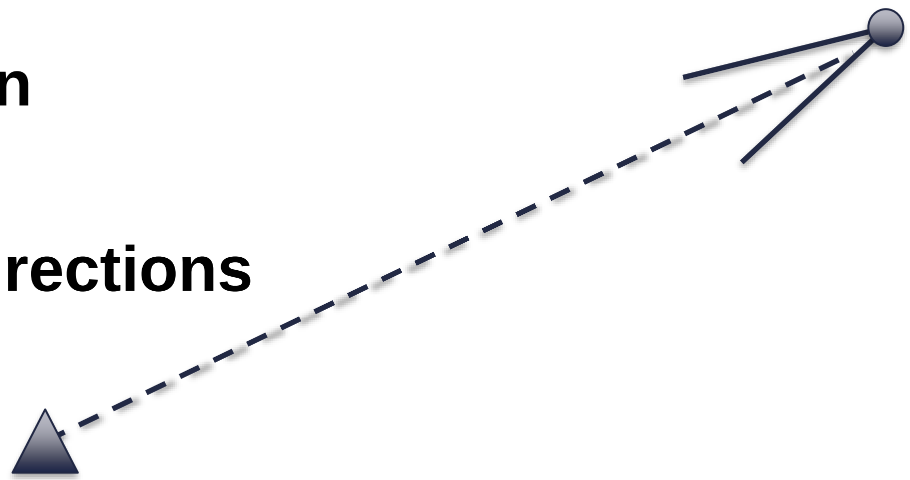
Other approaches

Received Signal Strength (RSS)

- Relies on acoustic attenuation models
- Less accurate than pseudo-ranging

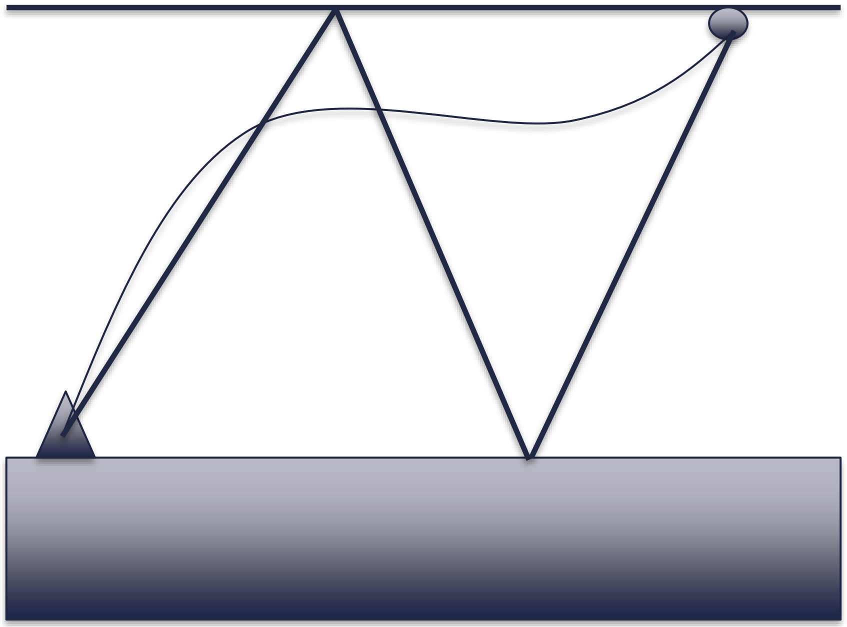
Directional hydrophones

- Strong attenuation of signal when direction of arrival
- Requires scanning of possible directions
- Less accurate than USBL



Non-ideal acoustics

- Under temperature/density variations, the wave front does not travel linearly
  - Pseudo-range and bearing become erroneous
  - May create shadow zone for direct path
- Multipath
  - Originates multiple detections



Outline

1. Overview of most common principles in acoustic localization
2. **Source localization – glider search** [1,2]
3. BTS localization challenge

[1] Bruno Ferreira, Paula Graça, José Alves, Nuno Cruz, “**Single receiver underwater localization of an unsynchronized periodic acoustic beacon using synthetic baseline**”, submitted to IEEE Journal of Oceanic Engineering, June, 2022.
[2] Bruno Ferreira, José Alves, Nuno Cruz, Paula Graça. “**On the localization of an acoustic target using a single receiver**”, to appear, IEEE/MTS OCEANS 2022, Hampton Roads, VA, USA.

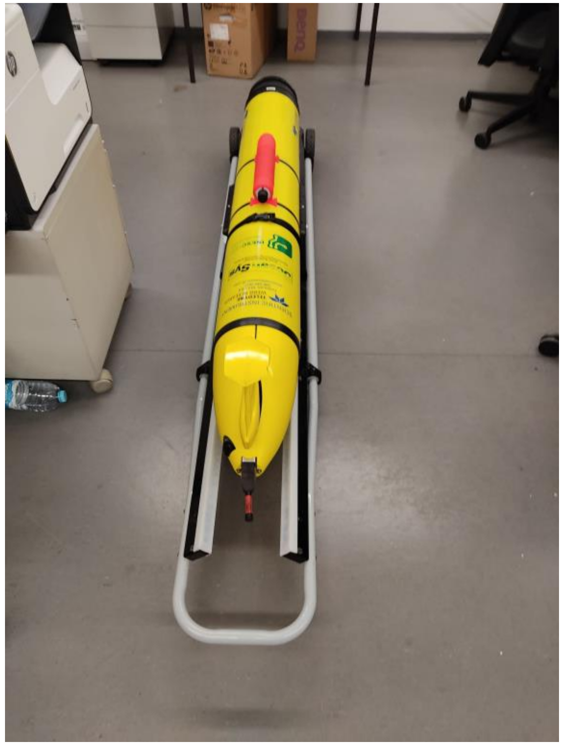
Glider operation – what did we know?

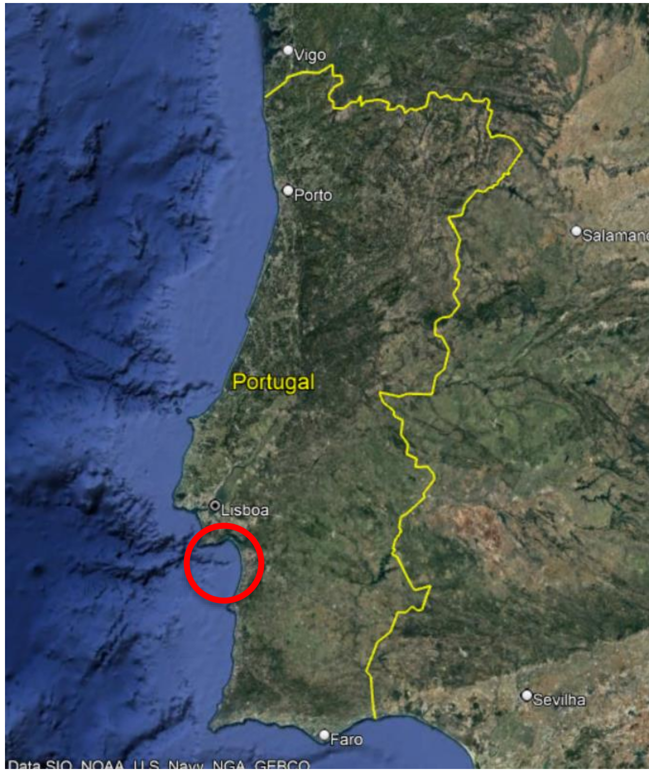
Teledyne Slocum equipped with

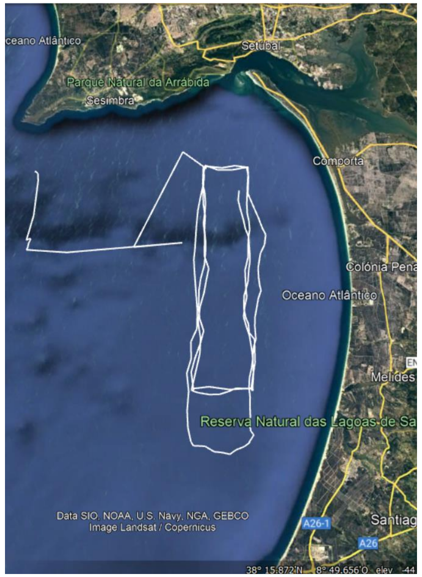
- Acoustic recorder
- CTD
- Dissolved oxygen
- Fluorescence
- **Acoustic pinger**

Operation

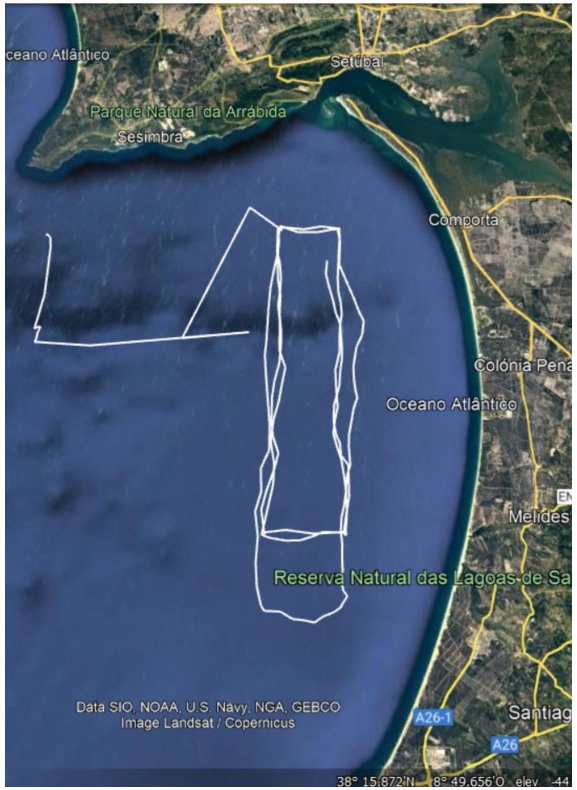
- South of Sesimbra
- 12-days long successful operation







Glider operation - planned recovery



Planned recovery

1. Go to a specified point (navy)
2. Go to surface
3. Wait 10min at surface
4. Submerge for 1h
5. Repeat from 2.

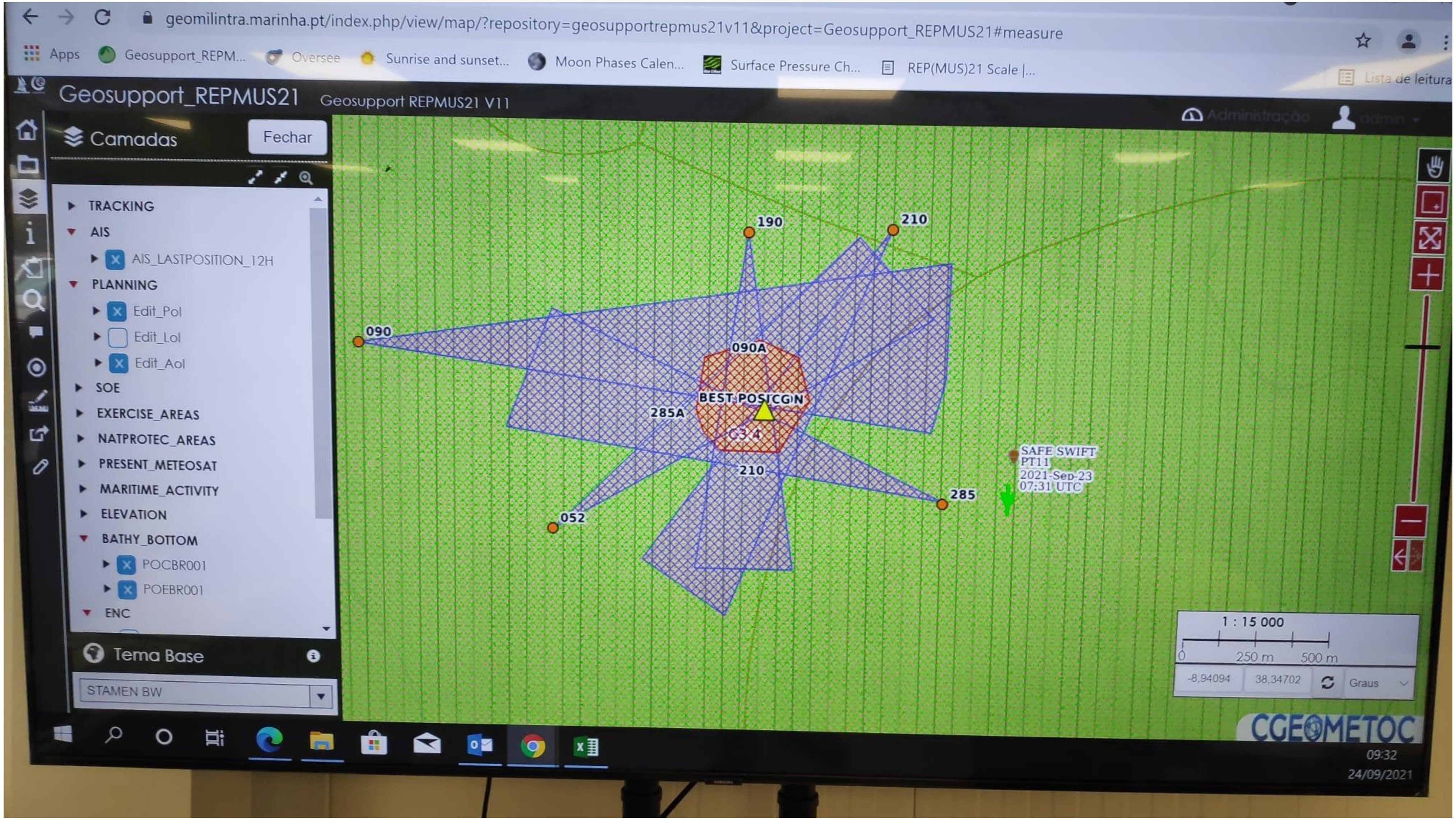
Facts

- Successfully reached the point
- Communicated last time on early afternoon of September 23, 2021.
- Did not surface anymore

Doubts

- Sunk, on the bottom?
- Caught in ghost fishing net?

First reference point



Step #1 – coarse localization

Objectives

- Ensure that the glider was in the area
- Obtain a coarse location estimate

Localization approach: **triangulation**

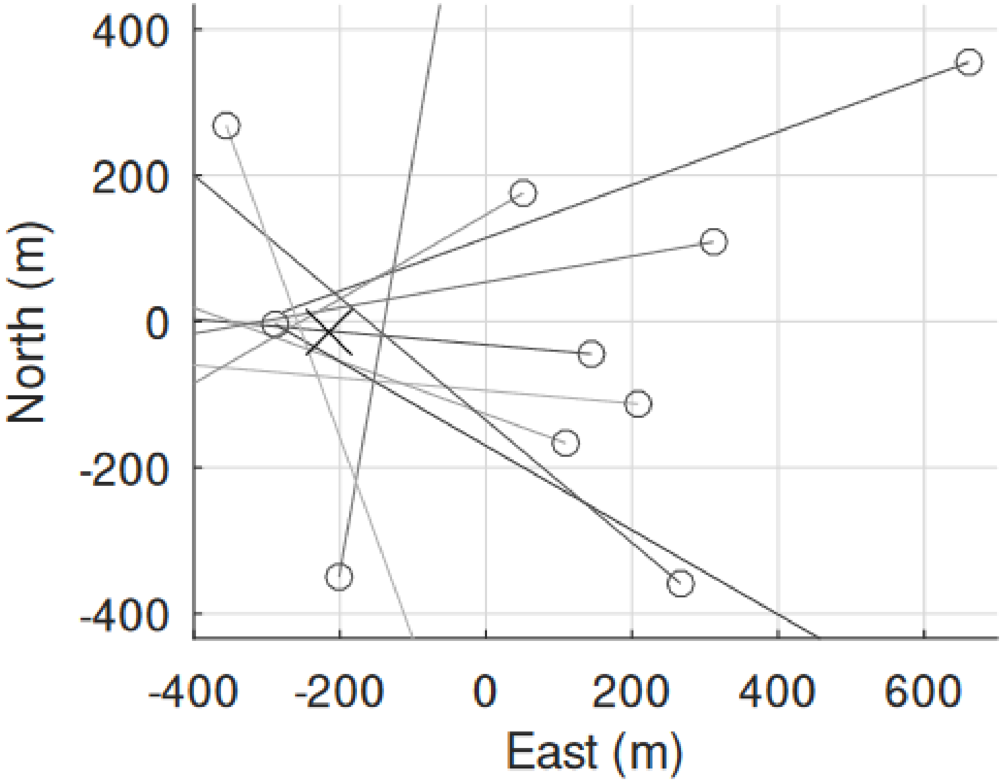
- Manually directing the hydrophone
- Estimate the direction based on sound amplitude
- Compute intersection of lines

Drawbacks

- Practically impossible to estimate depth

Step #1 – coarse localization

First estimate: $p_T^1 = [-15, -215, ?]$



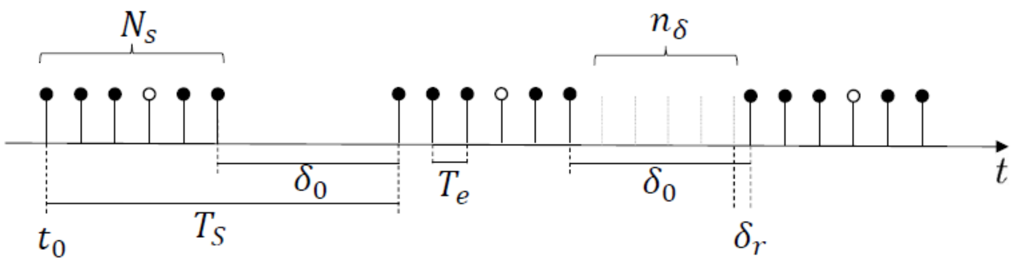
Options for recovery

	Divers	ROV
Pros	Agility, dexterity Versatility Faster (scooters) Simpler logistics	Higher depths No human life at risk Can stay longer Can cover larger areas
Cons	Limited depth Very limited time of operation Lower cost Human life at risk Small coverage (area <40m radius)	Large logistics Higher cost Slower than divers Work-class ROV required Preparation time

Strong requirement on localization!

- Divers cannot cover areas larger than circles with 30-40m of radius @~100m

Glider search

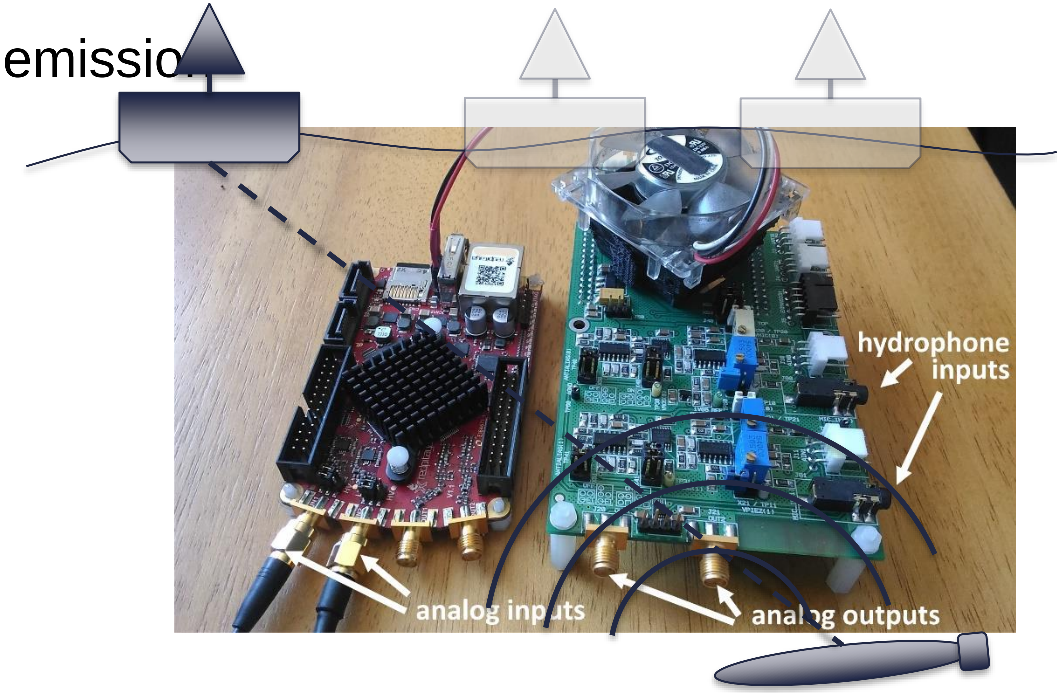


INESC TEC's localization solution

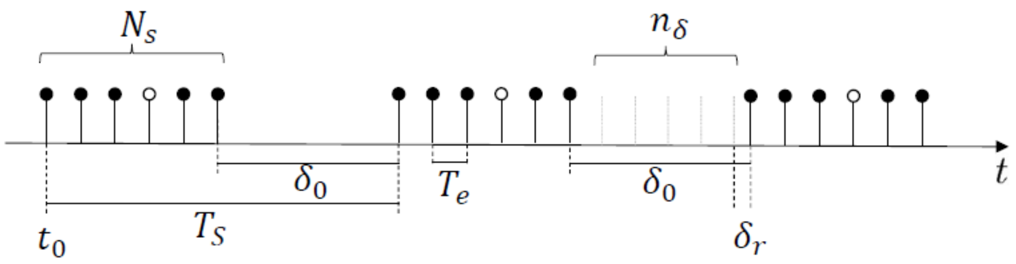
- **Synthetic baseline with ToA**-only measurements
  - Acquire timestamped and geolocalized acoustic signal to detect times-of-arrival at the surface
  - Estimate 3D coordinates and time of emission

Developments

- Specific hardware to acquire
  - ADC @ 250kSps
- Signal processing
- Outlier rejection
- Estimation

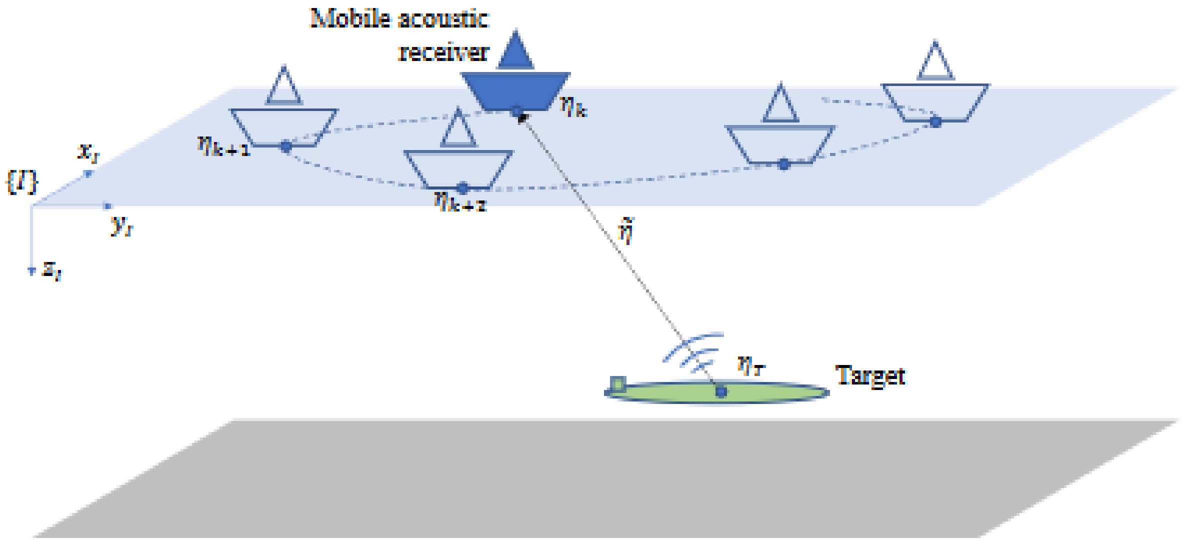


Localization strategy



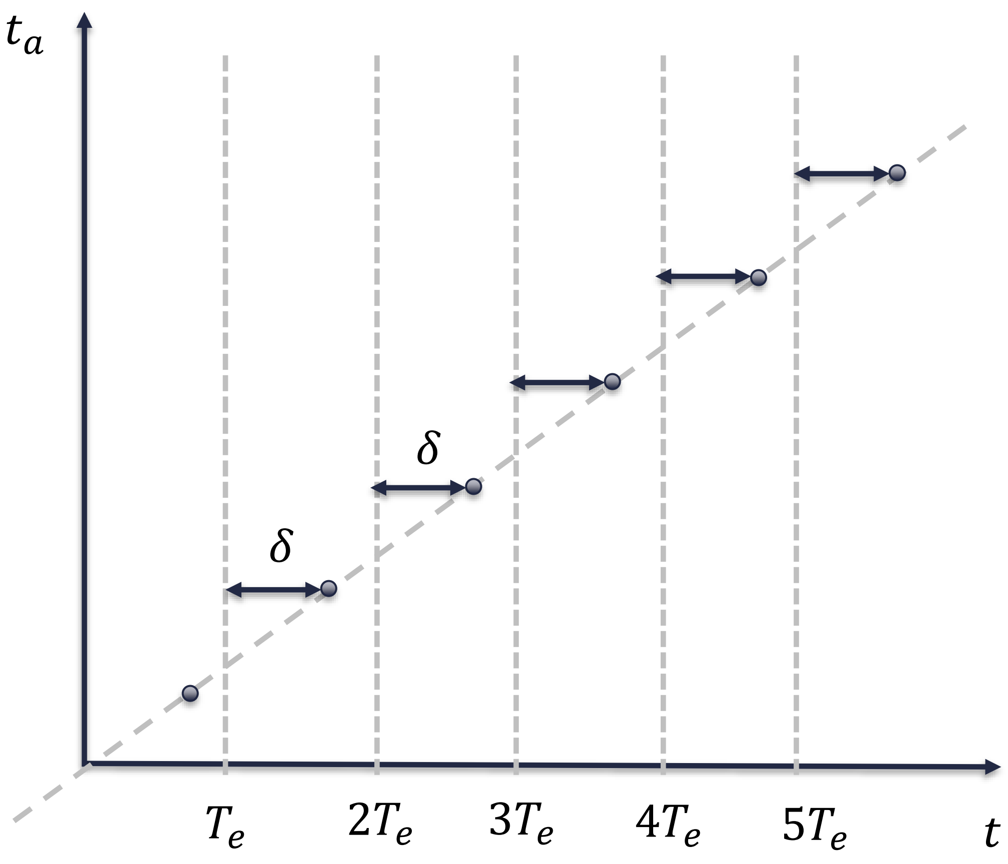
Recall from Synthetic Baseline ToA

$$t_i = \frac{||\boldsymbol{p}_i - \boldsymbol{p}_T||}{c} + t_0 + N_e T_e$$

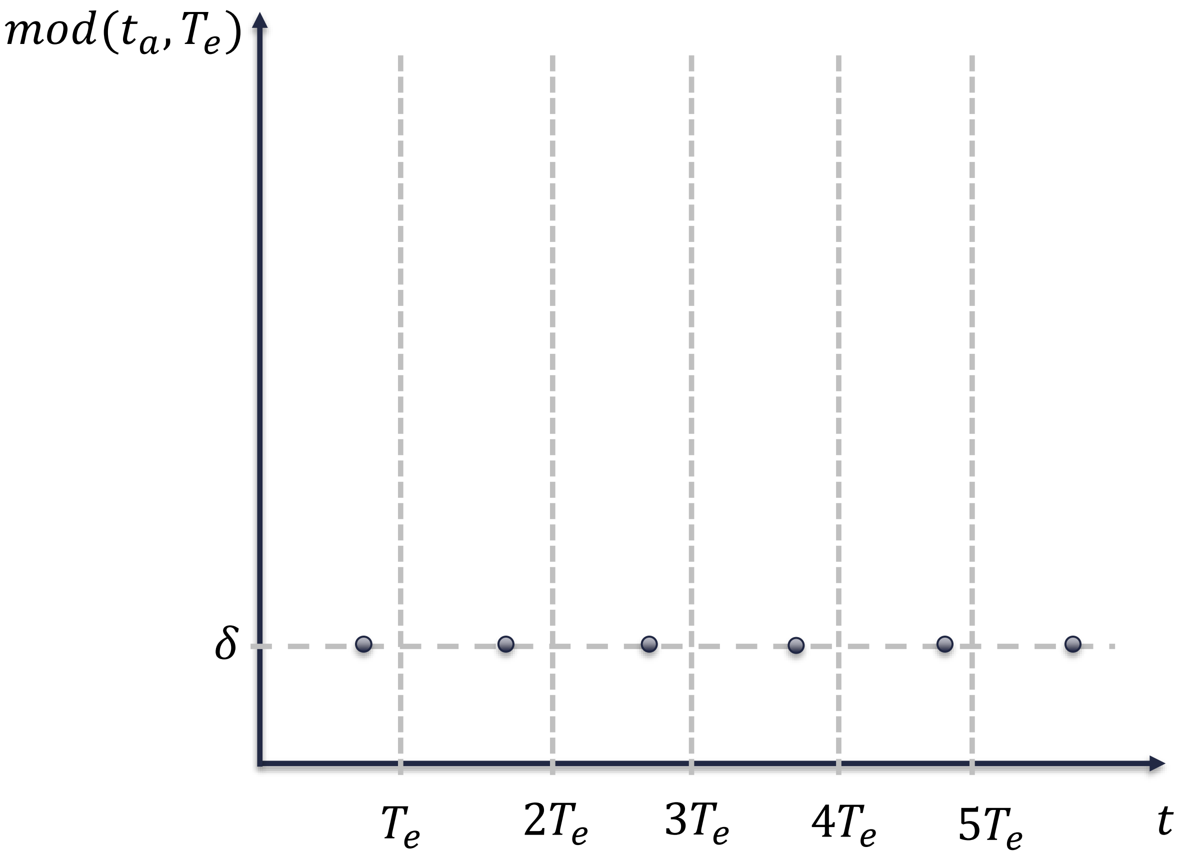


ToA candidates – main ideas

Time of arrival

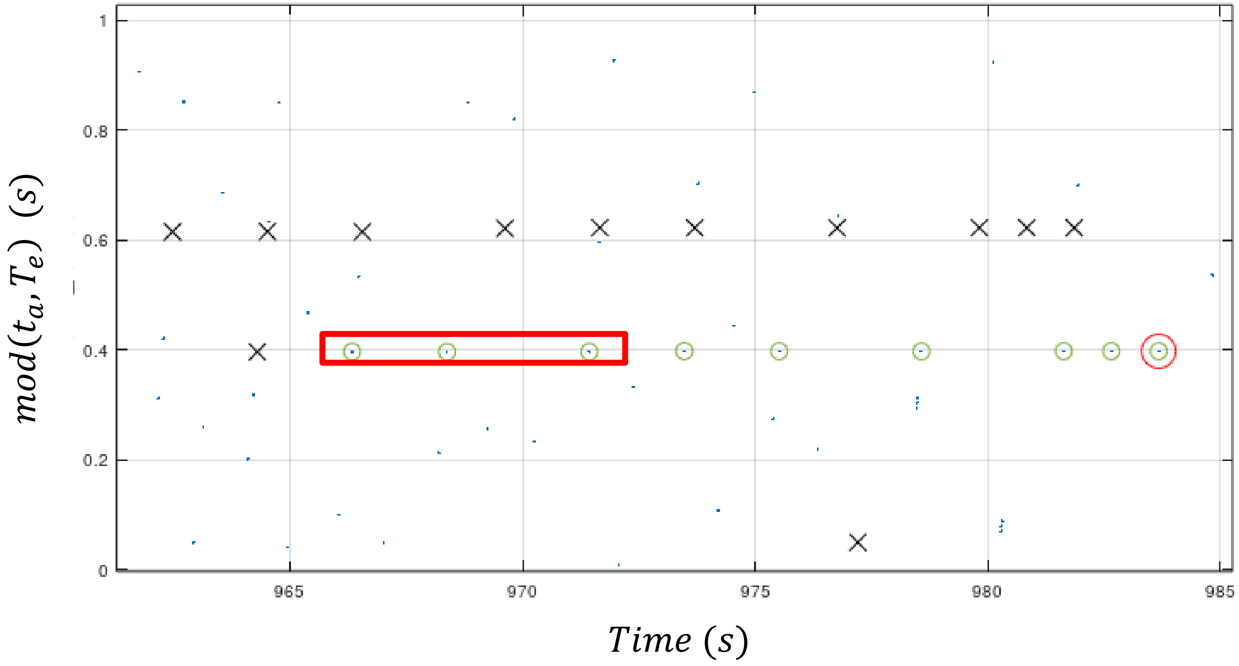


Remainder after division by T_e



Clustering and outlier rejection

1. Group measurements based on their distances in the space $\{t_a, mod(t_a, T_e)\}$
2. Reject small groups
3. Reject groups that arrive “just after” (multipath)



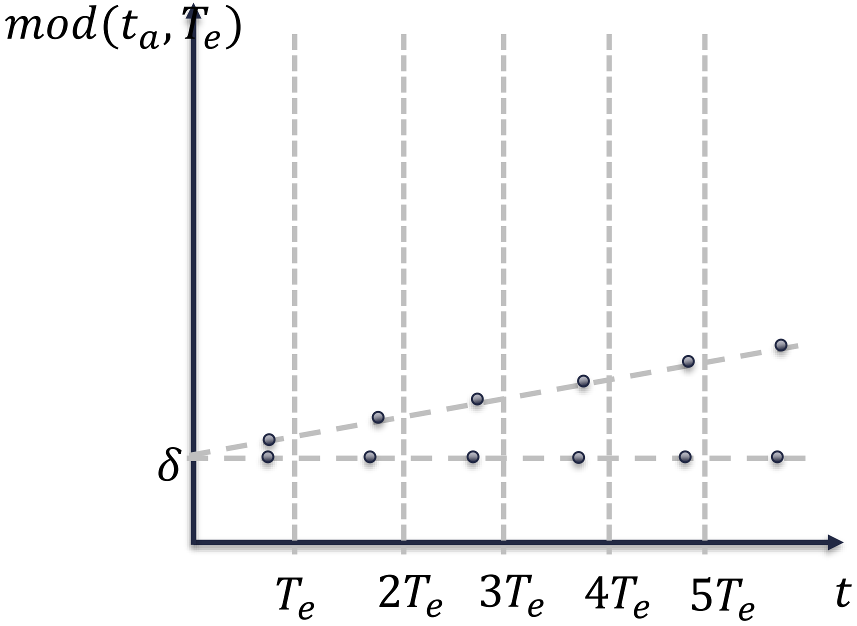
Drift compensation

Pinger internal clock may **offset up to 100ppm**

- Over **1h,** it is the **equivalent** to sound travelling **540m!**

Assumptions

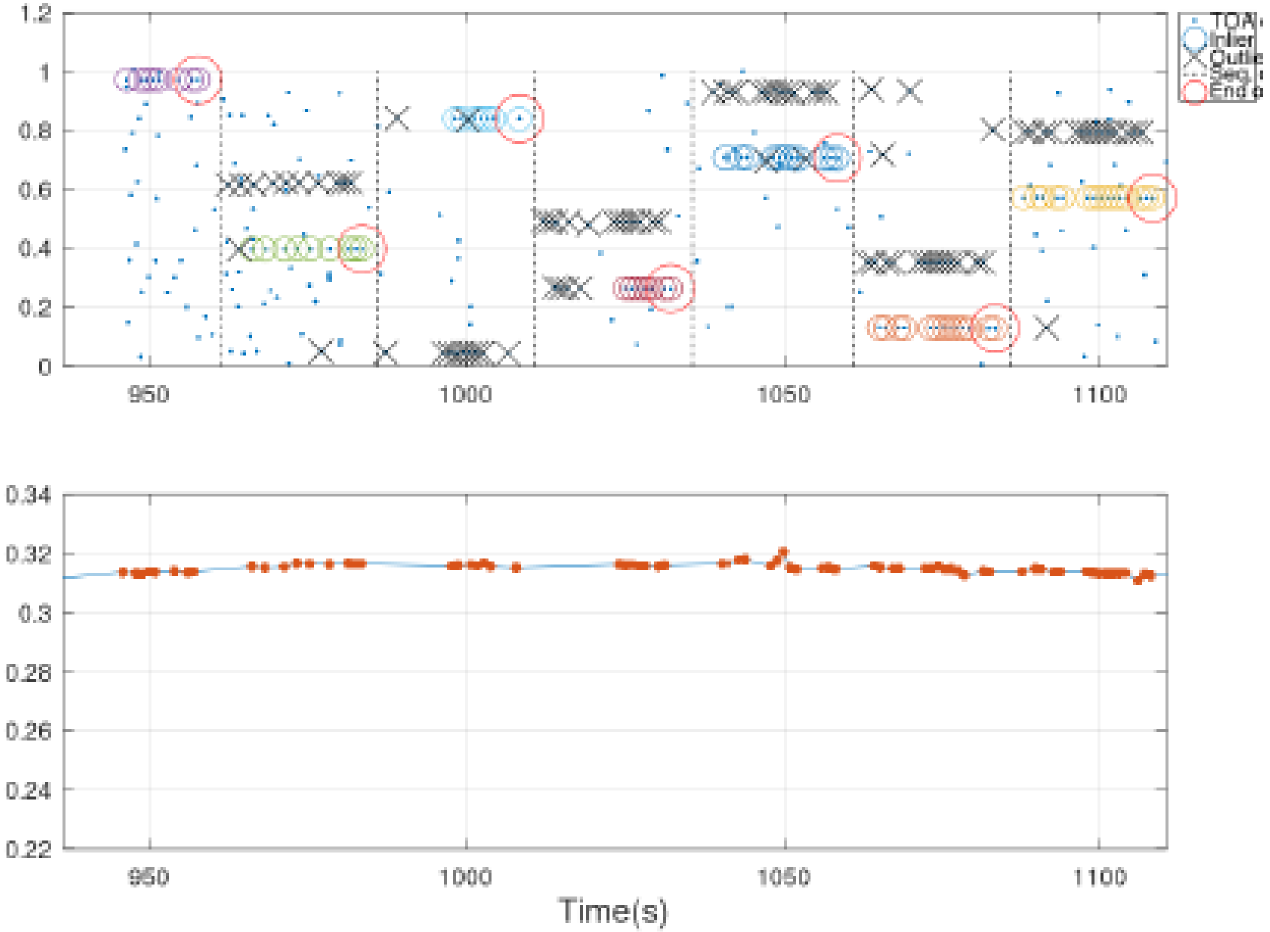
- The **offset** remains **constant** over short periods of time (few hours)



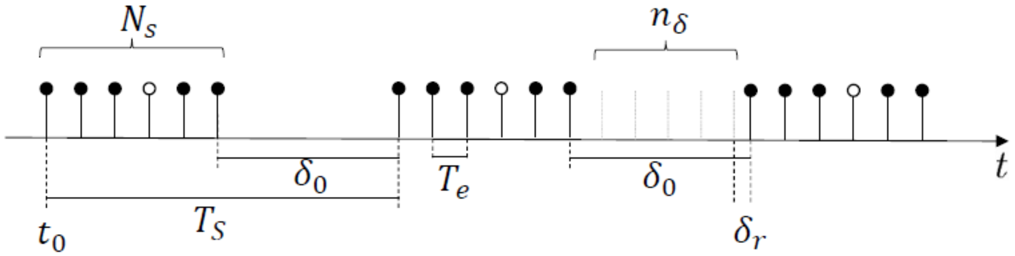
Solutions

1. Remain at the same location for sufficiently long time and estimate the drift
2. Visit the same location at least twice

Clustering and outlier rejection

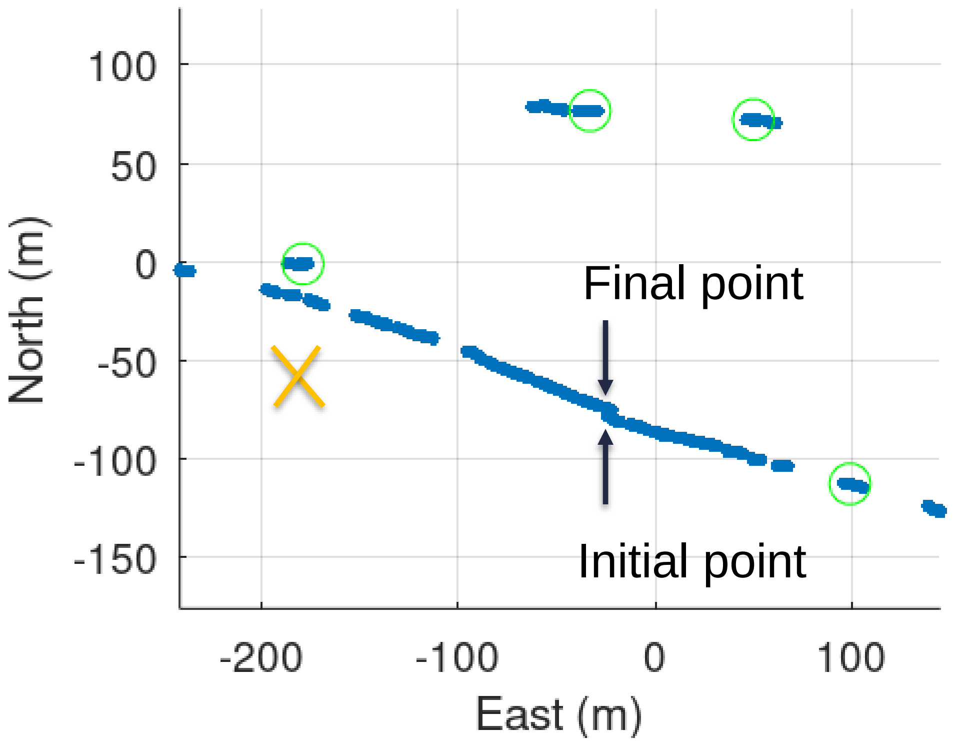


Time(s)



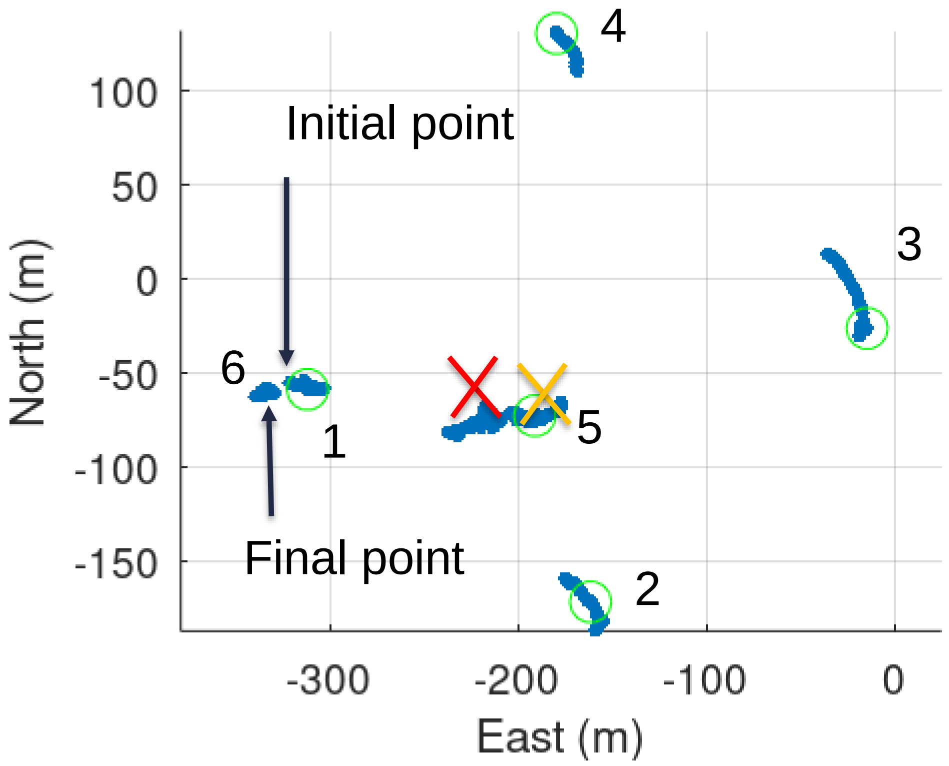
Synthetic baseline – placement of receiver

First attempt to estimate using ToA synthetic baseline



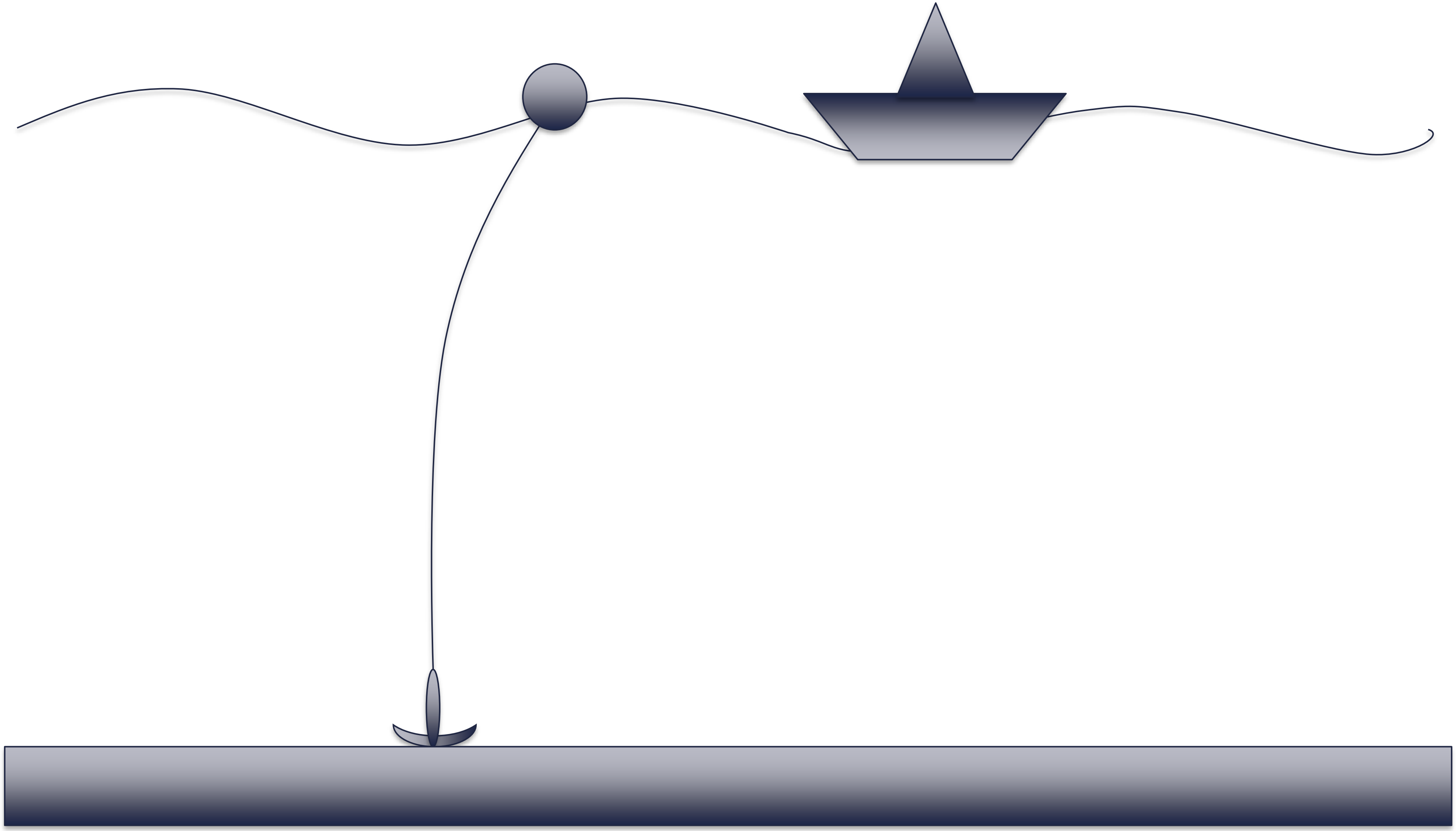
$$\widehat{\boldsymbol{p}}_T^2 = [-65, -186, 104]^T$$

Refinement of position estimate



$$\widehat{\boldsymbol{p}}_T^3 = [-61, -221, 114]^T$$

Rescue operation – preparation



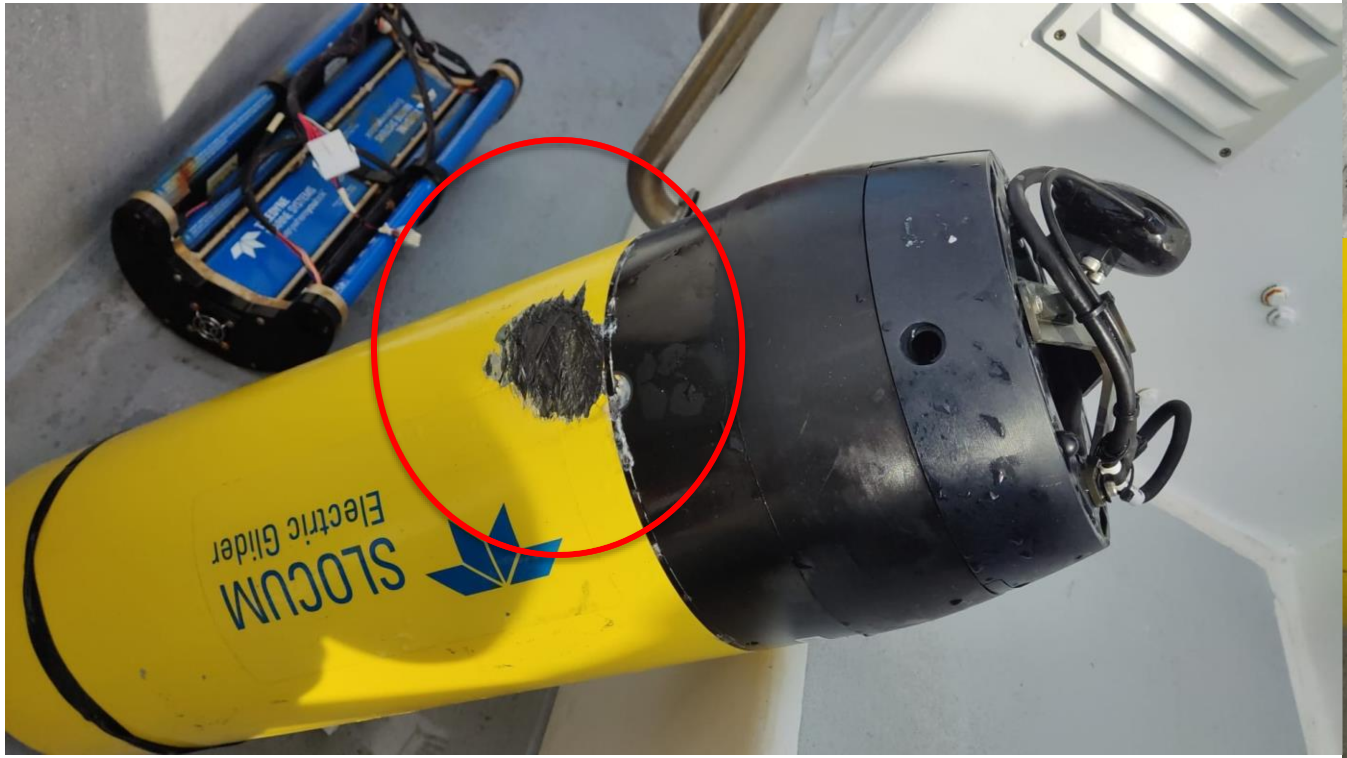
Diving operation

Glider “recovery”

INESCTEC

2022 25.09. - 2.10.
BREAKING THE SURFACE

Glider “recovery” (2)



The suspect

Conclusions

Multiple solutions are possible for **localization of acoustic sources**

- The adopted solution is not optimal but **enabled rapid deployment**

When compared with imaging sonar, the **beacon-receiver** approach can be **more effective**

- The ambiguity of multiple detections is reduced/removed
- The range is larger

Precision/accuracy of localization **depends on placement** of sensors

Outline

1. Overview of most common principles in acoustic localization
2. Source localization – glider search
3. **BTS localization challenge**

The BTS localization challenge – where's the pinger?

An acoustic pinger will be deployed within a specified area (to be announced)

- **Periodic pings every ~30s**

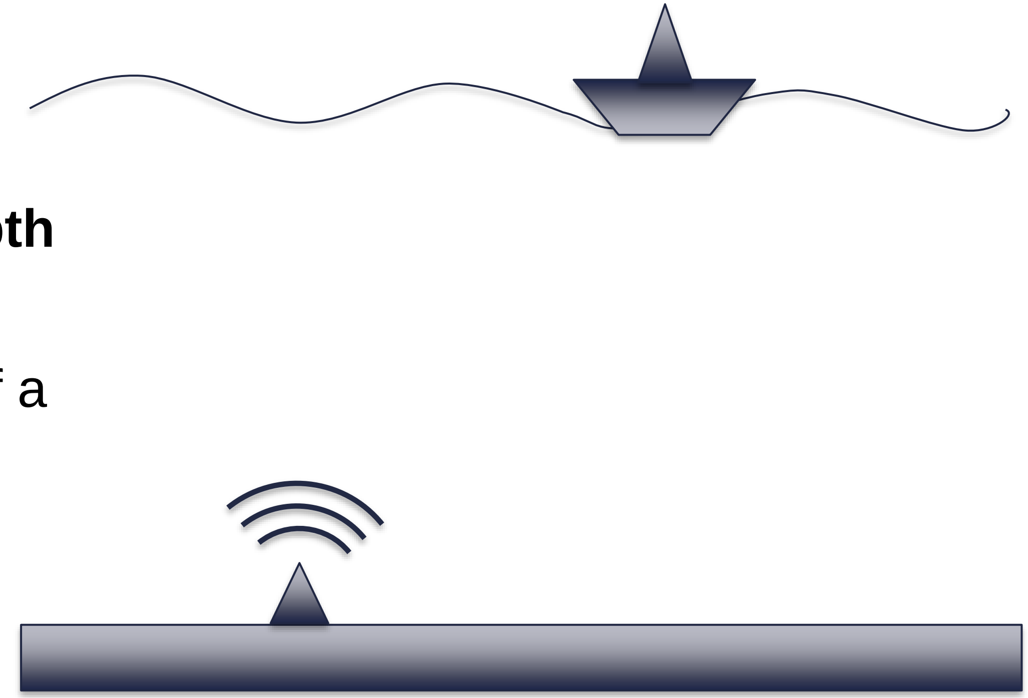
The teams will **compete to find its position**

Each team will have

- **Access to 3 acoustic receivers.** Each receiver provides **times-of-arrival, depth** and **ID of detections**
- **A maximum of 2 hours** of operation of a support boat (order defined randomly)

Geolocalization and orientation must be ensured by the contestant (if needed)

The localization approach is free



The BTS challenge

Contestant must provide (deadline to be announced)

- Latitude and longitude of pinger position

Score:

- Accuracy of the estimate (Euclidean distance)

More information on equipment and guidance on tutorial 6, by Roee Diamant

Thank You for your Attention!

Questions?

Comments?

Bruno Ferreira

bruno.m.ferreira@inesctec.pt

$$\min_{p_T} \sum_{i=1:N} \left(r_i - ||p_i - p_T||\right)^2$$