# Bayesian localization of sperm whales off SW Crete*

E.K. Skarsoulis

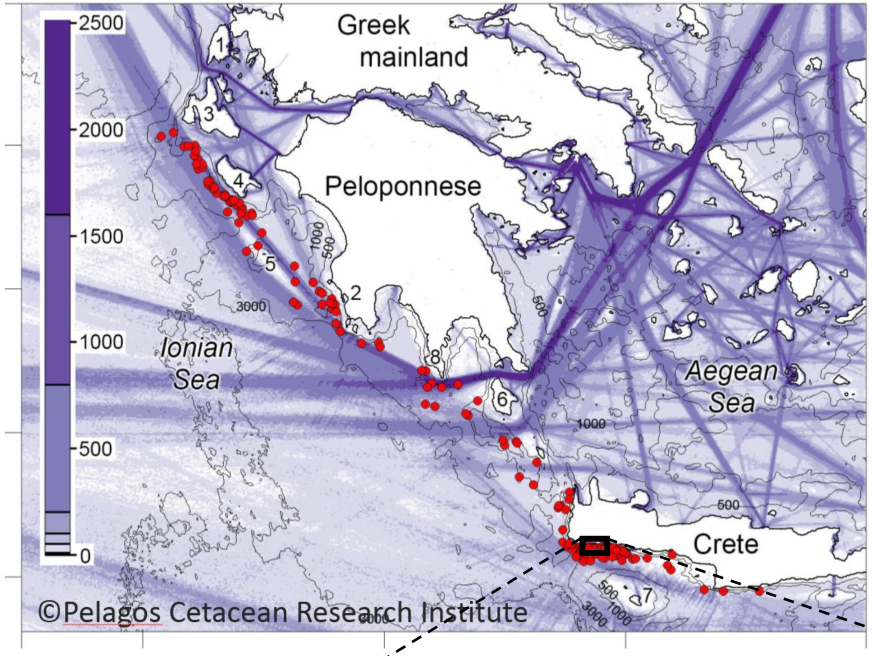
FOUNDATION FOR RESEARCH AND TECHNOLOGY – HELLAS
INSTITUTE OF APPLIED AND COMPUTATIONAL MATHEMATICS

* *Work carried out in the framework of the SAvE Whales project funded by* ocean care

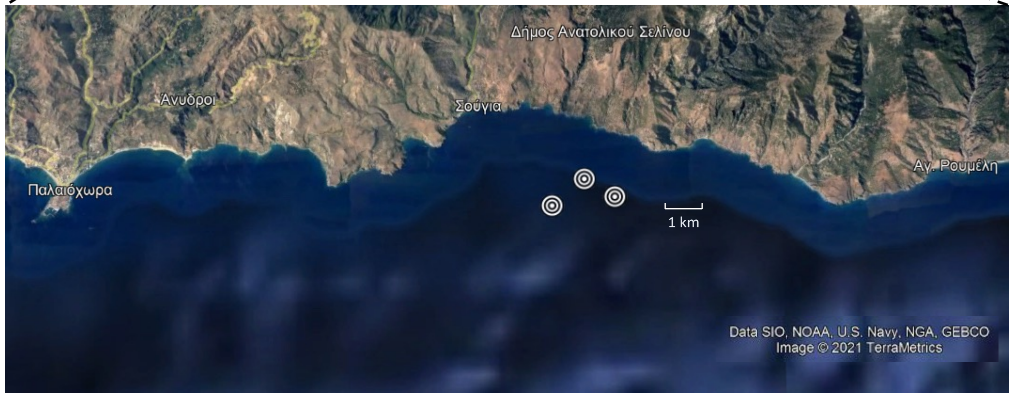
# SAvE Whales

+

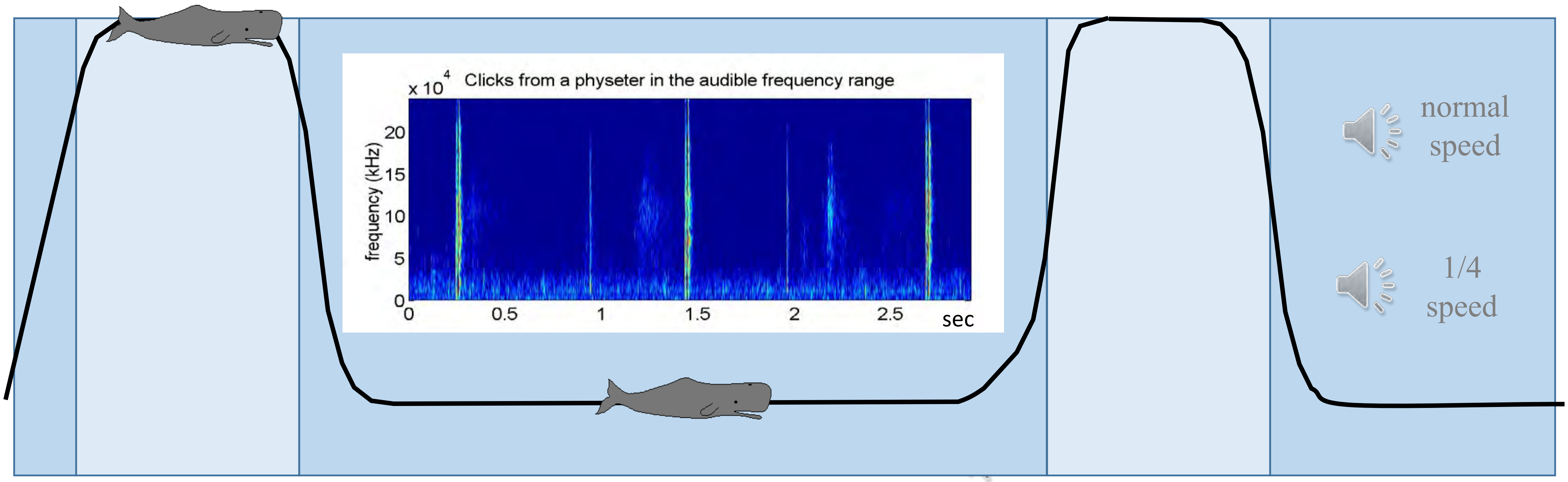

## The problem




## SAvE Whales observatory



# Sperm whales – The dive cycle

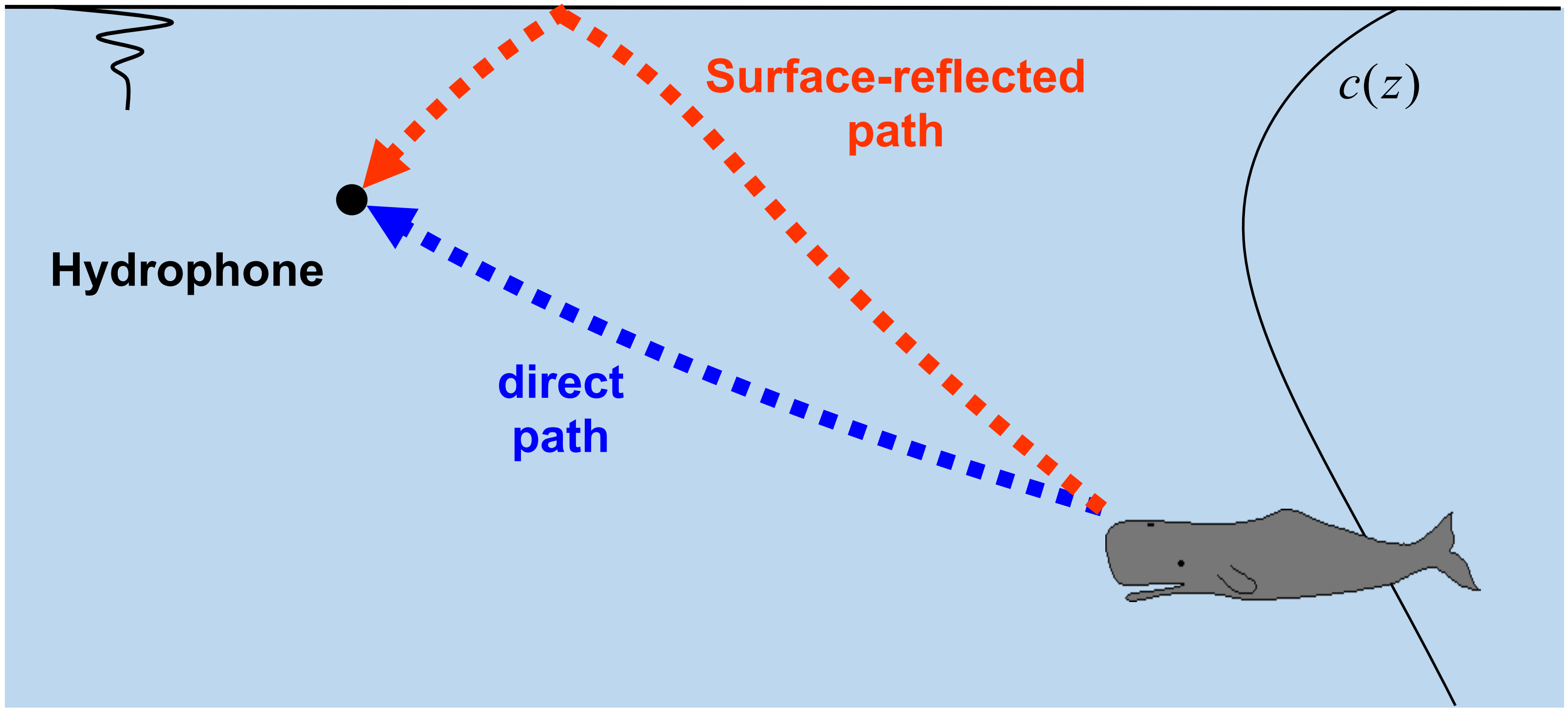


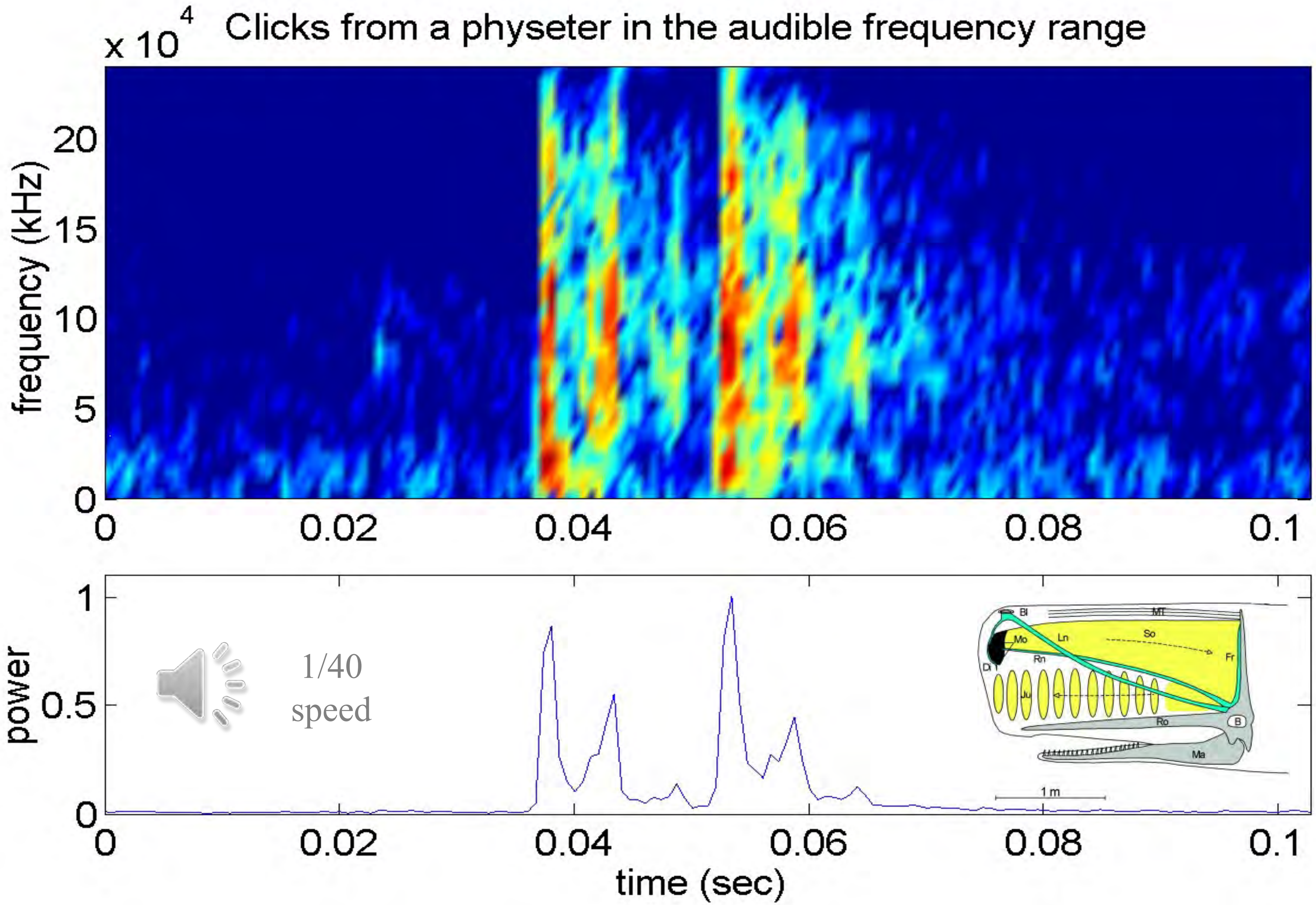

Surfacing
~10 min

Dive @ 700-1000 m
~45 min

Surfacing

Dive


Surface-reflected path
$c(z)$
Hydrophone
direct path


Clicks from a physeter in the audible frequency range
x 10^4
frequency (kHz)
0
5
10
15
20
0
0.02
0.04
0.06
0.08
0.1
power
0
0.5
1
time (sec)
1/40
speed
Bl
MT
So
Ln
Mo
Rn
Fr
Di
Ju
Ro
B
Ma
1 m

# 3-hydrophone 3D localization

## STEP 1: Range-depth estimation

**Data:** Time differences of direct and surface-reflected arrivals at 3 hydrophones of known depths ($h_1$, $h_2$, $h_3$)

$$\mathbf{d} = (\tau_{1r1}, \tau_{2r2}, \tau_{3r3}, \tau_{21}, \tau_{31})$$

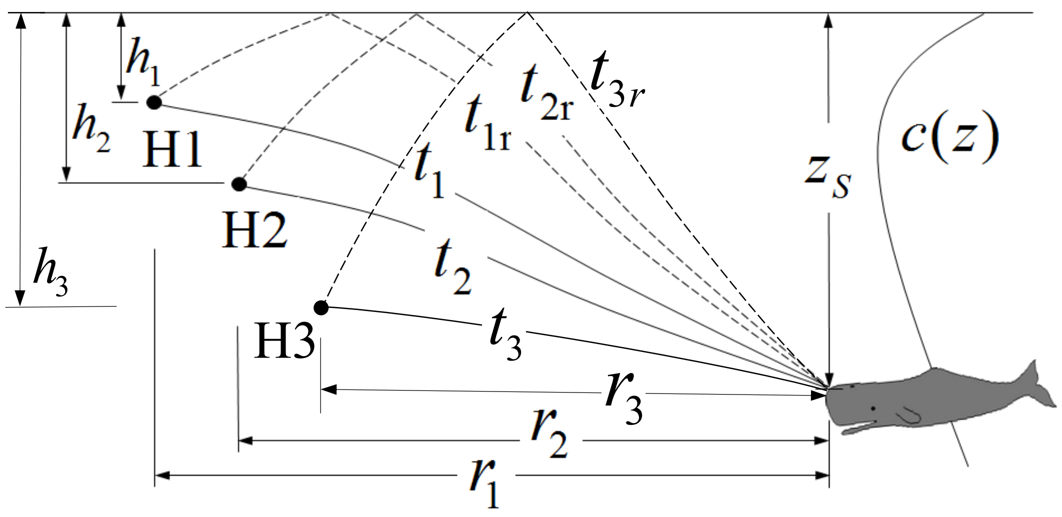
$$\tau_{1r1} = t_{1r} - t_1$$

$$\tau_{2r2} = t_{2r} - t_2$$

$$\tau_{3r3} = t_{3r} - t_3$$

$$\tau_{21} = t_2 - t_1$$

$$\tau_{31} = t_3 - t_1$$




**Sought:**

- Source ranges ($r_1$ , $r_2$ , $r_3$), source depth ($z_S$)
- Uncertainty estimates accounting for measurement errors and sound-speed uncertainties

$$\mathbf{m} = (r_1, r_2, r_3, z_S; h_1, h_2, h_3, \vartheta_c)$$

# Bayesian formulation – GM inversion

$$\mathbf{d}(\mathbf{m}) \approx \mathbf{d}(\mathbf{m}_L) + \mathbf{J}(\mathbf{m} - \mathbf{m}_L)$$

Model relations - linearization

$$P(\mathbf{m} \,|\, \mathbf{d}_{\mathbf{obs}}) \propto P(\mathbf{d}_{\mathbf{obs}} \,|\, \mathbf{m})\, P(\mathbf{m})$$

Bayes’ Rule: PPD $\propto$ Likelihood x Prior

$$P(\mathbf{m} \,|\, \mathbf{d}_{\mathbf{obs}}) \propto \exp\left\{ -\left[\, (\mathbf{d}_{\mathbf{obs}} - \mathbf{d}(\mathbf{m}))^T \mathbf{C}_{\mathbf{d}}^{-1} (\mathbf{d}_{\mathbf{obs}} - \mathbf{d}(\mathbf{m})) + (\mathbf{m} - \mathbf{m}_{\mathbf{p}})^T \mathbf{C}_{\mathbf{p}}^{-1} (\mathbf{m} - \mathbf{m}_{\mathbf{p}}) \,\right] / 2 \right\}$$

Gaussian pdf’s

Gauss-Markov solution $\left( P(\hat{\mathbf{m}} \,|\, \mathbf{d}_{\mathbf{obs}}) = \max \right)$

$$\hat{\mathbf{m}} = \mathbf{m}_{\mathbf{p}} + \left[ \mathbf{J}^T \mathbf{C}_{\mathbf{d}}^{-1} \mathbf{J} + \mathbf{C}_{\mathbf{p}}^{-1} \right]^{-1} \mathbf{J}^T \mathbf{C}_{\mathbf{d}}^{-1} \left[ \mathbf{d}_{\mathbf{obs}} - \mathbf{d}(\mathbf{m}_L) + \mathbf{J}(\mathbf{m}_L - \mathbf{m}_{\mathbf{p}}) \right]$$

Iterative scheme

$$\left. \begin{array}{l} \mathbf{m}_L \rightarrow \mathbf{d}(\mathbf{m}_L), \mathbf{J} \\ \mathbf{m}_{\mathbf{p}}, \mathbf{C}_{\mathbf{p}}, \mathbf{d}_{\mathbf{obs}}, \mathbf{C}_{\mathbf{d}} \end{array} \right\} \rightarrow \hat{\mathbf{m}}$$

Posterior covariance matrix

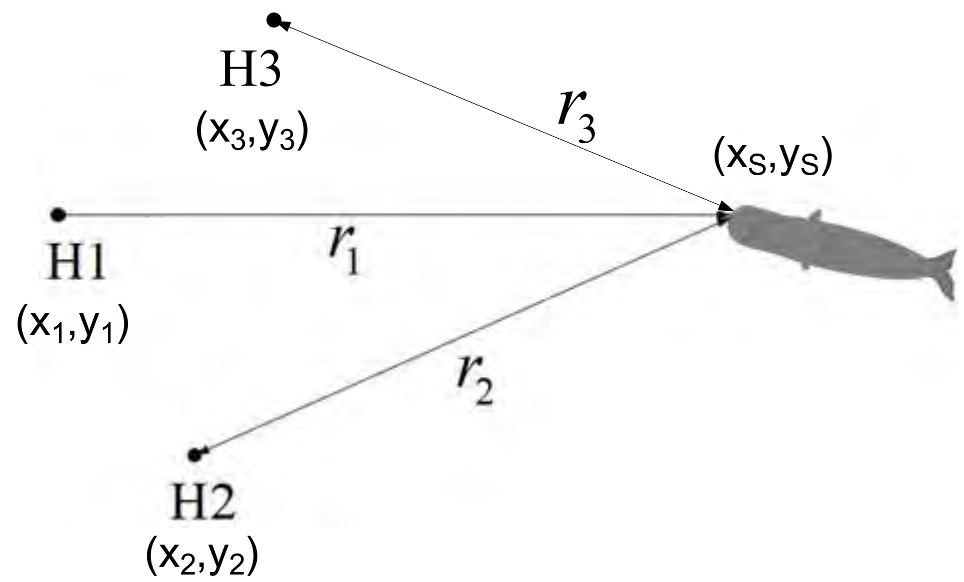
$$\mathbf{C}_{\mathbf{m}} = \left[ \mathbf{J}^T \mathbf{C}_{\mathbf{d}}^{-1} \mathbf{J} + \mathbf{C}_{\mathbf{p}}^{-1} \right]^{-1}$$

# 3-hydrophone 3D localization

## STEP 2: Localization in the horizontal

**Data:** Source ranges ($r_1$, $r_2$, $r_3$), and corresponding uncertainty estimates (from step 1), hydrophone positions and associated uncertainties

$$\mathbf{d} = (r_1, r_2, r_3)$$




**Sought**

- Source position ($x_S$,$y_S$)
- Uncertainty estimates accounting for range and hydrophone position uncertainties

$$\mathbf{m} = (x_S, y_S; x_1, y_1, x_2, y_2, x_3, y_3)$$

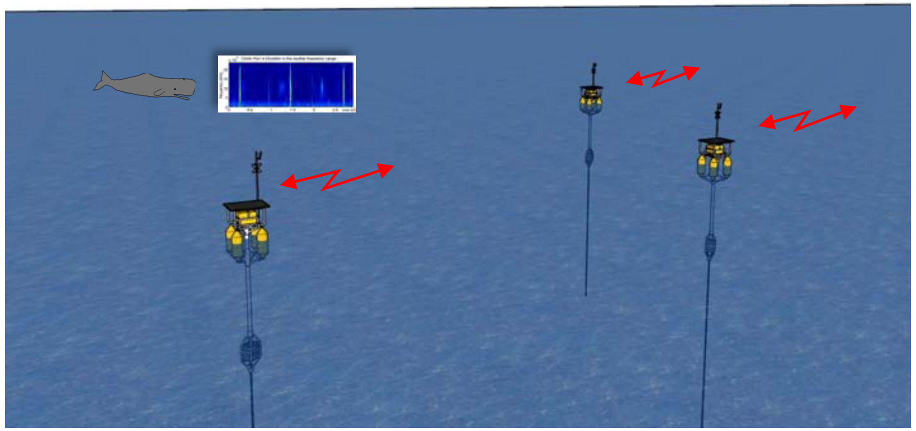
# **SAvE Whales**: System for the Avoidance of Ship Strikes with Endangered Whales

Notification of passing ships

MarineTraffic

SAvE Whales Coordination, Verification Campaigns

PELAGOS
Cetacean Research Institute



Buoy development, Localization methods, Real-time analysis & localization

FORTH
FOUNDATION FOR RESEARCH AND TECHNOLOGY – HELLAS
INSTITUTE OF APPLIED AND COMPUTATIONAL MATHEMATICS

*supported by*

30 Jahre
ocean care

# SAvE Whales observatory – Basic features

- Real-time detection & localization of vocalizing sperm whales
- Localization accounting for sound refraction effects (ray theory)
- Bayesian approach allowing for location uncertainty estimation

- Autonomous acoustic buoys
- Efficient, low-consumption on board processing
- Real time data telemetry and 2-way communication
- Synchronization through GPS


Skarsoulis and Kalogerakis, Ray-theoretic localization of an impulsive source in a stratified ocean using two hydrophones, *J. Acoust. Soc. America*, Vol. 118, 2005

Skarsoulis and Kalogerakis, Two-hydrophone localization of a click source in the presence of refraction, *Appl. Acoustics*, Vol. 67, 2006

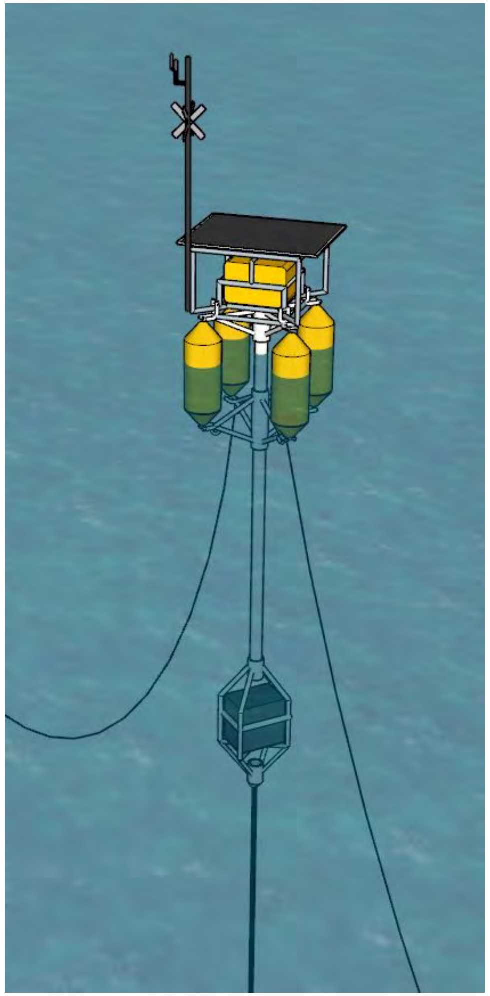
Skarsoulis and Dosso*,* Linearized two-hydrophone localization of a pulsed acoustic source in the presence of refraction, *J. Acoust. Soc. America*, Vol. 138, 2015

Skarsoulis et al., Underwater Acoustic Pulsed Source Localization with a Pair of Hydrophones, *Remote Sensing*, Vol. 10, 2018

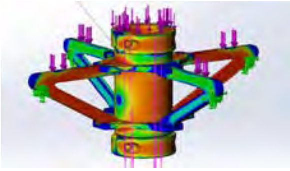
Pavlidi and Skarsoulis., Enhanced Pulsed-Source Localization with 3 Hydrophones: Uncertainty Estimates, *Remote Sensing*, Vol. 13, 2021

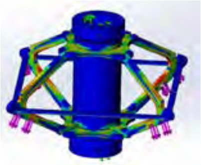
Skarsoulis et al., A Real-Time Acoustic Observatory for Sperm-Whale Localization in the Eastern Mediterranean Sea, *Frontiers in Marine Science*, Vol. 9, 2022

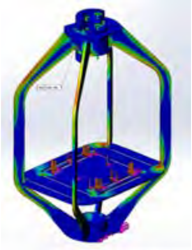
# SAvE Whales Buoy

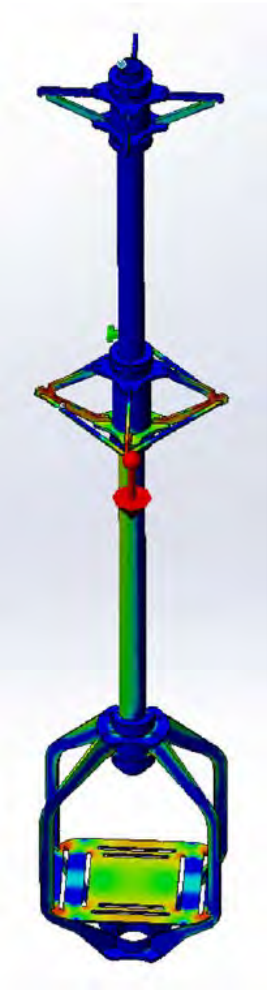


- Hydrophone @ 100 m depth
- Onboard click detection / time estimation
- GPS space/time reference/synchronization
- Two-way telemetry & communication
- Solar power supply





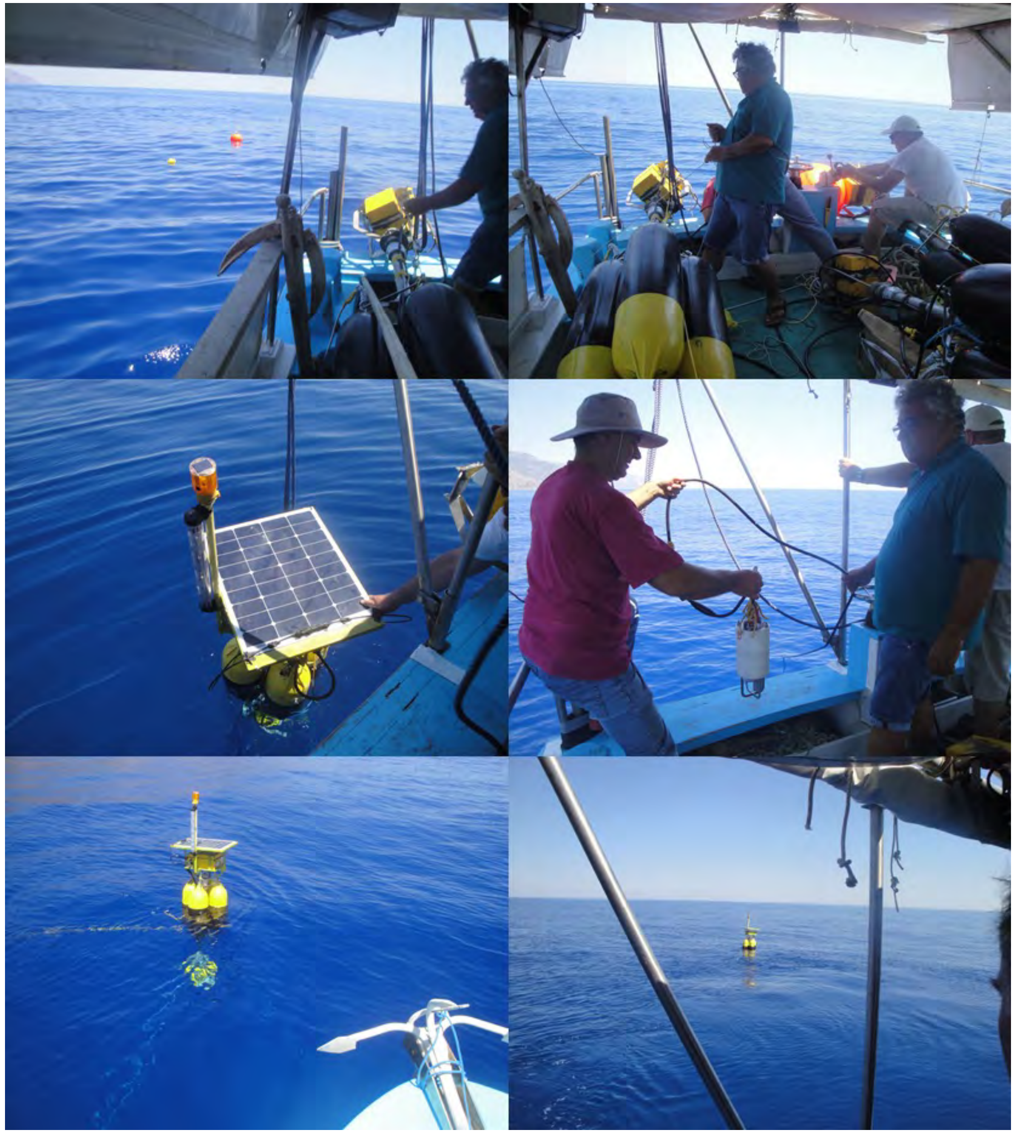




# SAvE Whales Buoy

Modular design

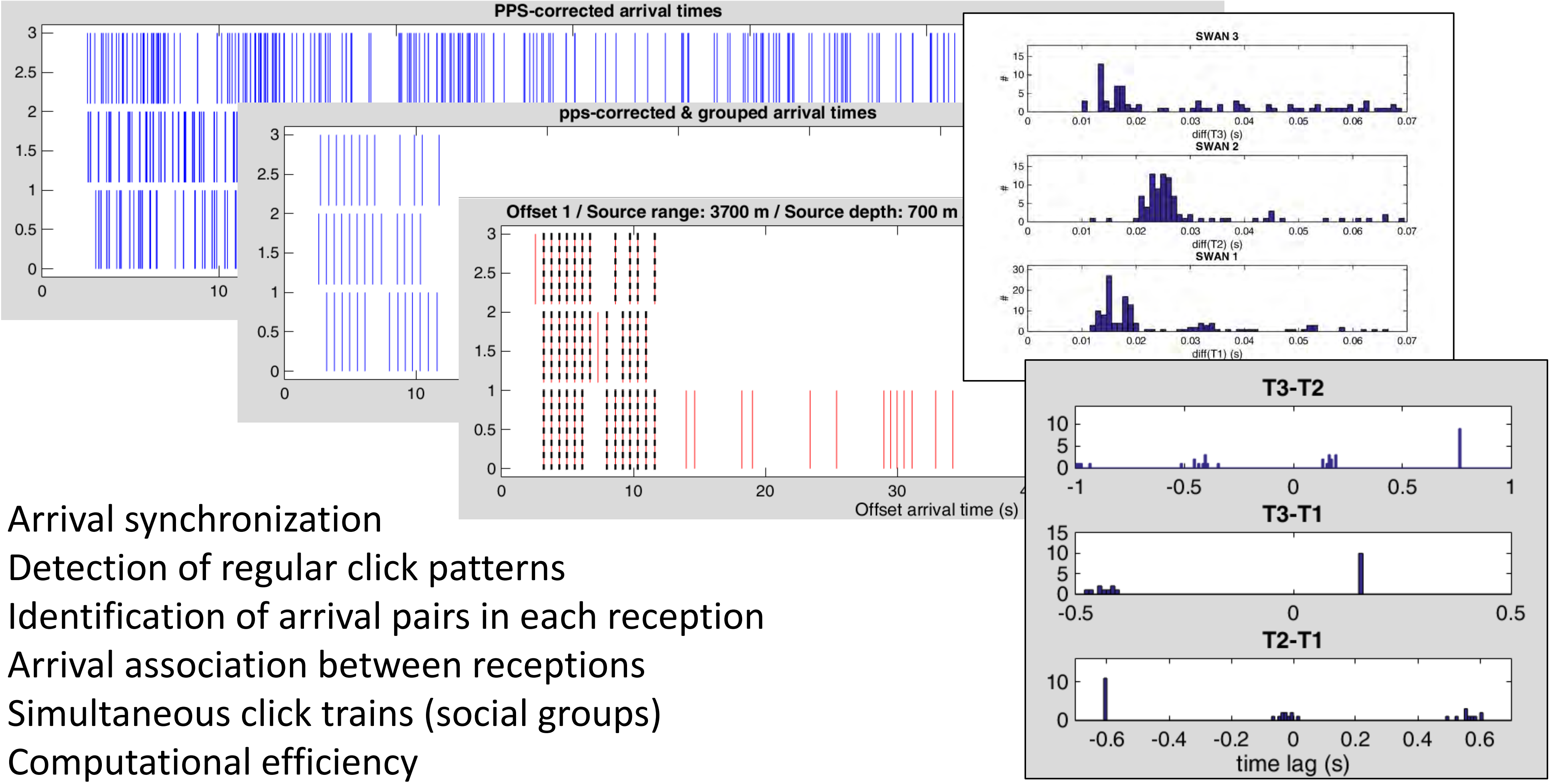
# Deployment



- Deployment 1: July-October 2020
- Deployment 2: May-September 2021

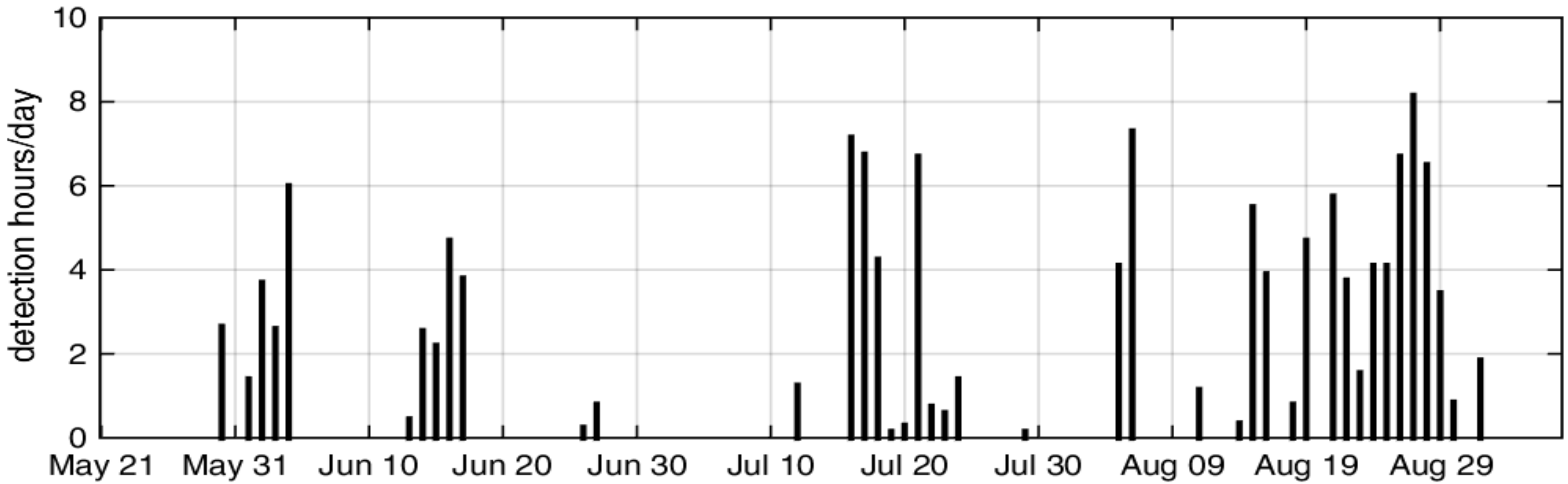
- 3 acoustic stations ~1 km apart
- 1 nm offshore (SW Crete)
- Water depth ~500 m
- Λ-shaped moorings


# SAvE Whales – Analysis challenges

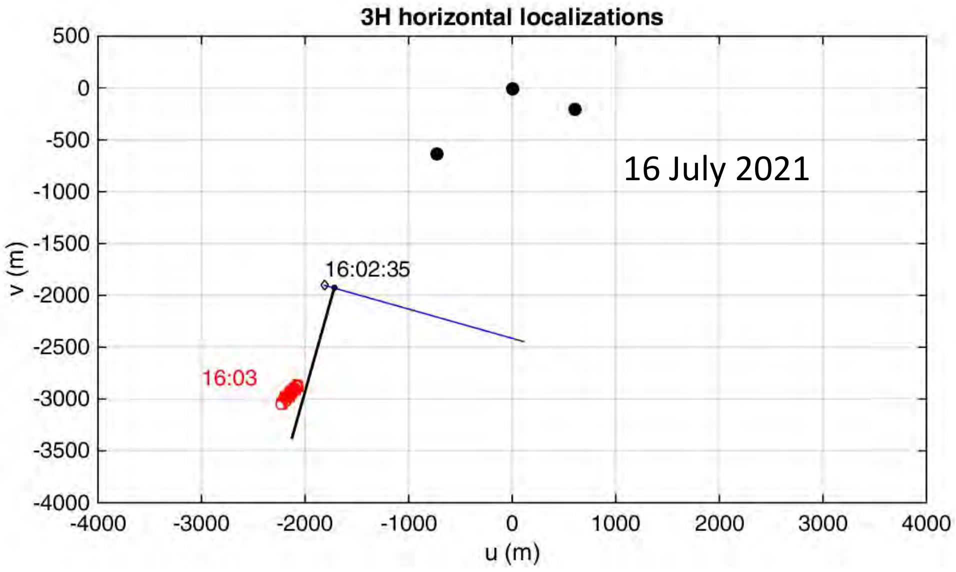


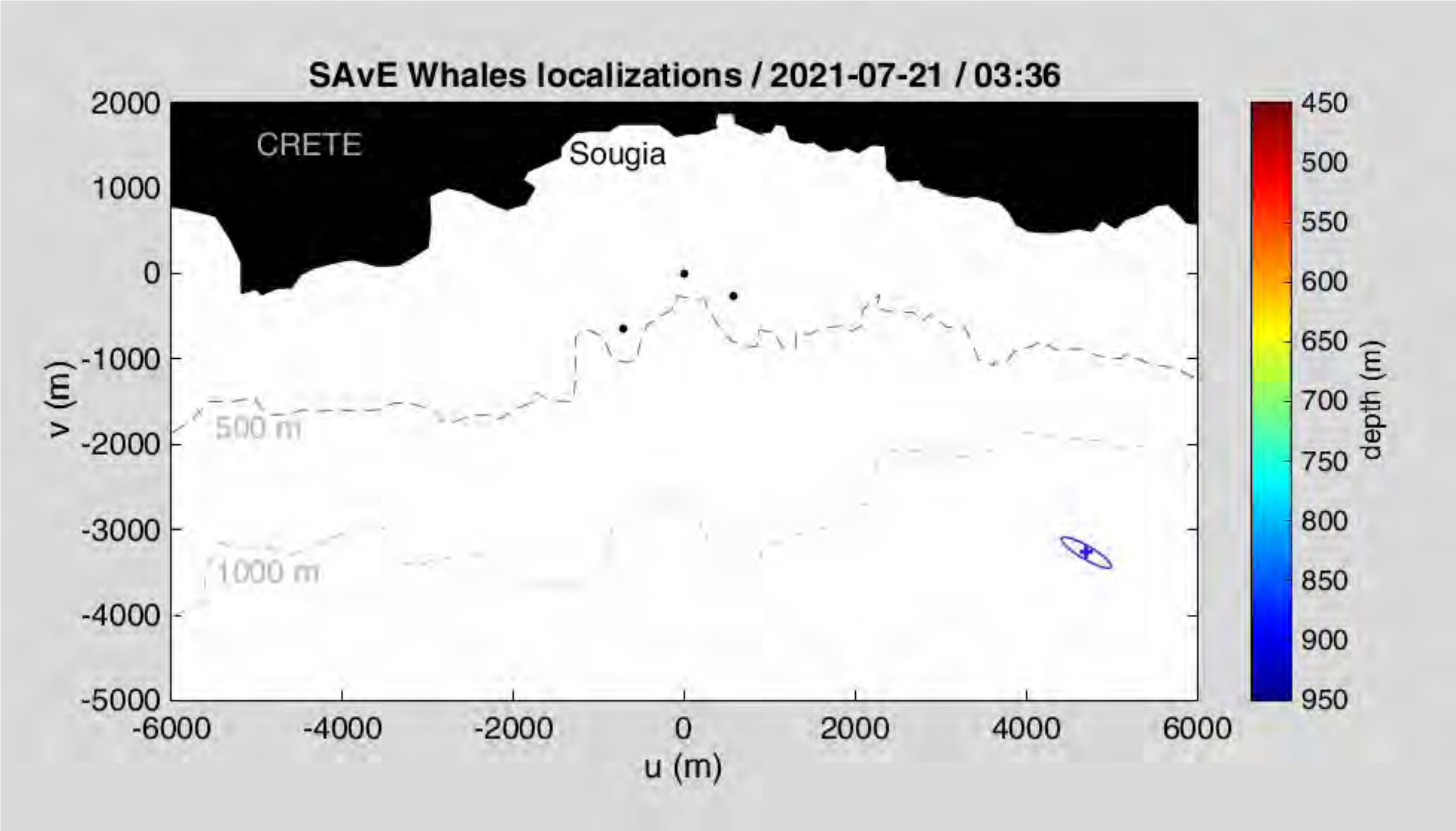

- Arrival synchronization
- Detection of regular click patterns
- Identification of arrival pairs in each reception
- Arrival association between receptions
- Simultaneous click trains (social groups)
- Computational efficiency

# SAvE Whales – Sperm-whale detections in summer 2021




# SAvE Whales – Sperm whale localizations




For more details:

https://sites.google.com/view/savewhales

Skarsoulis et al., A Real-Time Acoustic Observatory for Sperm-Whale Localization in the Eastern Mediterranean Sea, *Frontiers in Marine Science*, Vol. 9, 2022

# Keywords

# Keywords

**Κυματικά φαινόμενα**

Αλληλεπίδραση σώματος-κύματος

Στοχαστικές διαδικασίες

**Δώμα**

Μικρές ώρες

Copyplan

Σούμπασης

**Νέα Μάκρη**

Υπόγειο

Βρασμένο στάρι

**Ελένη**

Μανούσος

Αγησίλαος

**Πετράλωνα**

**Ντεσεβώ**

Δημοφώντος

Τρεις Ιεράρχες

**Κεφαλονιά**

Αίνος

Άγιος Γεράσιμος