PROJECT #33
PASSIVE ACOUSTIC MONITORING SYSTEM FOR UNDERWATER CO_2 LEAKAGE DETECTION

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cleaner energy for a sustainable future

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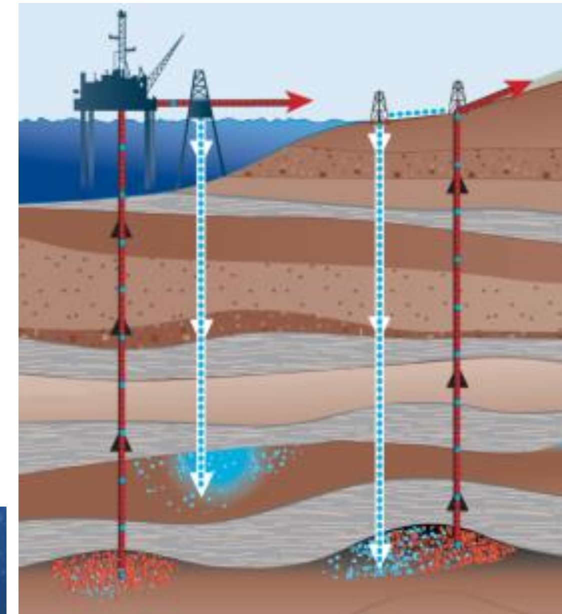
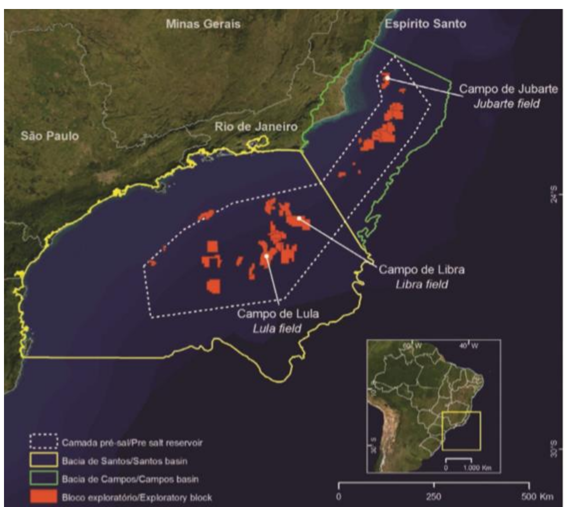
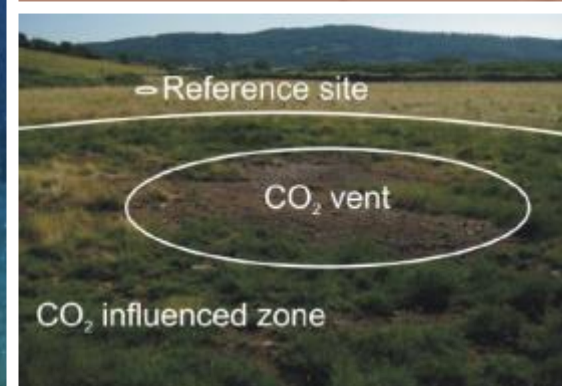
- Detect, locate and quantify CO_2 leakages

Introduction:
CO_2 capture and storage (CCS)



- CCS: mitigation of atmospheric CO_2 in atmosphere
  - Where to inject the CO_2?
  - How to ensure that CO_2 remains on the reservoir?
  - What are the impacts of a leakage?
  - How to monitor CO_2 leakages?





Introduction:

Monitoring leakages in CO_2 capture and storage (CCS) reservoirs

- Available Monitoring Techniques

J. Blackford et al. / International Journal of Greenhouse Gas Control 38 (2015) 221–229 227

Table 1
An overview of the spatial and temporal criteria for baseline data acquisition, for the proposed range of monitoring methodologies, that could be considered.

Methodology	Variables	Temporal sampling interval	Spatial sampling scale	Notes
Active acoustics	Sea floor bathymetry, including pockmarks.	In shallow waters where the seafloor sediments are exposed to storm driven resuspension and biological sedimentation a seasonal discrimination, in the first instance. In deeper waters where sediments are disconnected from weather driven events an initial survey, followed by a repeat survey 1–2 years later.	The spatial extent of the storage reservoir in addition to allowing for lateral movement of migrating CO_2.	Assists identification of existent natural seeps.
	Free gas in surface sediments and water column.	An initial survey, followed by a repeat survey 1–2 years later.		Useful for attribution.
Passive acoustics	All noise at relevant frequencies.	Seasonal in addition to targeted short term deployments to assess event driven noise.	Targeted to known fixed installations or shipping routes.	Necessary for quantification, not essential for detection.
	Acoustics of existent natural gas seeps.	Seasonal and targeted short term deployments to account for intermittent gas flow.	Spatial extent of the storage reservoir as well as allowing for lateral movement of migrating CO_2.	Required for detection.
Geochemistry	Water column pH, pCO_2, temperature, salinity, pressure. TA or DIC and O_2 if possible.	Hourly measurements for at least part of the seasonal cycle, corresponding with periods of biological or physical activity. Weekly for entire annual cycle. Repeated for at least one subsequent year to assess inter-annual variability and then on an approximately decadal repeat to assess longer term trends.	For high frequency data, if the storage site is large or includes significant changes in water depth or other hydrodynamic properties, at least a pair of landers deployed across the site. Spatial extent of the storage site via AUV deployment.	Required for detection.
	Isotope composition ratios: e.g. $C^{13}:C^{12}$	Occasional (not dynamic)	Occasional (not dynamic)	Addresses attribution
Biology	Community structure, indicator species and related indices.	Weekly during periods of intense biological activity, otherwise monthly. Repeated for at least one subsequent year to assess inter-annual variability and then on an approximately decadal repeat to assess longer term trends.	Significant differences in water depth and-or different sediment types within the complex would need separate characterisation. Multiple replicates are required for statistical certainty.	Principally for impact assessment.

A survey on gas leak detection and localization techniques

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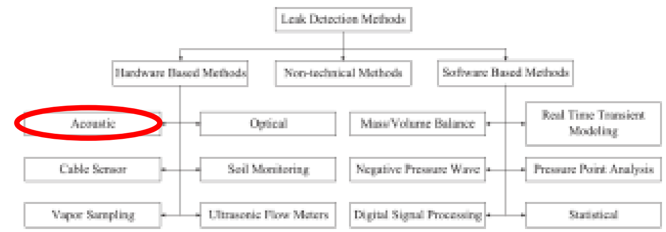


Fig. 1. Classification of gas leak detection techniques based on their technical nature.

Quantification of undersea gas leaks 503

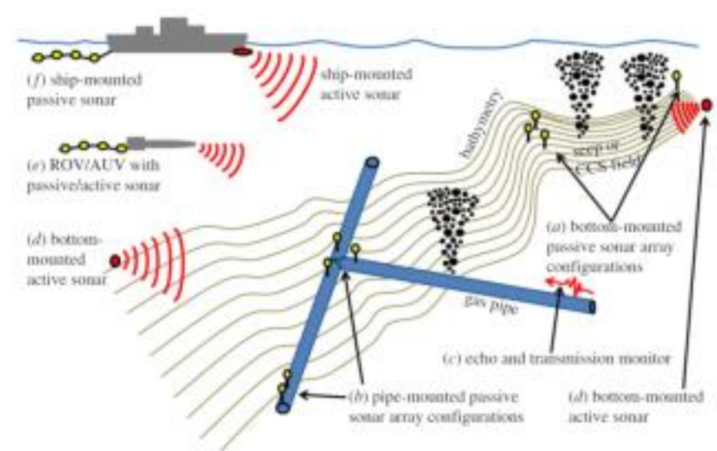
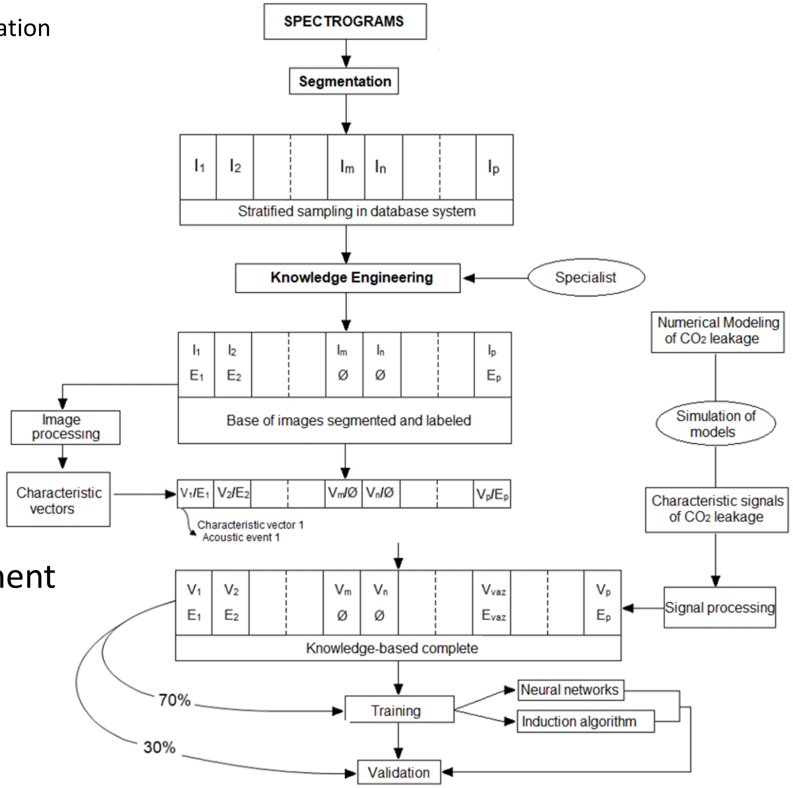


Figure 8. Schematic indicating options for practical implementation (leaks from pipes and seeps are shown to cover example cases). (Online version in colour.)

Project Objectives – Scope of Work

Development of Passive Acoustic Monitoring equipment

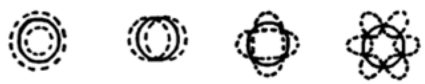
- Detect, locate and quantify CO_2 leakages ocurring in submarine reservoirs
  - Understanding bubble acoustics as a phenomenon:
    - Analytical and numerical modeling of the sound emitted during bubble formation
    - Experimental measurements of Bubble characteristic acoustic signal
  - Detecting a leakage event
    - Identification of typical bubble acoustic signature the signal
  - Quantifying the leakage:
    - Estimation of the emitted frequency → Bubble size calculation
    - Estimation of frequency of bubble occurrences → Leakage quantification
  - Locating the leakage source:
    - Hydrphone arrays
    - Localization techniques
  - Design and build underwater acoustic monitoring equipment



Bubble Acoustics - Theory

1933 – Minnaert | 1956 - Strassberg | 1994 – Leighton | 2011 - Ainsle & Leighton | 2012 - Leighton & White

- Sound emitted at bubbles forma



  - Volumetric oscillation: main source
  - zeroth order vibration [f0]→ Minnaert Frequenc $f_m = \frac{1}{T} = \frac{1}{2\pi r}\sqrt{\frac{3kp_0}{\rho_0}}$
- Variations in frequency
  - Air-water, water-solid interfaces
  - Surface tension
  - Viscosity
  - Heat transfer
  - Mass transfer

$$R_{\text{Laplace}} = 2\tau / P_{\text{liq}}.$$

$$l_{\text{vis}}(\omega) = \sqrt{\frac{2\eta_S}{\rho_{\text{liq}}\omega}},$$

$$l_{\text{th}}(\omega, R_0) = \sqrt{\frac{D_P(R_0)}{2\omega}}$$

$$D_P(R_0) \equiv \frac{K_{\text{gas}}}{\rho_{\text{gas}}(R_0) C_P},$$

$$p_s = p_0 e^{-(\pi \delta f_0 t)} \cos(2\pi f_0 t - \vartheta)$$

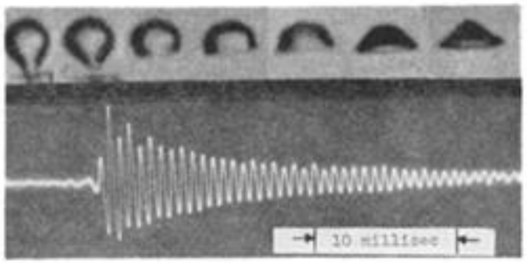


FIG. 3. Oscillogram of the sound pulse from an individual gas bubble leaving a nozzle, with synchronized high-speed photographs of the bubble itself. The horizontal location of each bubble photograph is chosen so that the time each photograph was taken corresponds to the point on the oscillogram below the center of the bubble.

- Corrections on Minnaert oscillation frequency:

$$\omega_0 = \frac{1}{R_0\sqrt{\rho_0}}\sqrt{3\kappa\left(p_0 - p_v + \frac{2\sigma}{R_0}\right) - \frac{2\sigma}{R_0} + p_v - \frac{4\eta^2}{\rho_0 R_0^2}}.$$

- Far-field bubble emission:

$$P_{b1}(t) \approx \mathrm{Re}\left\{\rho_0 \frac{(\omega_0 R_0)^2}{r} R_{\varepsilon 0i} e^{j\omega_0 (t - t_i)} e^{-\omega_0 \delta_{\text{tot}}(t - t_i)/2} H(t - t_i)\right\}$$

$$= (\omega_0 R_0)^2 \frac{\rho_0}{r} R_{\varepsilon 0i} e^{-\omega_0 \delta_{\text{tot}}(t - t_i)/2} H(t - t_i) \cos \omega_0 (t - t_i)$$

Bubble acoustics – Typical experiments

- Water tank
- Hydrophones
- Compressed air
- Data acquisition system
- Nozzles and/or Syringe

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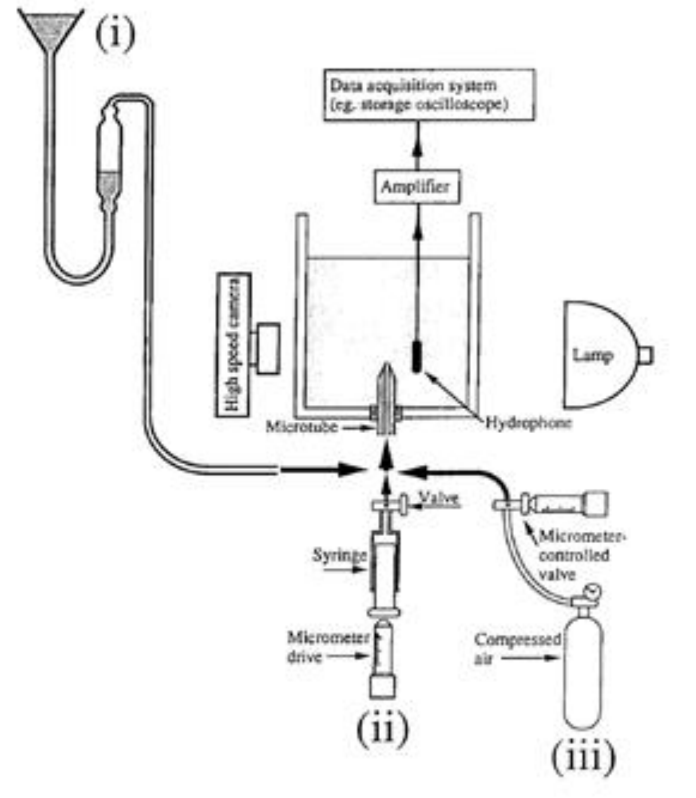
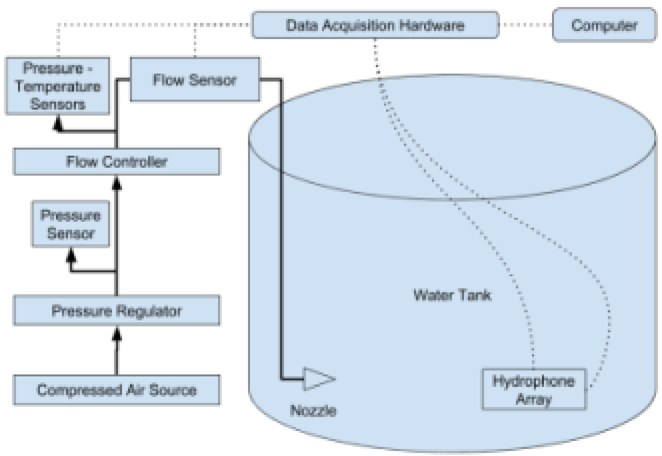


Figure 3.21 The apparatus to detect the acoustic emissions of an injected bubble. Three gas flow techniques are illustrated: (i) Minnaert [4], (ii) Leighton and Walton [41], (iii) Longuet-Higgins *et al.* [25].

Infrastructure, Instrumentation & Software:

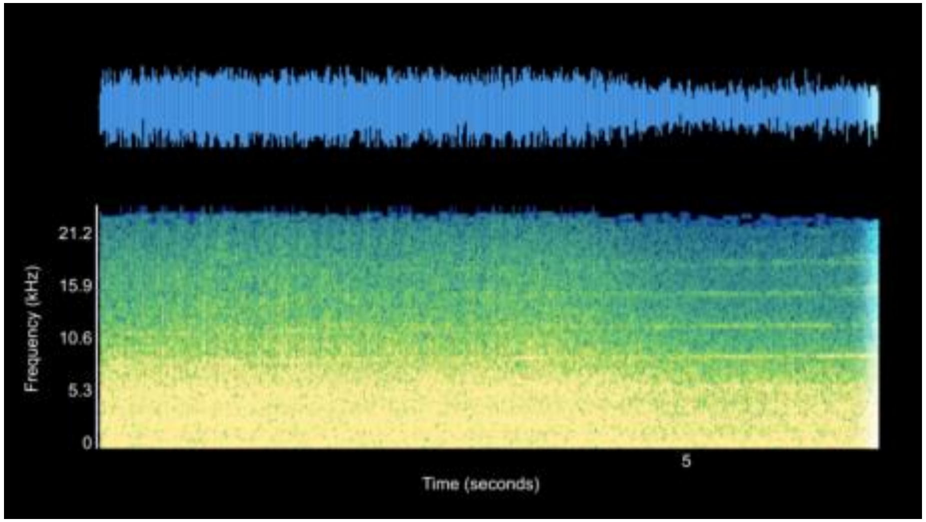
Available at the moment

- Hydrophone and signal conditioner
  - Frequencies range: 1 Hz and 80 kHz
- Hydrophones calibration system
  - Frequency range: 5 kHz up to 100 kHz
- Data acquisition system
- Experimental set-up for controlled bubble production

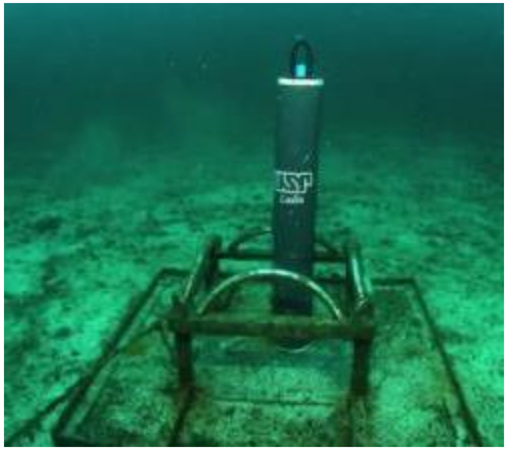


Infrastructure, Instrumentation & Software:

Next steps:



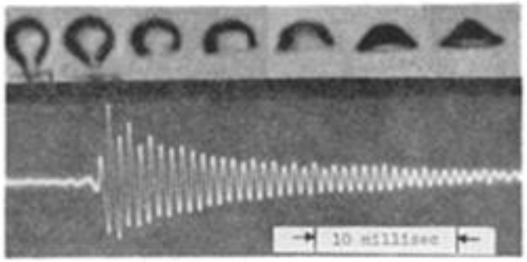
- Hydrophone calibration system for 100 Hz to 5 kHz
- Development of Hydrophone array systems
- Controlled bubble production at marine environment
- Autonomous monitoring unit
- Signal Processing tools:
  - Source Identification
  - Source localization

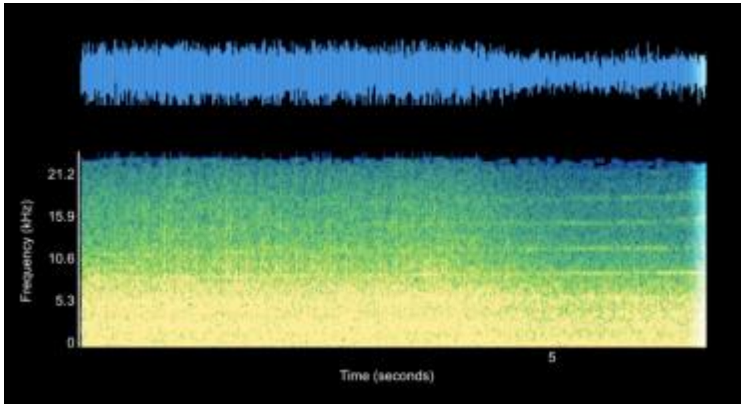


Signal identification

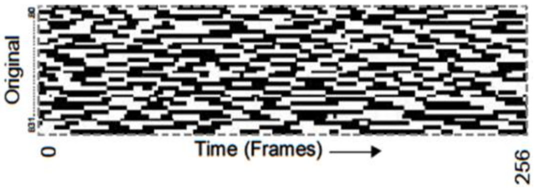
Creation of a characteristic vector

- Extraction of signal features
  - Reduced amount of information
  - Fingerprints





$$F(n,m)=\begin{cases}1 \text{ if } E(n,m)-E(n,m+1)-\left(E(n-1,m)-E(n-1,m+1)\right)>0\\0 \text{ if } E(n,m)-E(n,m+1)-\left(E(n-1,m)-E(n-1,m+1)\right)\le 0\end{cases}$$



  - Landmarks

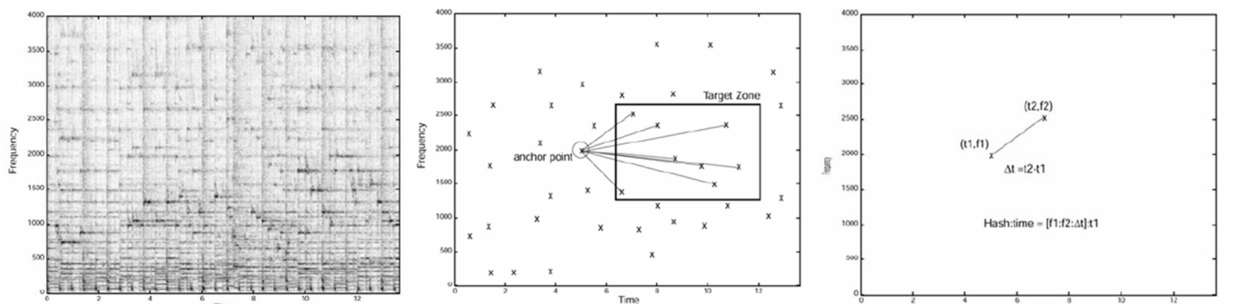


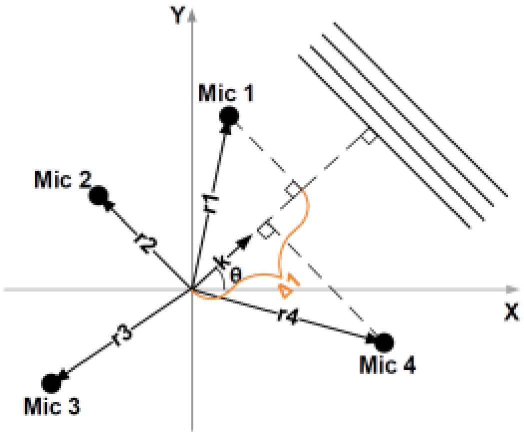
Fig. 1A - Spectrogram

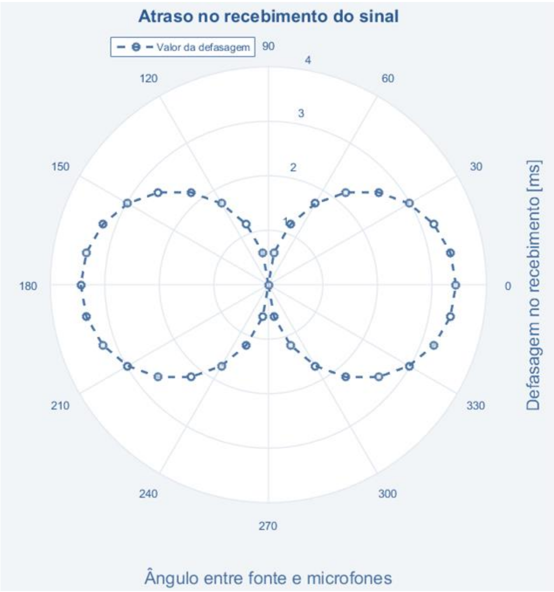
Fig. 1C - Combinatorial Hash Generation

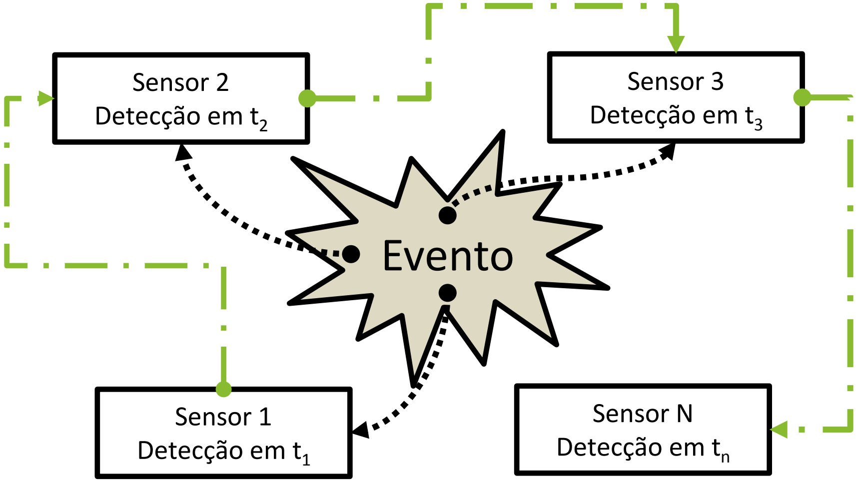
Fig. 1D - Hash details

Bubble leakage localization

- Differences between sensors:
  - Angle of arrival ($n_s = 2$)
  - Position of the source (if $n_s > 3$)

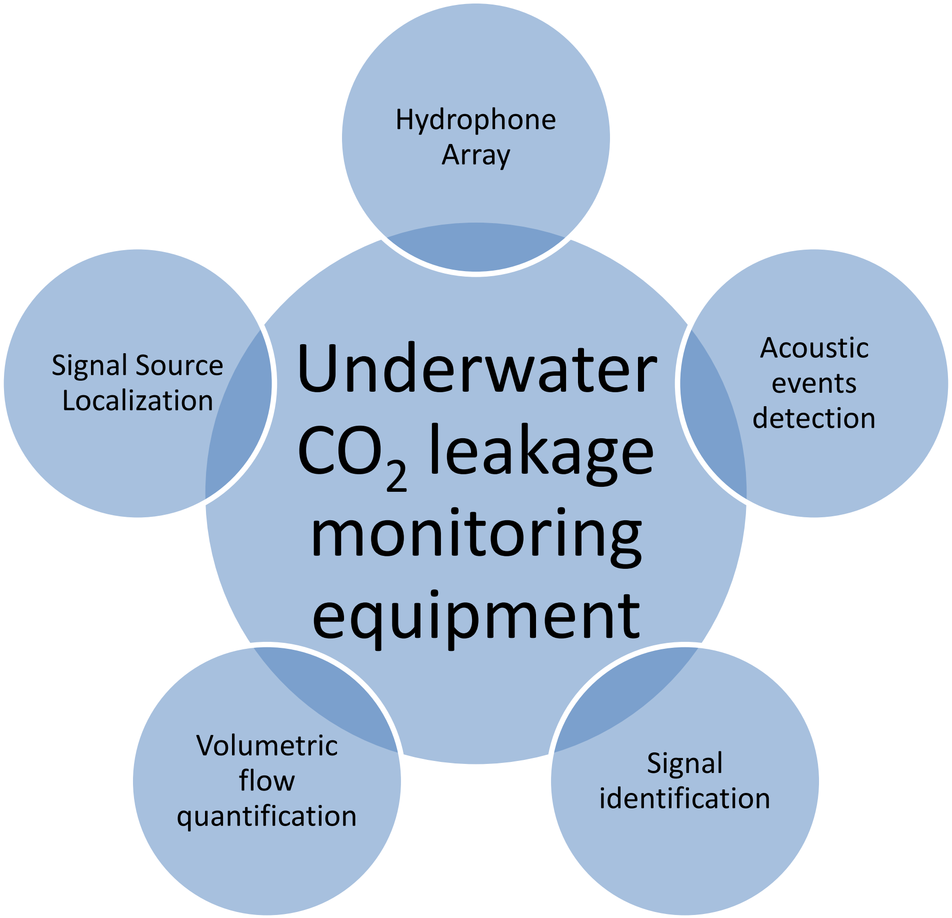






Passive Acoustic Monitoring equipment

Ensemble of Signal Processing Techniques and Bubble Acoustics



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