Exploring Karst with Robots

Exploration Robotics for Confined, Unstructured Subaquatic Environment

FARO, 26-27 November 2024,
LIX, Polytechnique, Palaiseau

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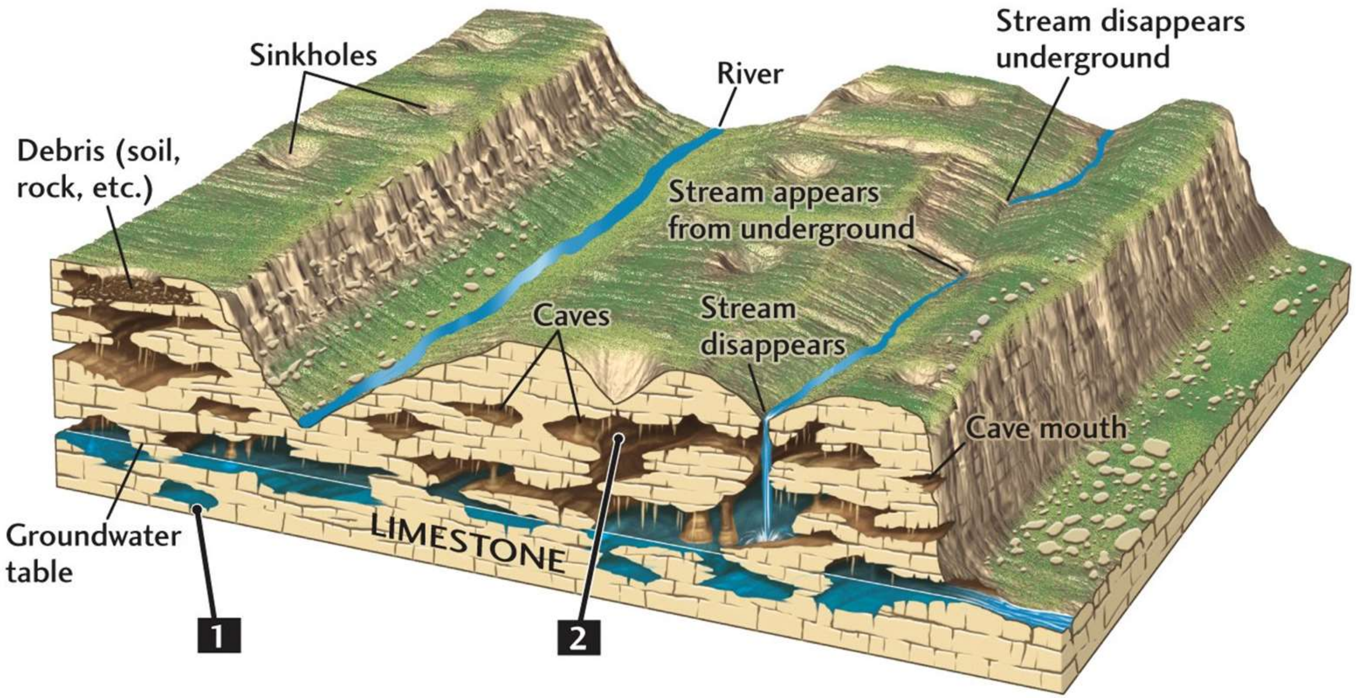
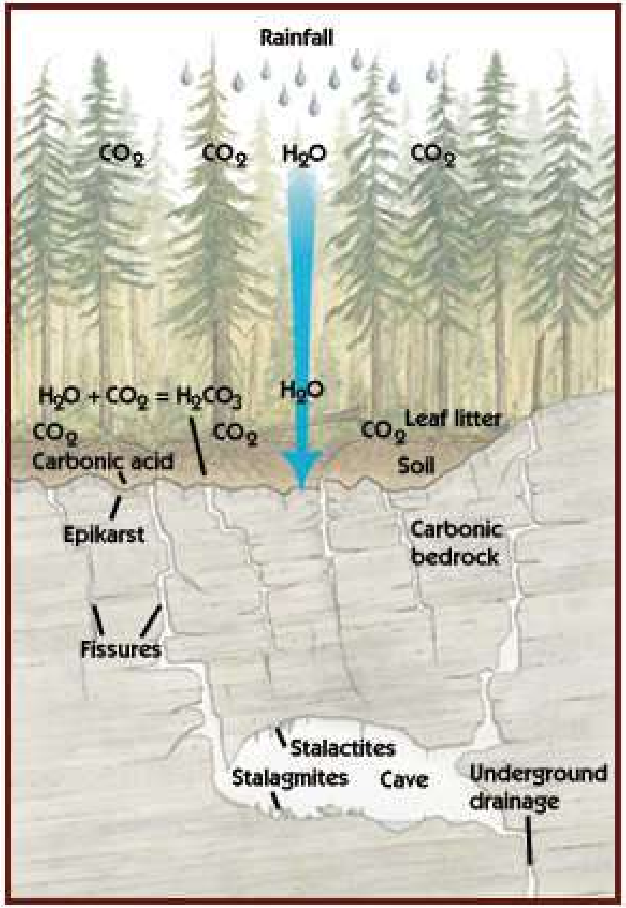
KARST : DEFINITION

- A topography formed from the dissolution of soluble rocks such as limestone, dolomite, and gypsum,



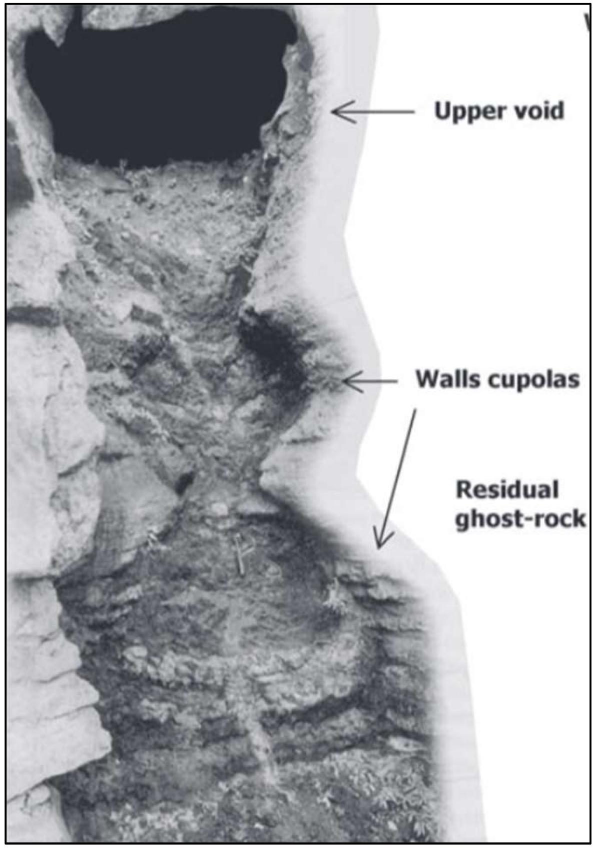
- Characterized by **underground drainage hydrosystems** with sinkholes and caves.

KARSTOGENESIS



$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$

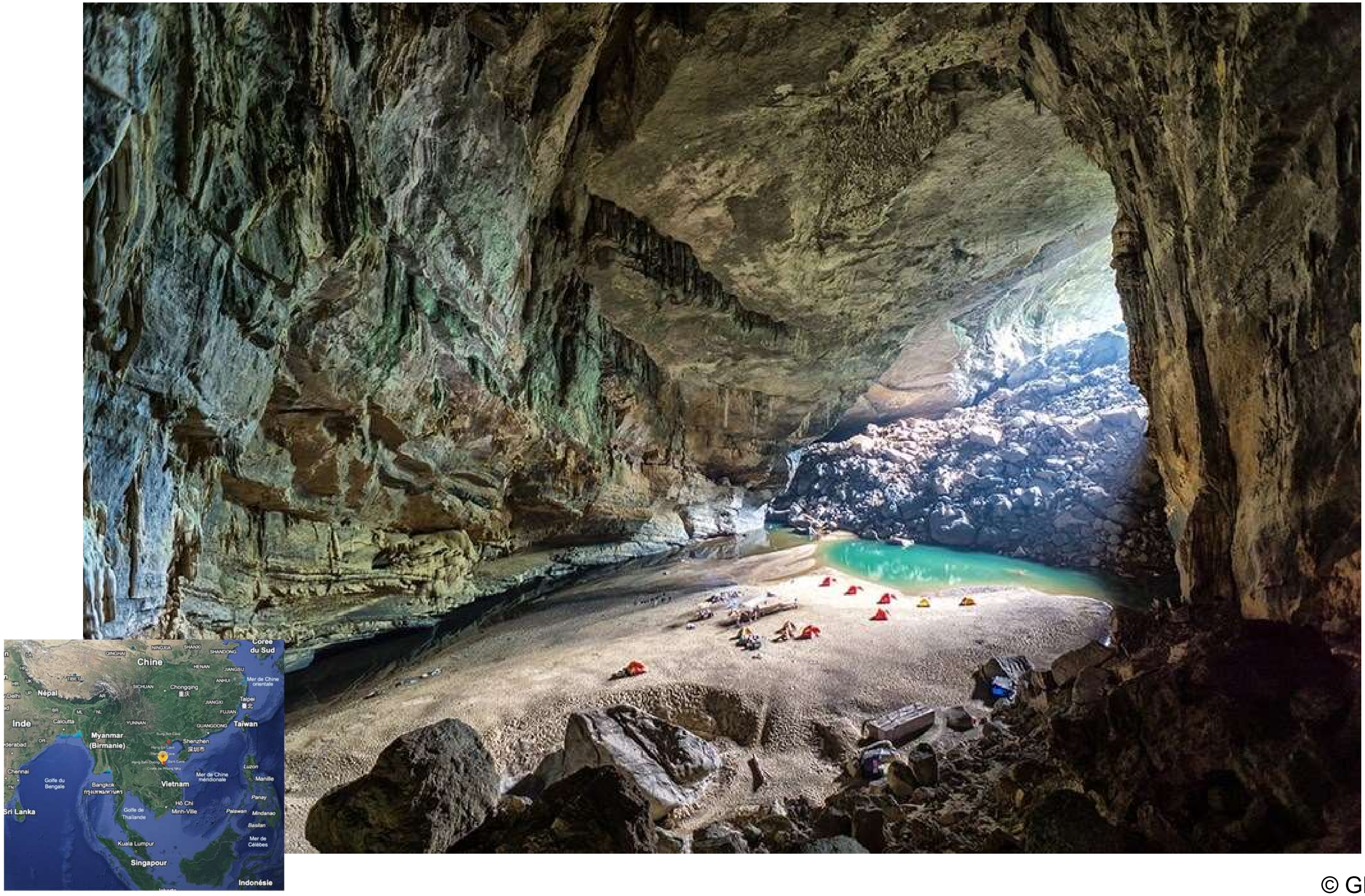
$$CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^+ + 2\ HCO_3^-$$



Speleogenesis by phantomization (ghost-rock models)

KARST : REMARKABLE HIDDEN ENVIRONMENT

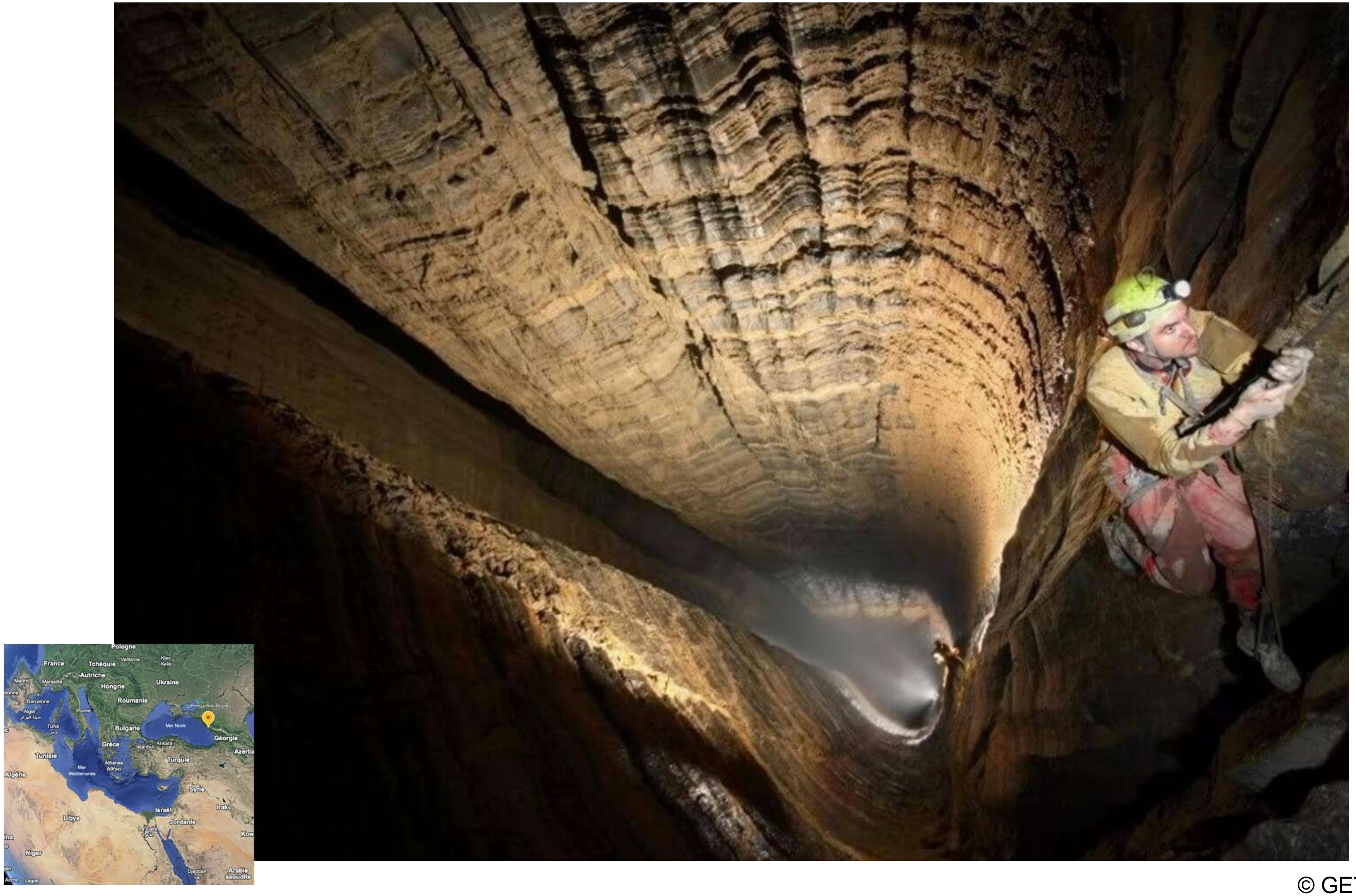
- The Largest (known) cave : Son Doong, Vietnam (2010)




© Vin Pearl

KARST : REMARKABLE HIDDEN ENVIRONMENT

- The Deepest (known) cave : Veryovkina Cave, Abkhazia, 2209 m (202



KARST : REMARKABLE HIDDEN ENVIRONMENT

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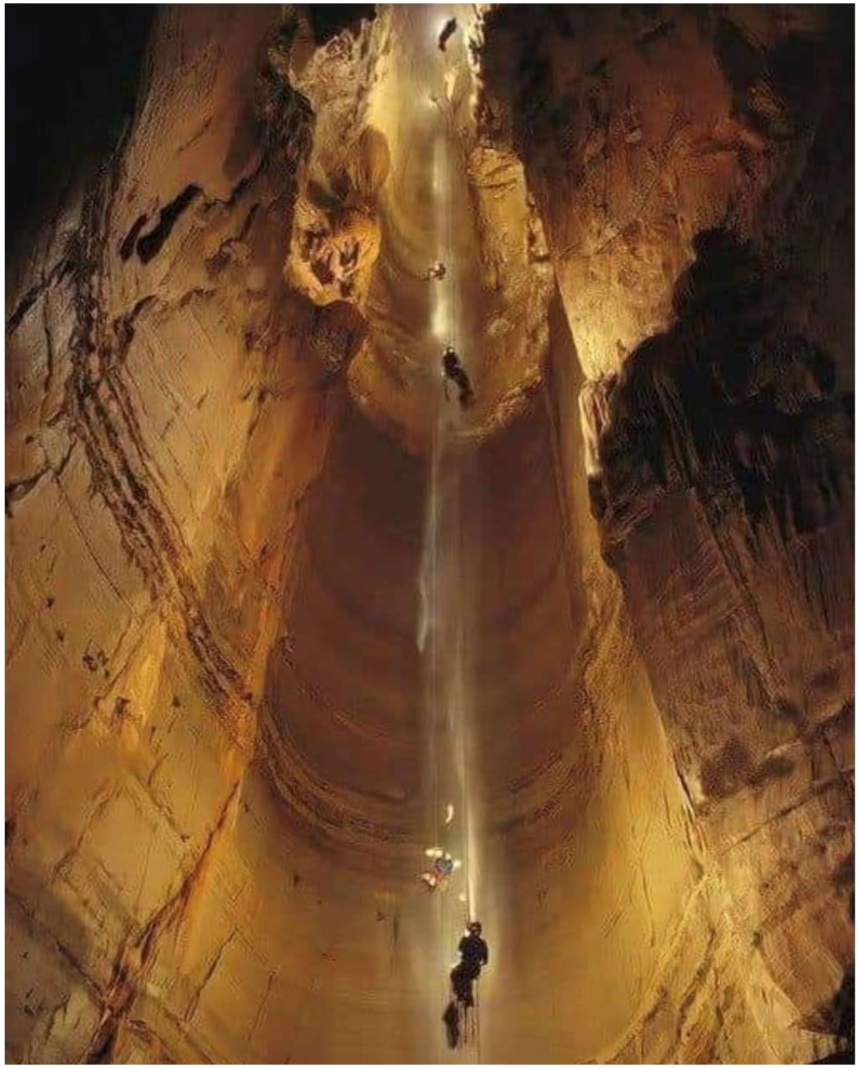
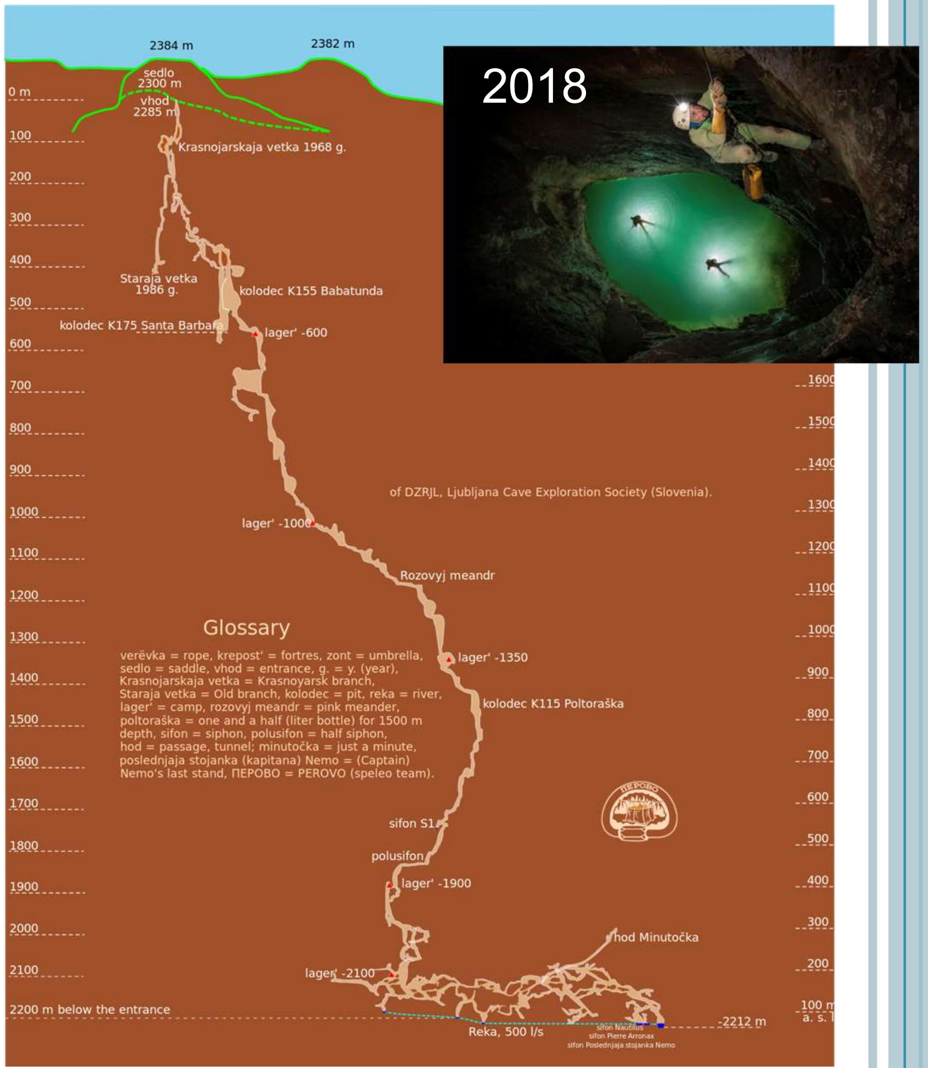


© Julia Ferra



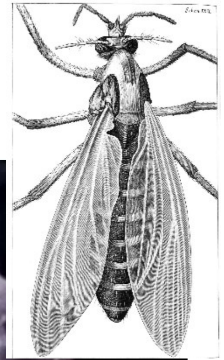
© P Jakopin

Karst : Remarkable Hidden Environment

- The Strangest cave (1) : Cueva de los cristales, Mexico (2000)

KARST : REMARKABLE HIDDEN ENVIRONMENT

- The Strangest cave (2) : Waimoto cave, New Zealand



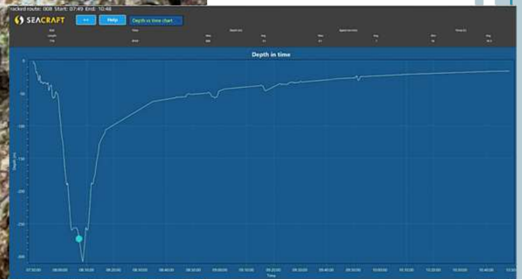
Arachnocampa luminosa (Skuse, 1891)

KARST : REMARKABLE HIDDEN ENVIRONMENT

- The Longest Underwater cave (1) : Sistema Sac Actun, Mexico

KARST : REMARKABLE HIDDEN ENVIRONMENT

- The Deepest cave diving: F. Swierczynski, Font Estramar, France

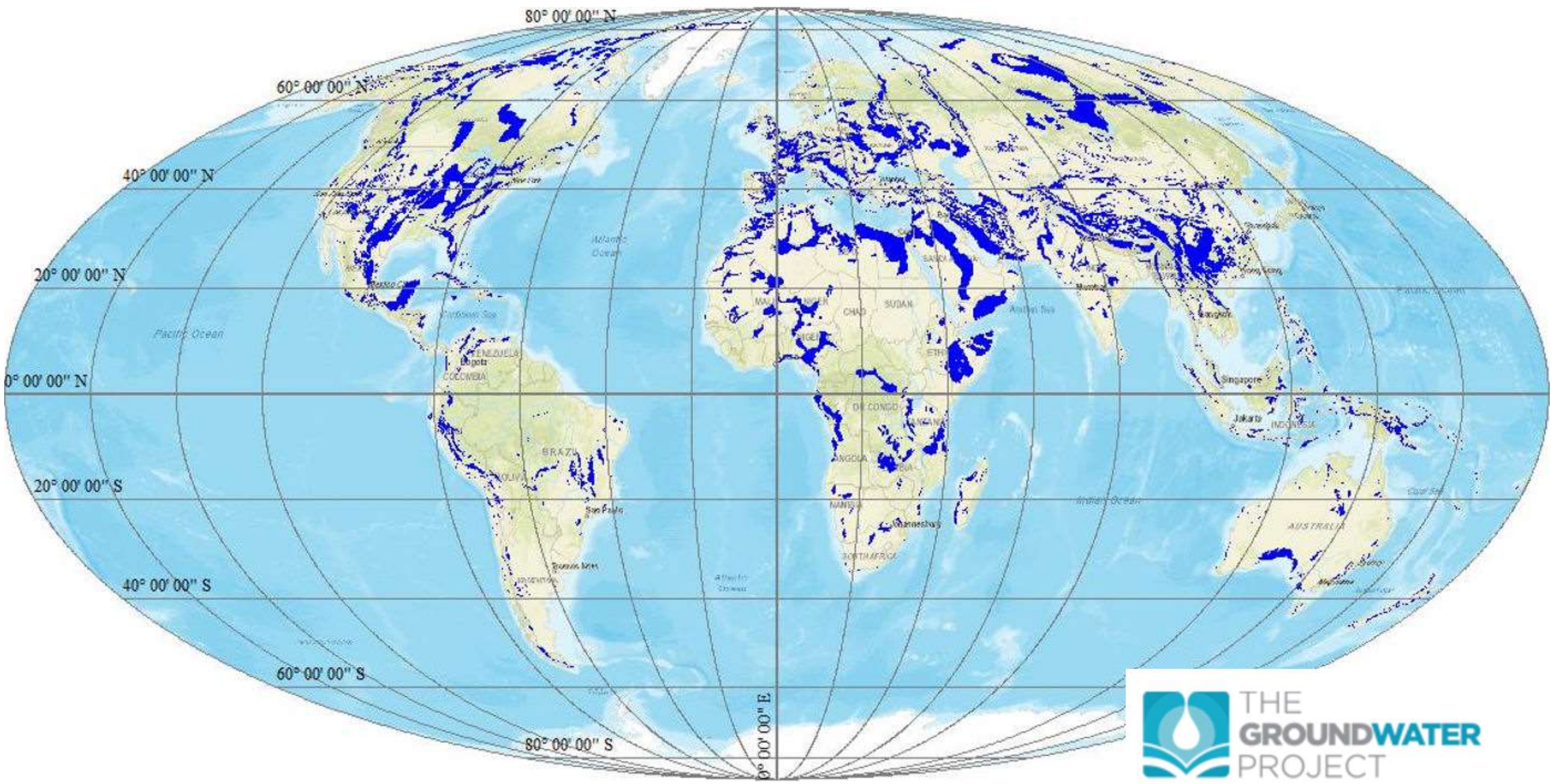


-308m, 3rd November, 2023, 11h

KARST : GROUNDWATER RESERVOIR

GROUNDWATER IN KARST SETTINGS

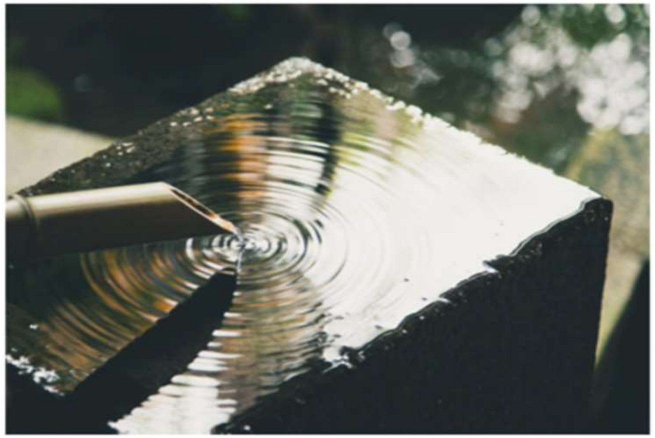
- With carbonate bedrock forming about 15% of Earth's ice-free surface, more than 25% of the world's population either lives on, or obtains its water from, karst aquifers



GLOBAL WATER CRISIS

- Key facts
  - Four billion people — almost two thirds of the world's population — experience severe water scarcity for at least one month each year.
  - Over two billion people live in countries where water supply is inadequate.
  - Half of the world's population could be living in areas facing water scarcity by as early as 2025.
  - Some 700 million people could be displaced by intense water scarcity by 2030.
  - By 2040, roughly 1 in 4 children worldwide will be living in areas of extremely high water stress.

unicef



Why is Groundwater Critical to Solving the Global Water Crisis?

The global water crisis is in fact a groundwater crisis because **groundwater makes up 99% of all liquid fresh water** and **in times of drought, groundwater is the only freshwater available in many regions**. Yet much of the educational material needed to solve the crisis exists behind expensive paywalls and global university programs are at present inadequate to address the issue.

THE GROUNDWATER PROJECT

GLOBAL WATER CRISIS

PLANETA FUTURO

EL PAÍS

EMERGENCIA CLIMÁTICA

La crisis del agua: no solo falta inversión, también necesitamos nuevas políticas

Dos próximas cumbres mundiales pueden ayudar a empezar a responder a los desafíos hídricos: la COP27 en Egipto en noviembre de este año y la cumbre del Agua de ONU en Nueva York en marzo de 2023

UNESCO Report : Global water crisis is threatening world peace and prompting calls for change

About 2.2 billion people live without access to safely managed drinking water

Emergenza idrica: 1,4 milioni di persone muoiono ogni anno nel mondo

di Vito de Ceglia

la Repubblica

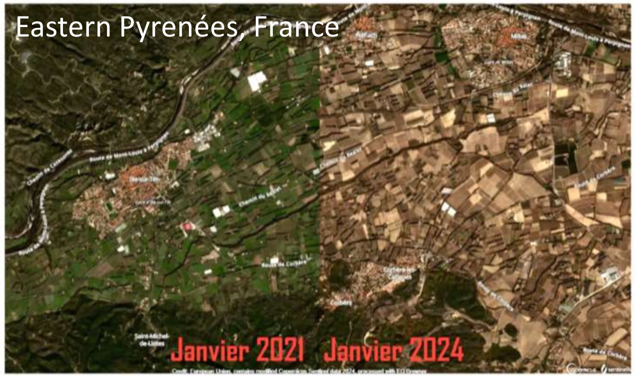
I rischi legati all'acqua aumenteranno a ogni incremento di grado del riscaldamento globale. Secondo Bcg e Wwf settore pubblico e privato, istituzioni finanziarie e Ong devono agire con un piano condiviso e dare priorità a soluzioni nature-based

FOTOGRAFIA

Uma visita a Aceredo, a aldeia que a seca devolveu à paisagem da Galiza

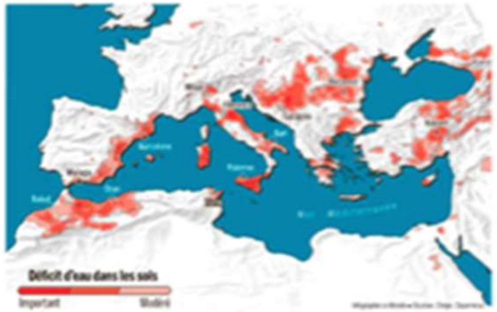
P3 . 22 de Fevereiro de 2022, 7:55

Público



Le Monde

UNE SÉCHERESSE CRITIQUE S'INSTALLE DANS LE BASSIN MÉDITERRANÉEN



Orovile Lake, California, USA. 2011 vs 2014

Drought Touches a Quarter of Humanity, U.N. Says, Disrupting Lives Globally

The New York Times

The crisis, worsened partly by climate change, has been accompanied by soaring food prices and could have consequences for hunger, elections and migration worldwide.

Water as a war weapon

The Guardian

As water becomes a weapon of war, we must focus on cooperation and peace

Peter Gleick

Record increase in water-related violence shows how urgently we need to reduce these tensions between countries

CDKN Climate & Development Knowledge Network

Water for peace, or water for war? Notes on weaponisation of water for World Water Day 2024

Le Monde

David Blanchon, géographe : « A l'échelle internationale, les "guerres de l'eau" ne sont pas une fatalité »

Propos recueillis par Claire Legros

Publié le 27 juillet 2024 à 05h00

NewSecurityBeat

the blog of the Environmental Change and Security Program

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ON THE BEAT

The Global Challenge of Water's Weaponization in War: Lessons from Yemen, Ukraine, and Libya

March 22, 2024 | By Lauren Herzer Risi & Eleanor Greenbaum

Revue Défense Nationale 2020/3 N° 828

Article de revue

L'eau, cause et instrument de guerre ?

Par Alain Lamballe

Pages 75 à 80

APPLICATIONS OF HYDROLOGY IN MILITARY PLANNING AND OPERATIONS

MILITARY HYDROLOGY BULLETIN 1

JUNE 1957

Protection des points d'eau

Évaluation de la mise en œuvre de l'arrêté du 4 mai 2017

Courrier international

GÉOPOLITIQUE • GUERRE EN UKRAINE

Récit. Des Romains à l'Ukraine, la longue histoire de l'eau comme arme de guerre

Le 6 juin, le barrage de Kakhovka sur le fleuve Dniepr, dans le sud de l'Ukraine, a été détruit. Ce qui semble être un acte de sabotage n'est pas un cas isolé dans l'histoire, pointe le quotidien italien "La Repubblica". Depuis deux millénaires, en effet, l'eau est utilisée pour bloquer ou détruire des armées ennemies.

Franck Galland

Préface de Cédric Lewandowski

Guerre et eau

L'eau, enjeu stratégique des conflits modernes

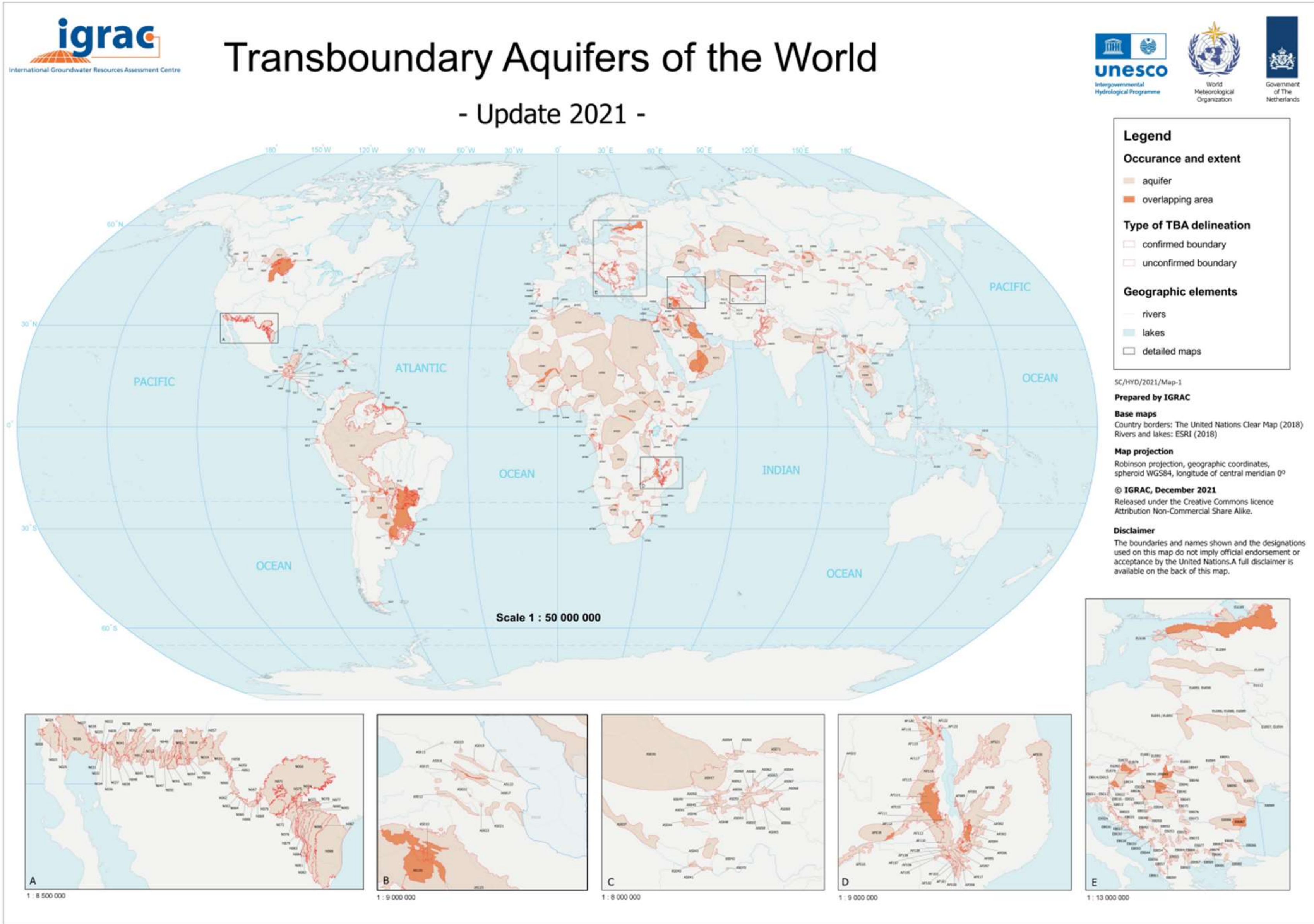
Robert Laffont

DefenseNews

Opinion | **Hydraulic warfare is here to stay. NATO should plan for it.**

By Lionel Beehner, Liam Collins and John Spencer — Jun 14, 2023

TRANSBOUNDARY AQUIFERS AND CONFLICTS



WATER CONFLICTS

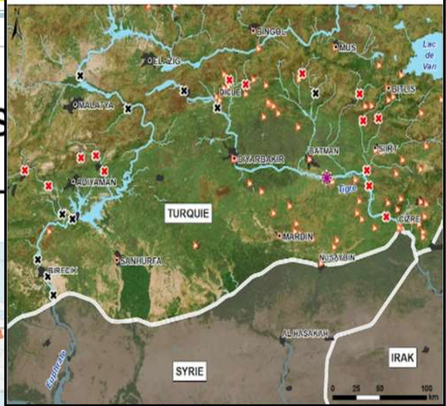
PACIFIC INSTITUTE — THE WORLD'S WATER

Information on the World's Freshwater Resources

- "**Trigger:**" Water as a trigger or root cause of conflict, or underlying cause of ongoing tension that is contributing to conflict, where there is a dispute over the control of water or water systems, or where economic or physical access to water, or scarcity of water, triggers violence.
- "**Weapon:**" Water as a weapon of conflict, where water resources, or water systems themselves, are used as a tool or weapon in a violent conflict.
- "**Casualty:**" Water resources or water systems as a casualty of conflict, where water resources, or water systems, are intentional or incidental casualties or targets of violence.

The Southeastern Anatolia Project (GAP): Between Colossal Economic Undertaking and Unprecedented Counter-insurgency Tool

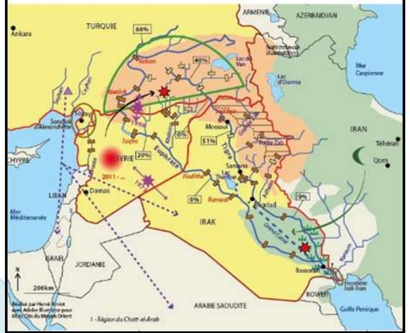
By Emile Bouvier, Published on 05/11/2020 • Updated on 05/11/2020 •



Water: Cause or Pretext for Conflicts? The Example of the Tigris and Euphrates

By Hervé Amiot, Published on 11/28/2013 • Updated on 05/11/2020

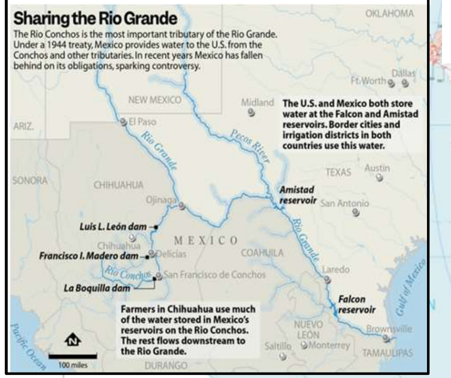
The Tigris and Euphrates form the fertile crescent of Mesopotamia, where Neolithic civilization emerged in the 9th millennium BCE. Today, however, the waters of these rivers are less associated with prosperity and more with conflicts. Population growth requires ever-increasing withdrawals from the two rivers to support the agricultural and hydroelectric sectors.



The water war between the US and Mexico

By Devika Rao, Published on 06/27/2024 • THE WEEK

The U.S. and Mexico are experiencing another border dispute, and this one is about water. The conflict stems from an 80-year-old treaty where the countries agreed to share water from the Colorado River and the Rio Grande. However, because water is in more demand but scarcer than ever, sharing has not been going to plan.



Water disputes in the Mekong basin

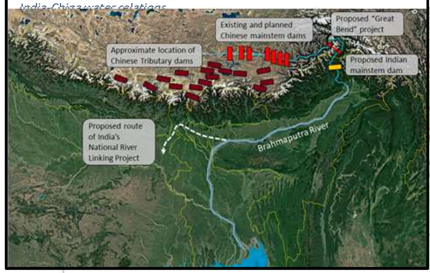
By Hervé Amiot, Published on 11/28/2013 • Updated on 05/11/2020

The Mekong is south-east Asia's longest river (around 4 900km). From its source in Tibet, it flows southwards through the Chinese province of Yunnan before passing through five south-east Asian countries (Myanmar, Thailand, Laos, Cambodia and Vietnam). Nearly half of the river is in China, where it is known as the Lancang. For the 70 million people who live in the Mekong basin, the river is a vital source of food and water, as well as an important transport route. Increasingly, it is being used to generate hydroelectricity. Human activity threatens the river's fauna and flora, and competition for natural resources is intensifying.

The Water Wars : India, China and the Brahmaputra

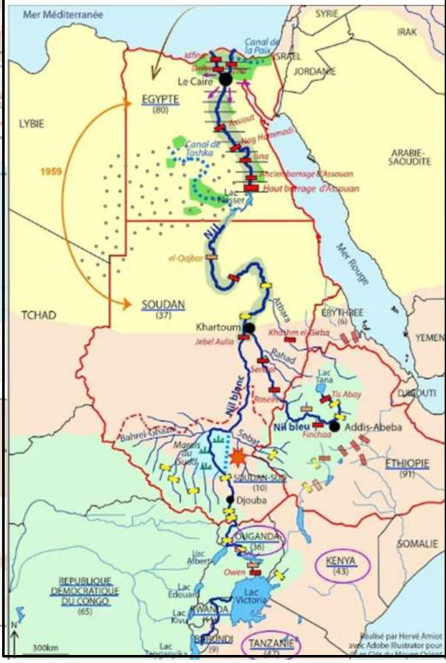
By Anya Wahal, Published on December 8, 2022

What the hydrology and geopolitics of the Brahmaputra River mean for India-China water relations



The Nile: A Driver of Economic Development and Geopolitical Tensions

By Hervé Amiot, Published on 11/28/2013 • Updated on 05/11/2020



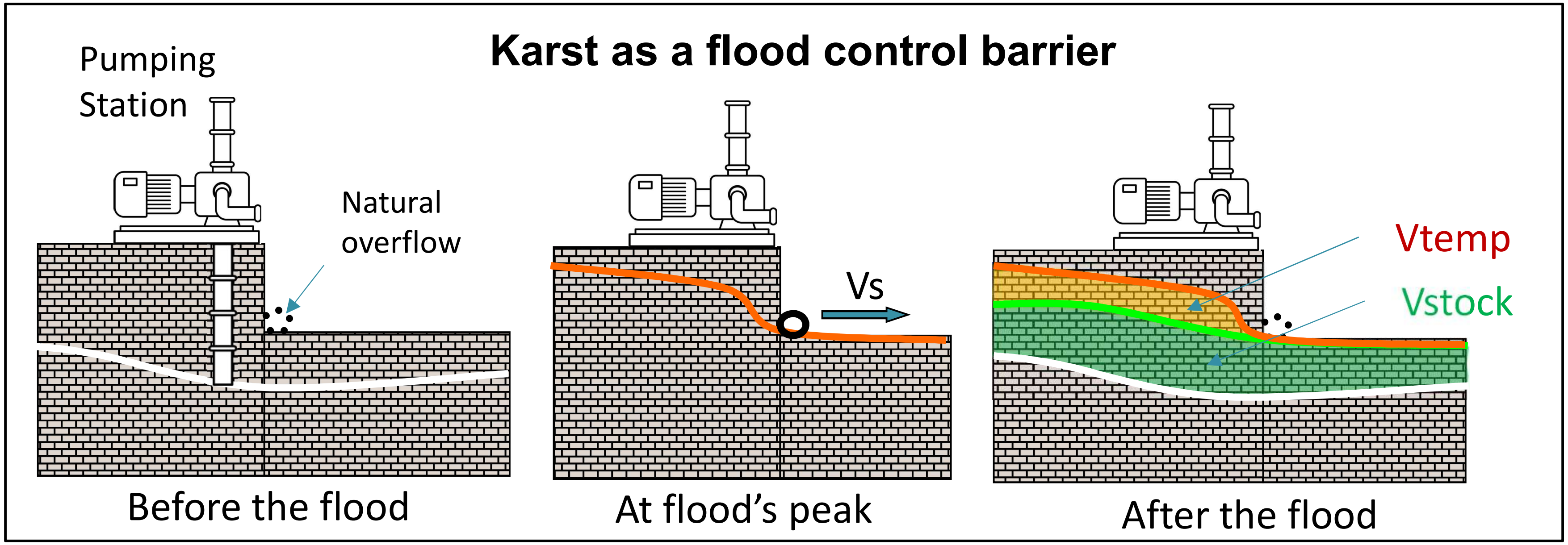
Water and Conflicts in the Jordan Basin

By Hervé Amiot Published on 12/12/2013 • Updated on 03/11/2018 •

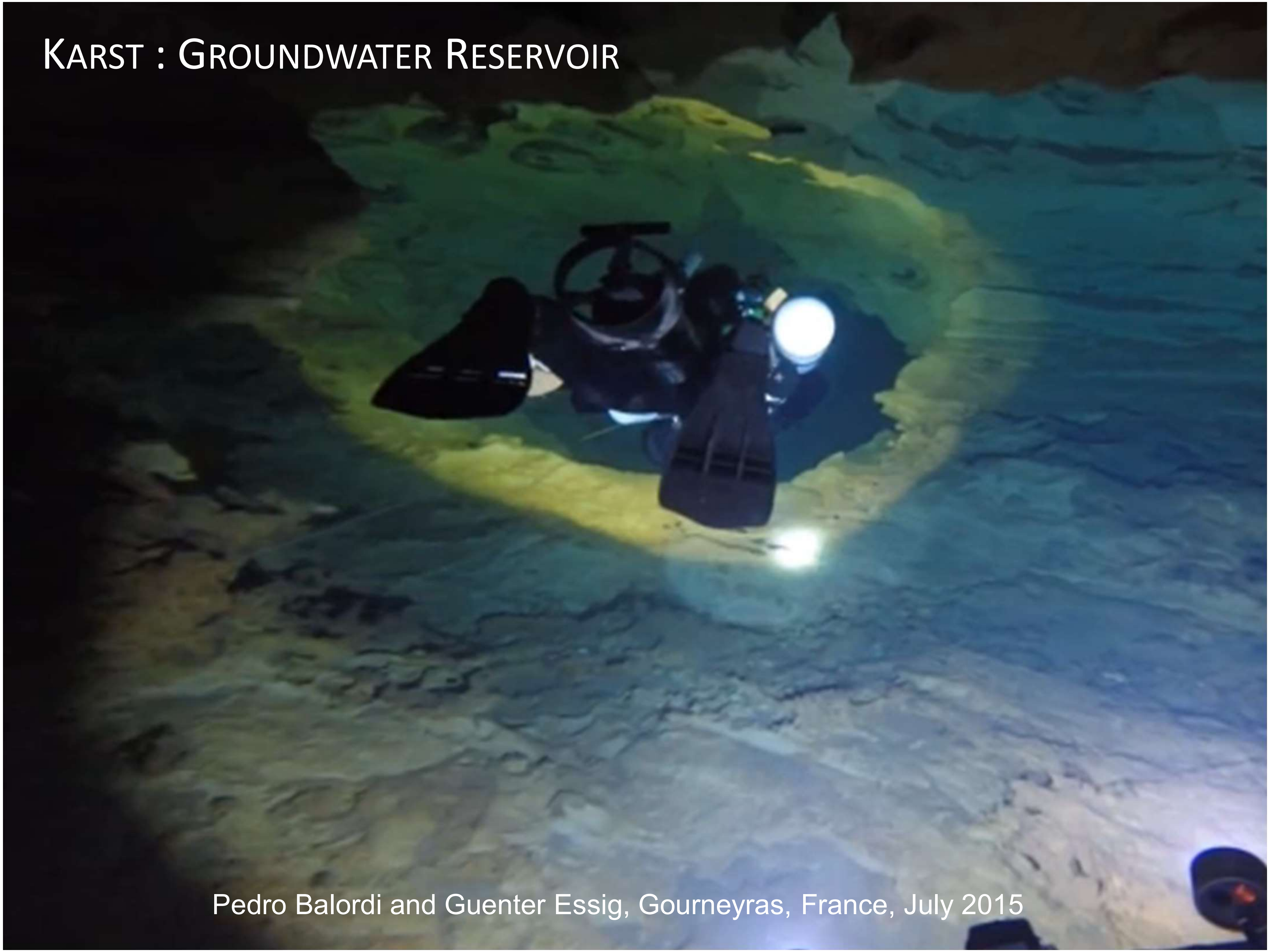
While the Jordan Basin is not as large as those of the Tigris-Euphrates or the Nile, it is nevertheless the site of perhaps more frequent and intense conflicts. Originating in Lebanon, the Jordan River separates Israel from neighboring Arab states, Syria and Jordan.

Robinson projection, geographic coordinates, spheroid WGS84, longitude of central meridian 0º

Role of Karst in Flash Floods



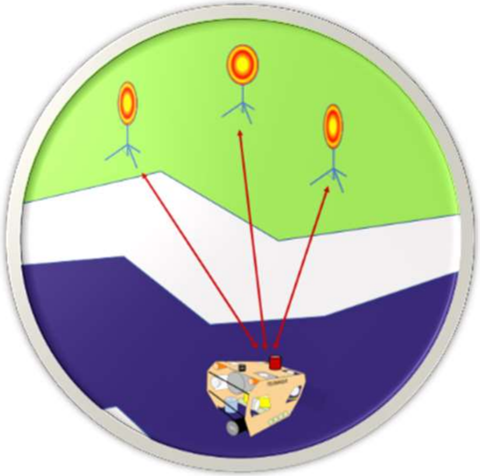
KARST : GROUNDWATER RESERVOIR

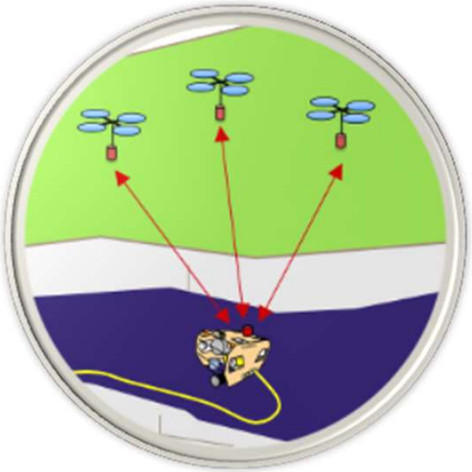


Pedro Balordi and Guenter Essig, Gourneyras, France, July 2015

KARST EXPLORATION : CONSTRAINTS

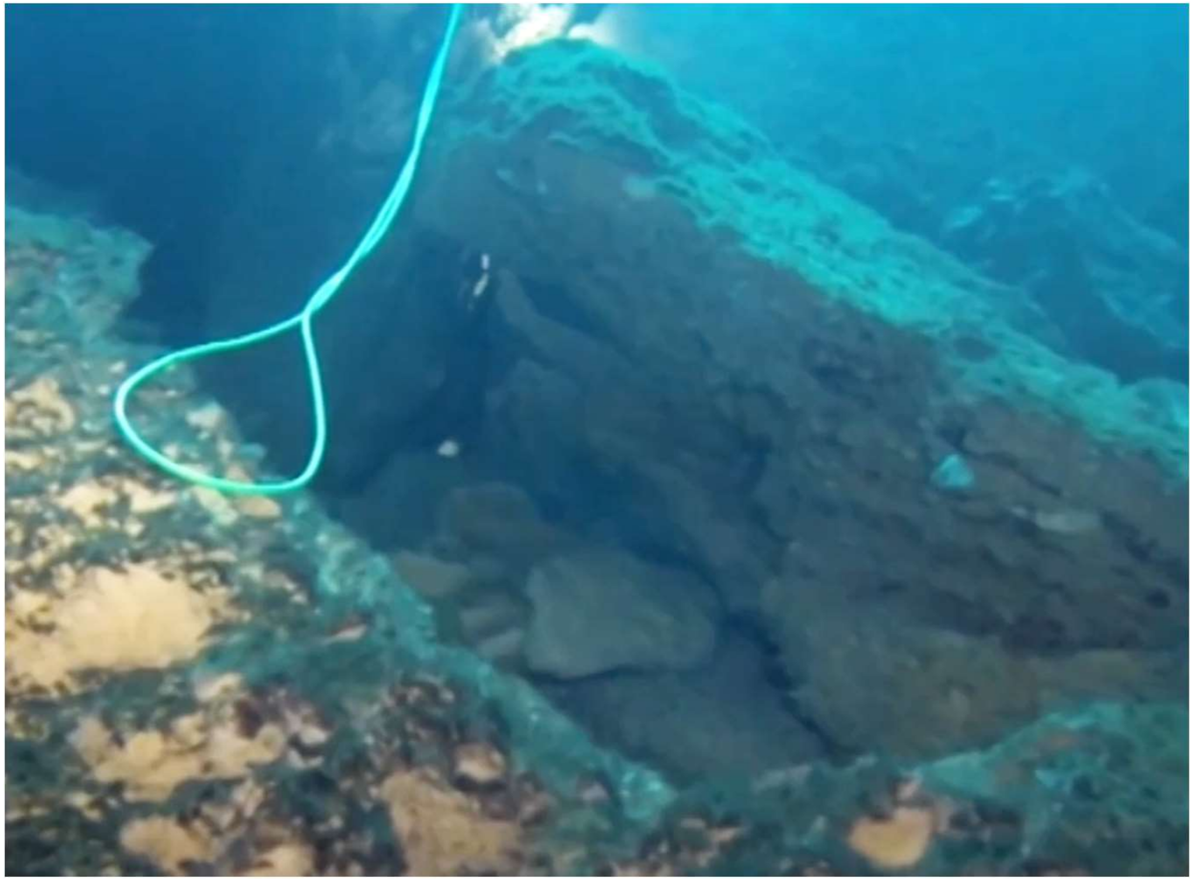
- Exploration of Confined, Unstructured, Subaquatic Environment
  - GPS denied -> Undergound GPS : **Dirac System** © Syera





KARST EXPLORATION : CONSTRAINTS

- Exploration of Confined, Unstructured, Subaquatic Environment
  - No GPS -> Undergound GPS : **Dirac System** © Syera
  - Cable / No cable ?

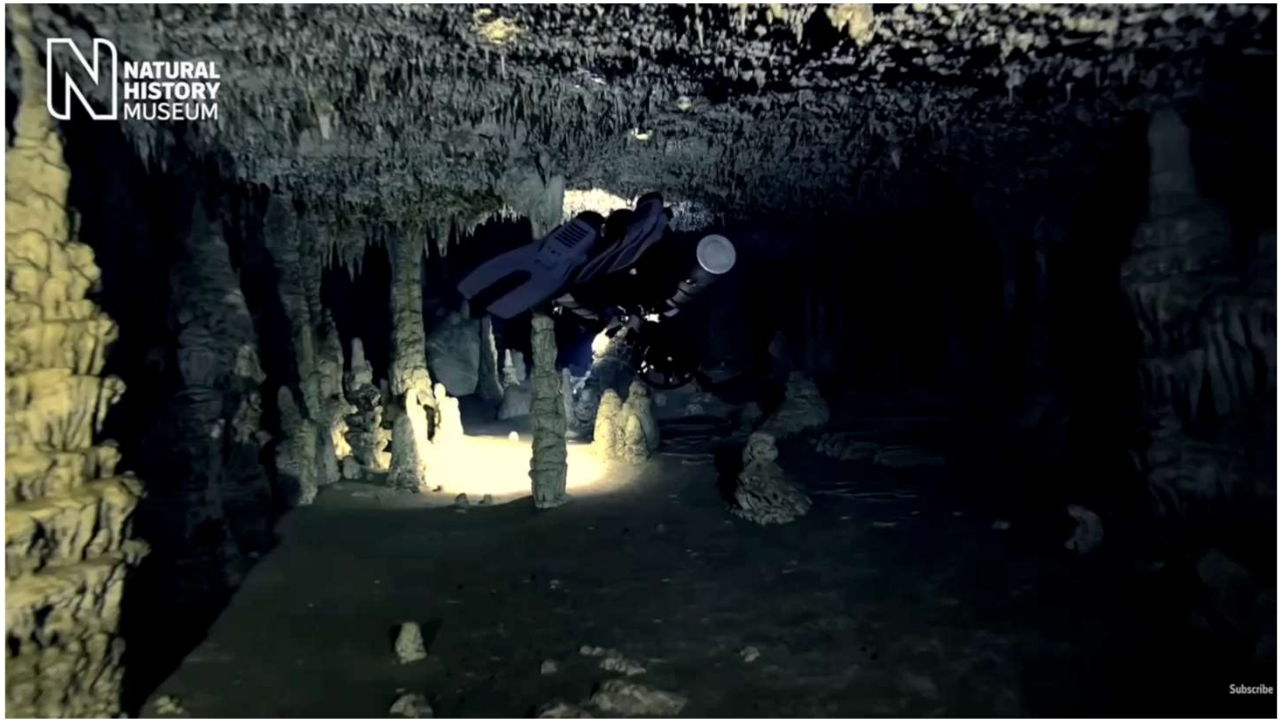


KARST EXPLORATION : TRADITIONAL / UNCONVENTIONAL TOOLS

- Exploration of Confined, Unstructured, Subaquatic Environment
  - No GPS -> Undergound GPS : **Dirac System** © Syera
  - Cable / No cable ?
  - Vision or Acoustic ?

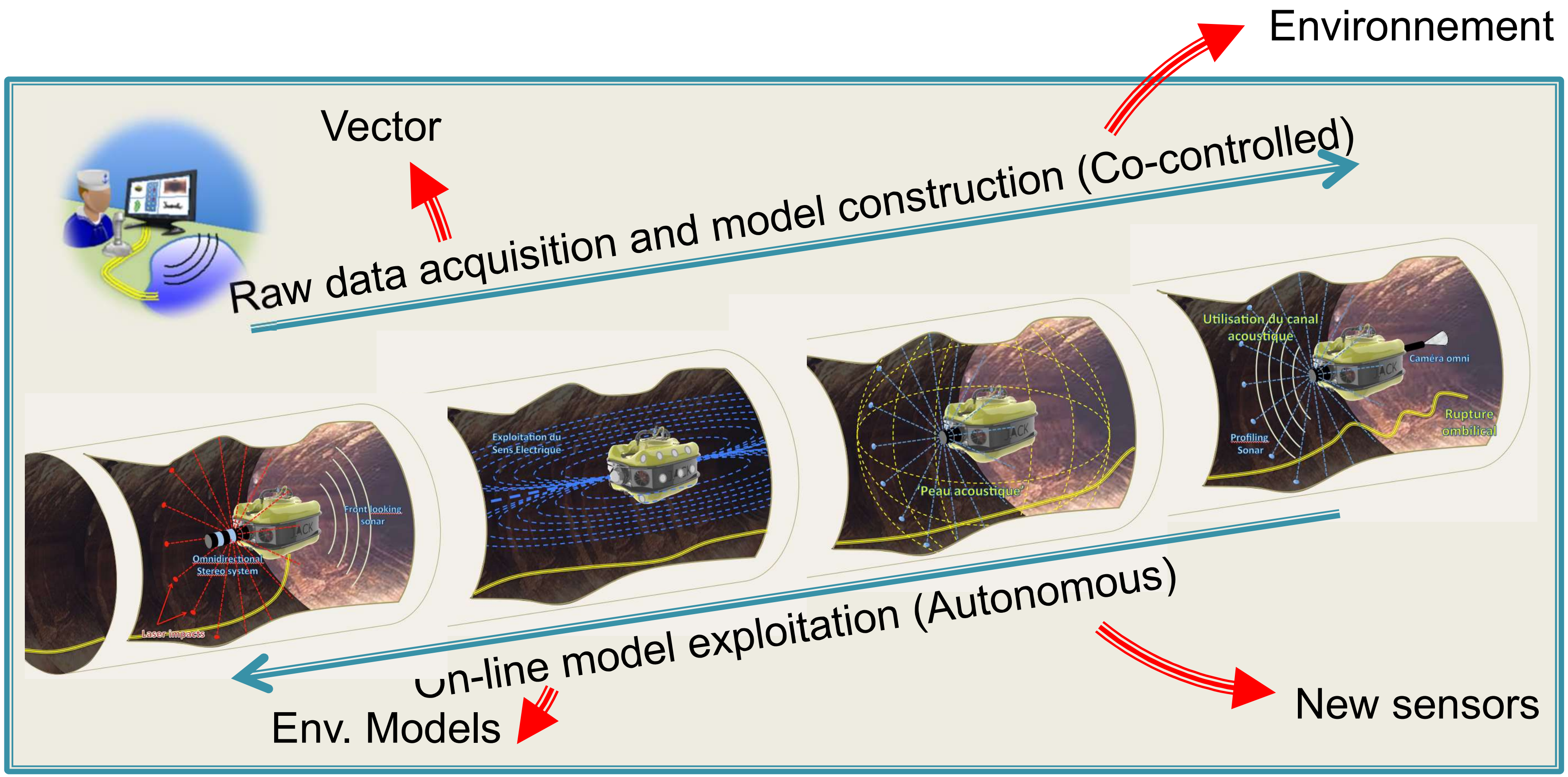
KARST EXPLORATION : TRADITIONAL / UNCONVENTIONAL TOOLS

- Exploration of Confined, Unstructured, Subaquatic Environment
  - No GPS -> Undergound GPS : **Dirac System** © Syera
  - Cable / No cable ?
  - Vision or Acoustic ?
  - Environmental disturbances and complexity



KARST EXPLORATION : GLOBAL STRATEGY

- Exploration of Confined, Unstructured, Subaquatic Environment

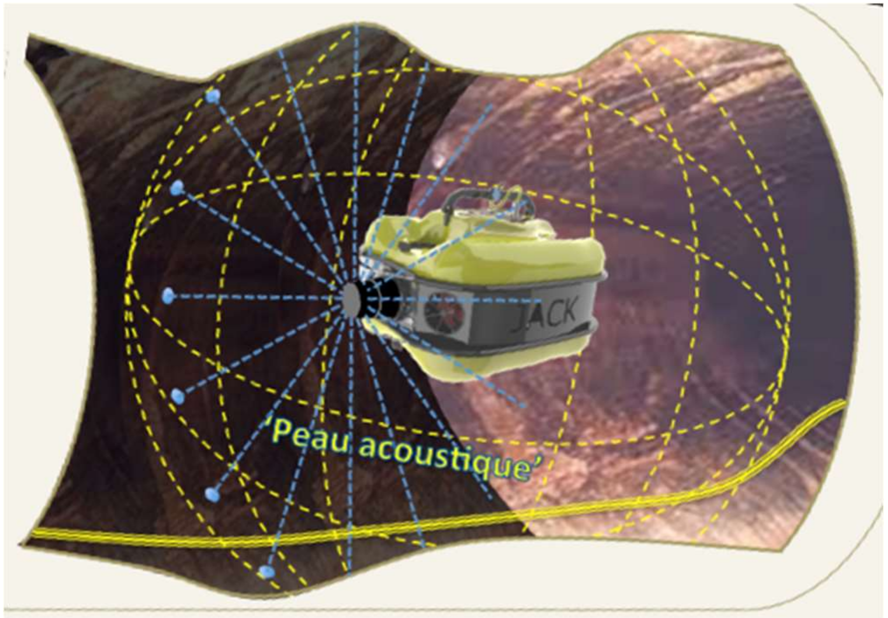


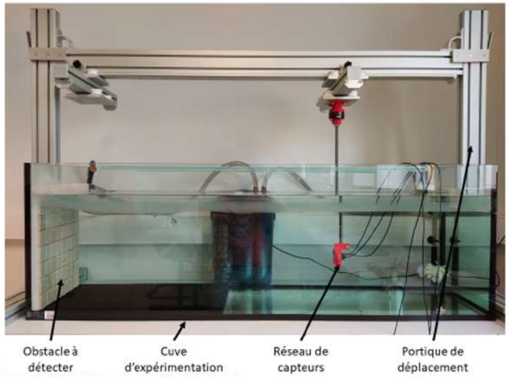
Karst Exploration : The Robotic Challenges

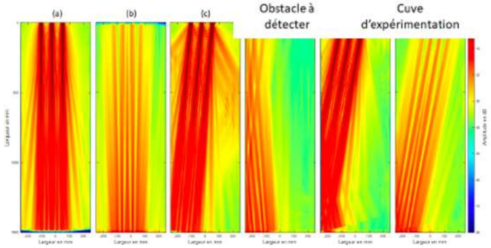
- **Unconventional Sensors**
  - Acoustic Skin
  - Active Umbilical
  - Electric Sense
  - Acc. Interf. patterns as inv. landmarks
- **Navigation**
  - Global Navigation System / Mag. Pos.
  - No distinction btw nav. sensors / payload
  - Acoustic / visual SLAM
  - Vacancy Evidence Grids
  - Clustering and Saliency Data Analysis
- **Guidance**
  - Autonomous Centring
  - Autonomous Targeting
  - Env. Models on-line building / exploit°
- **Models**
  - Multi-modality & Scalability
  - Uncertainty Consideration
- **Control**
  - Robustness
  - Co-control,
  - Open-loop stability
- **Actuation**
  - Reactive redundant A.S.
  - Variable Geometry A.S.
  - Anguilliform Locomotion
- **Mission Management**
  - Management of sensors (acc. jamming)
  - Adaptive Autonomy
  - GoP & Interval approach
- **Technology**
  - Active Truncanner, NRJ opt.
  - Magnetic Positionning
- **Economic**
  - Evangelization of a Blue Ocean

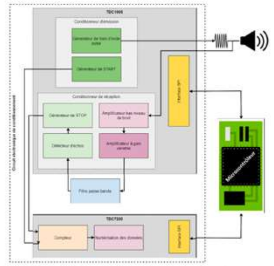
KARST EXPLORATION : UNCONVENTIONAL SENSORS

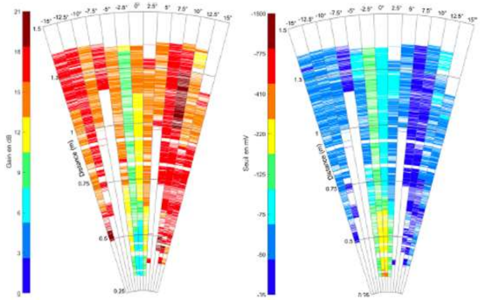
- **Acoustic Skin**



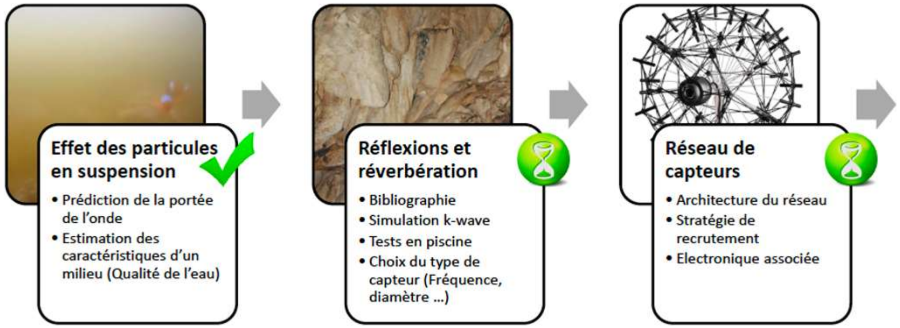


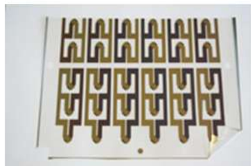


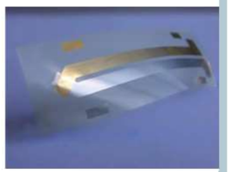




IGURE 5.12 – Variation du gain (à gauche) et du seuil (à droite) de détection de rcuit de conditionnement en fonction de la distance de détection et l'angle d'incidence. onfiguration : 3 transducteurs émetteurs espacés de 5 cm, réflexion contre le paroi de iquarium en verre. Représentation des variations sur le transducteur centrale.

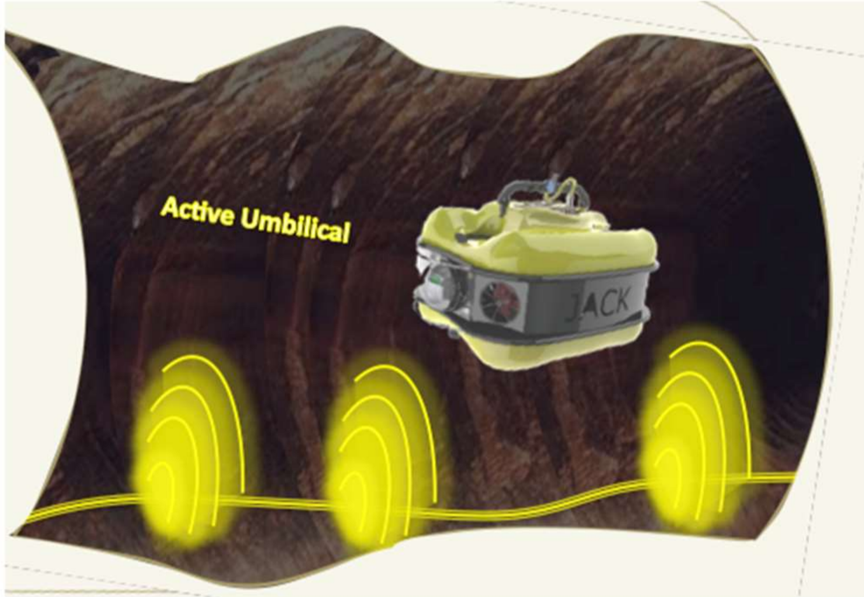




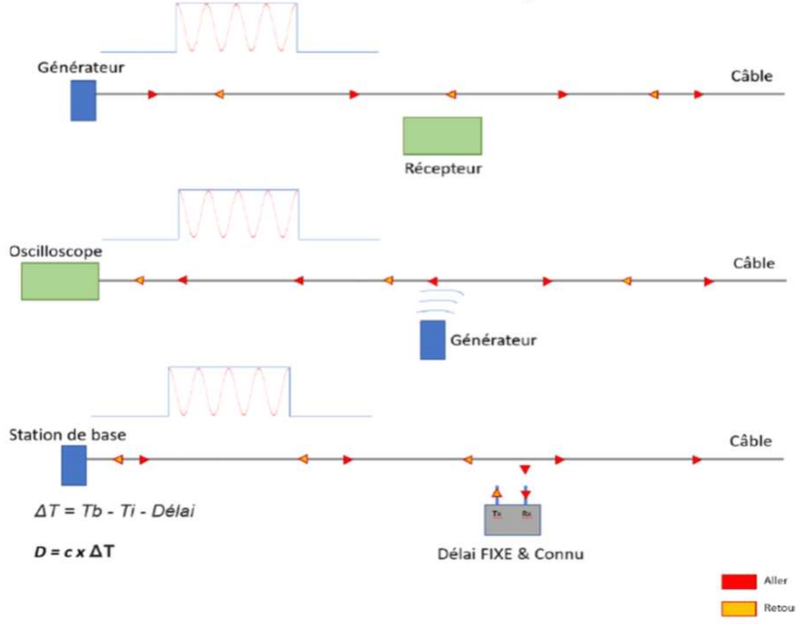


Karst Exploration : Unconventional Sensors

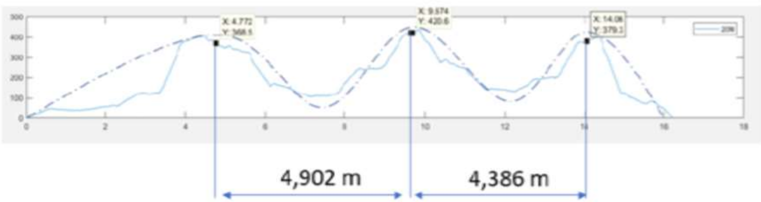
- **Active Umbilical**

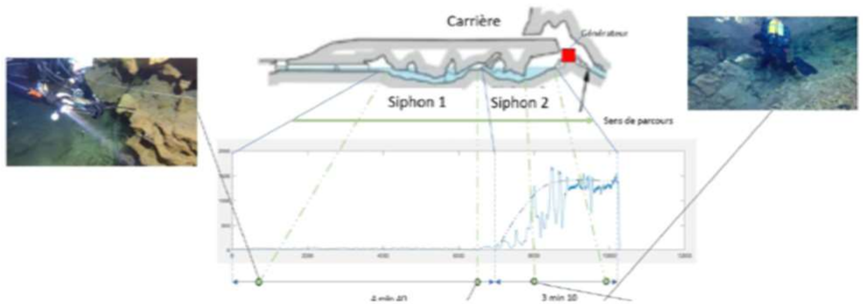


Wireless Communication/localisation with Burst signal



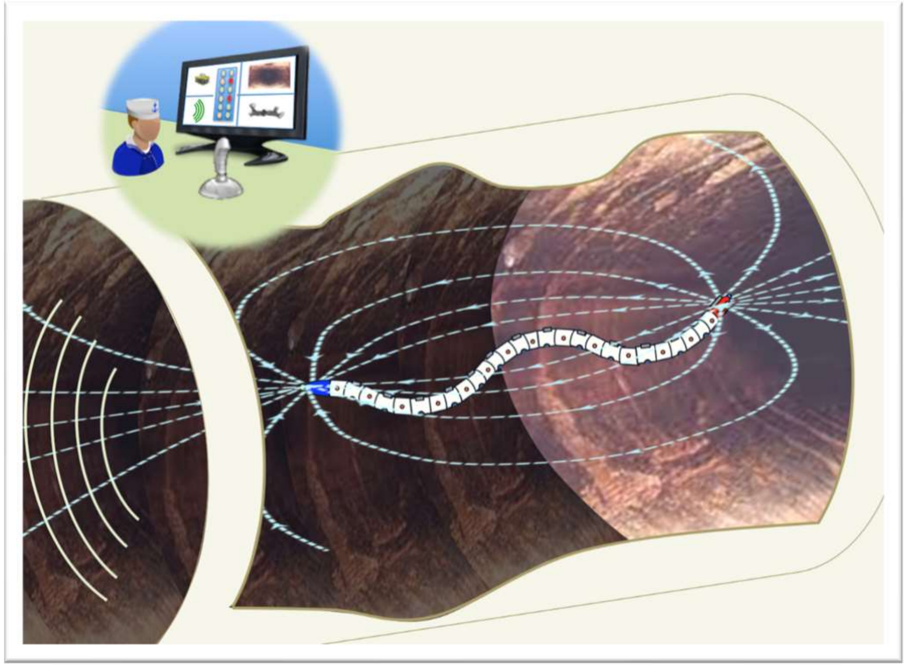
Détection of Stationnary waves in single wire

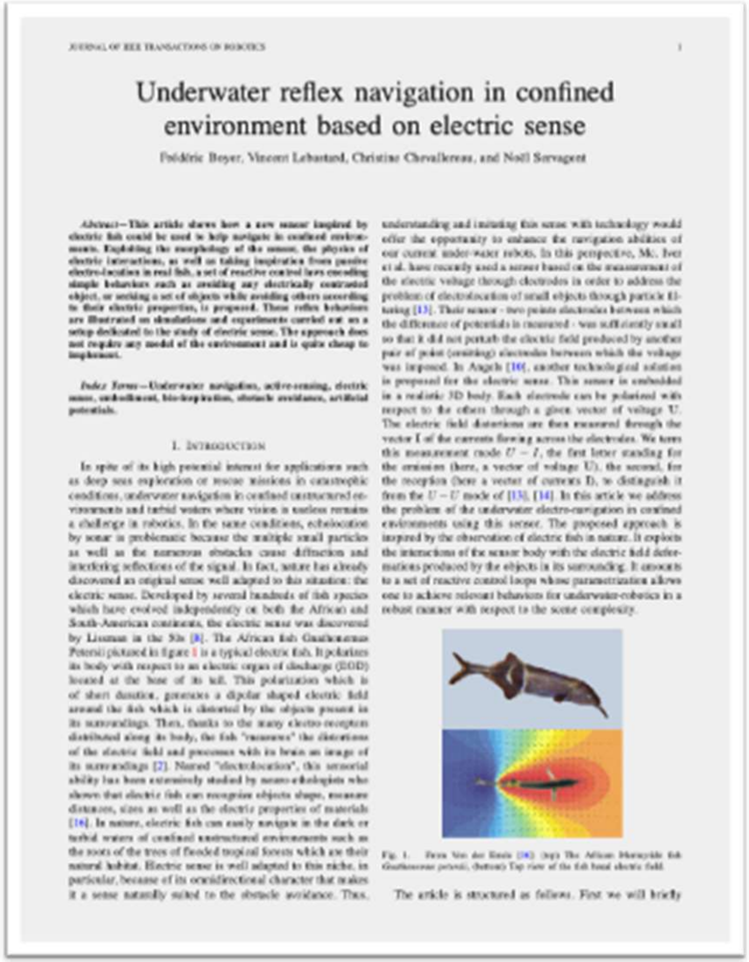




Karst Exploration : Unconventional Sensors

- **Electric Sense**





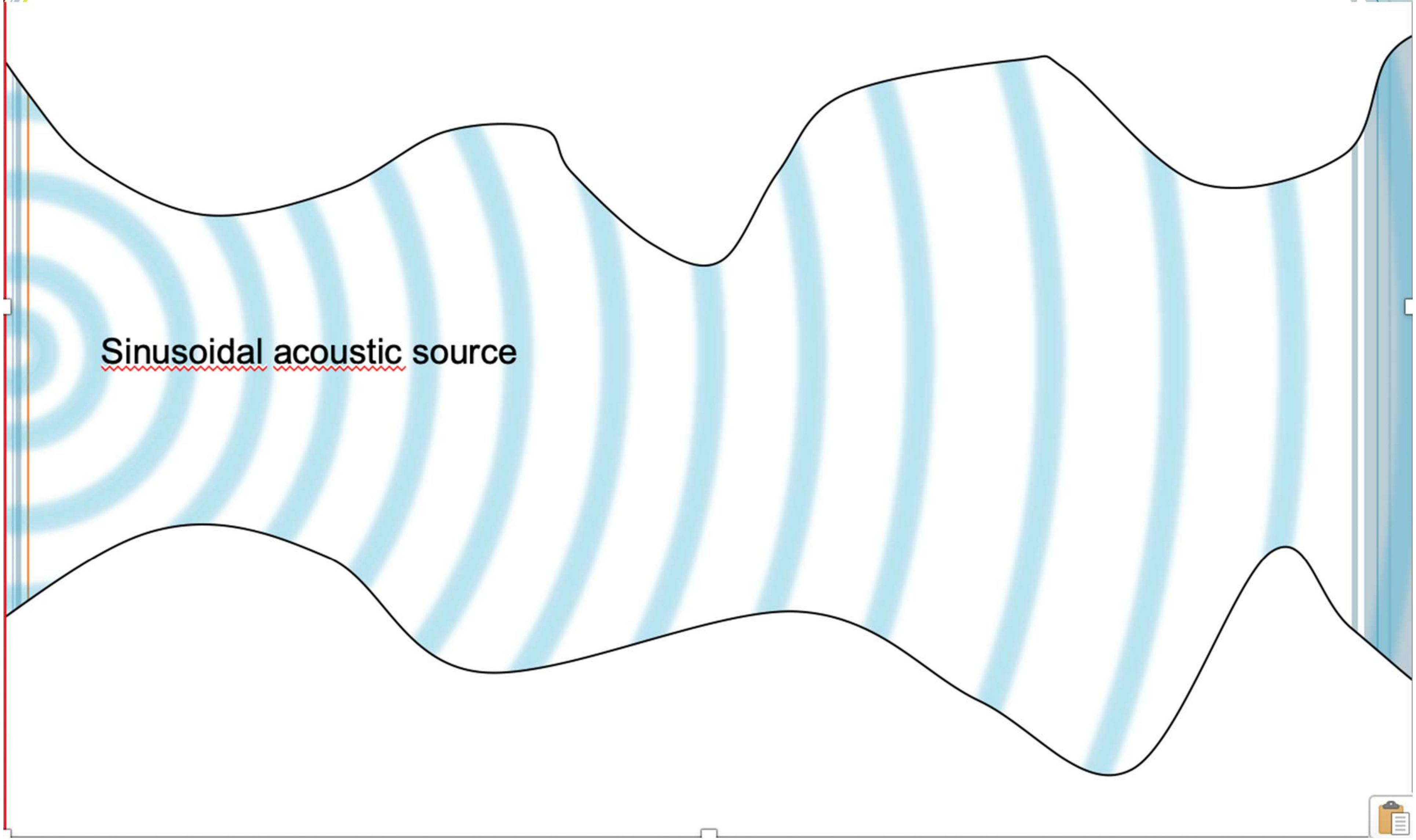
Underwater reflex navigation in confined environment based on electric sense

Frédéric Boyer, Vincent Lebastard, Christine Chevallereau, and Noël Servagent

I. Introduction

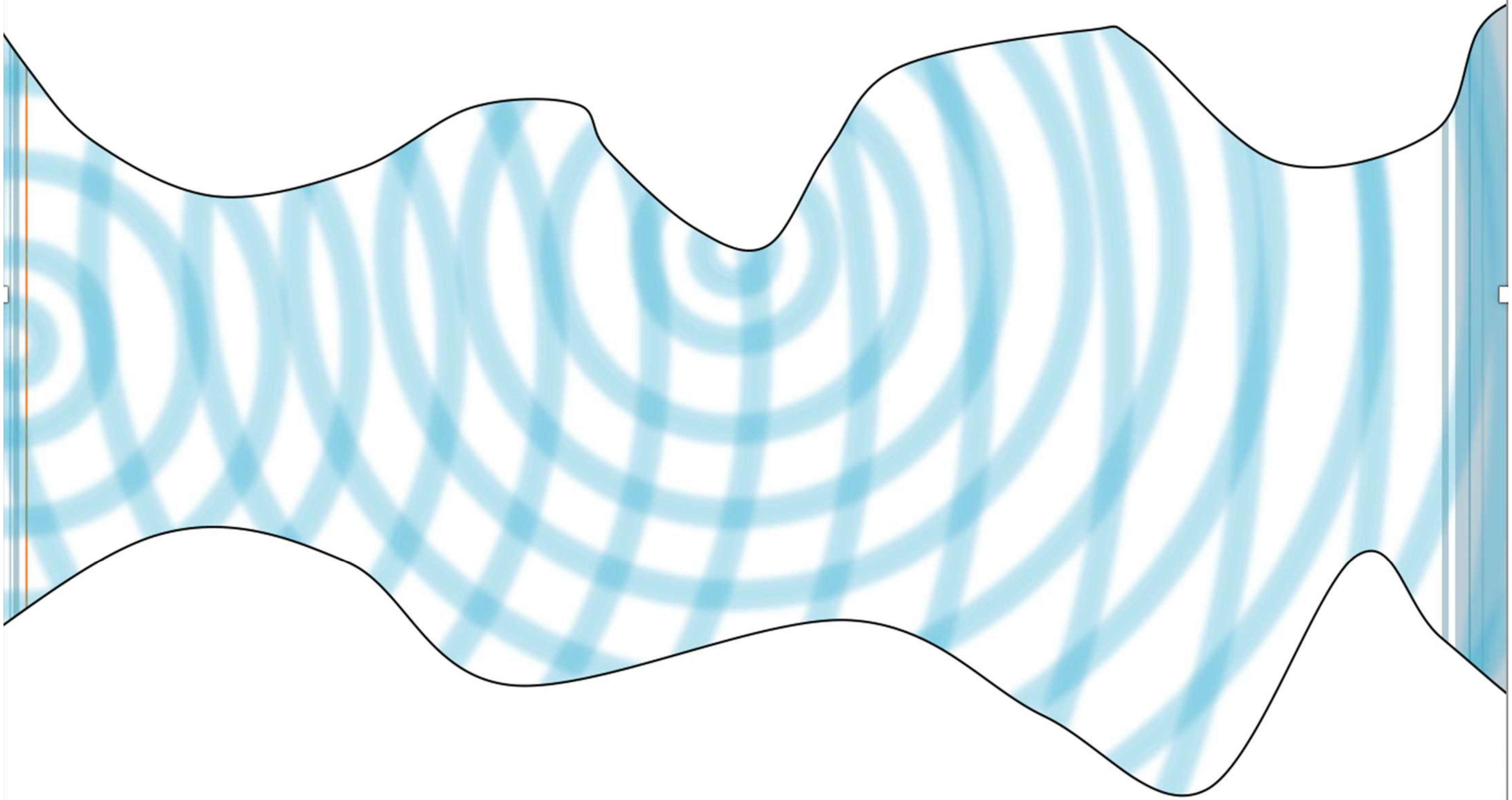
KARST EXPLORATION : UNCONVENTIONAL SENSORS

- **Acoustic Interference Paterns as Invariant Landmarks**



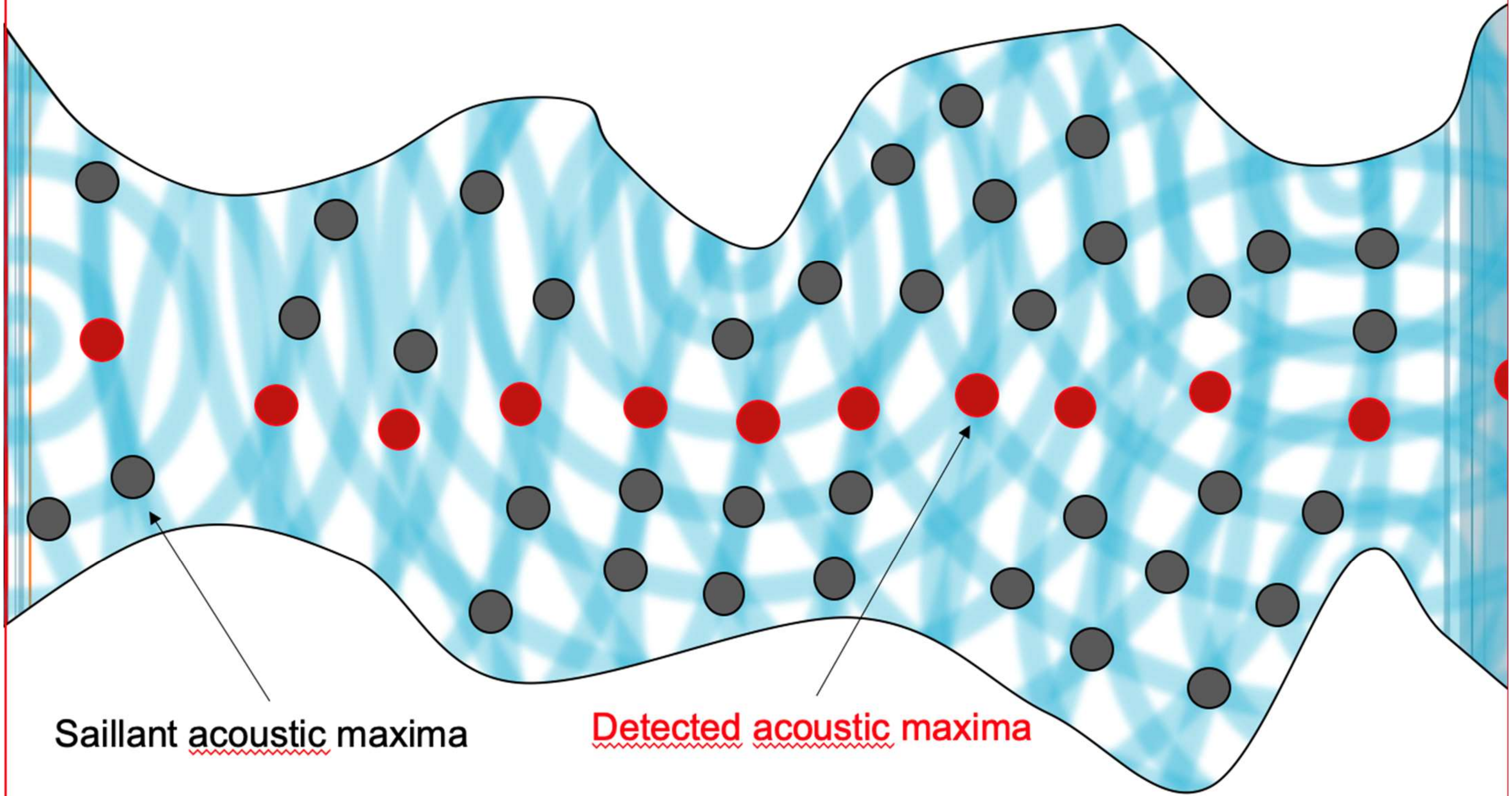
KARST EXPLORATION : UNCONVENTIONAL SENSORS

- **Acoustic Interference Paterns as Invariant Landmarks**



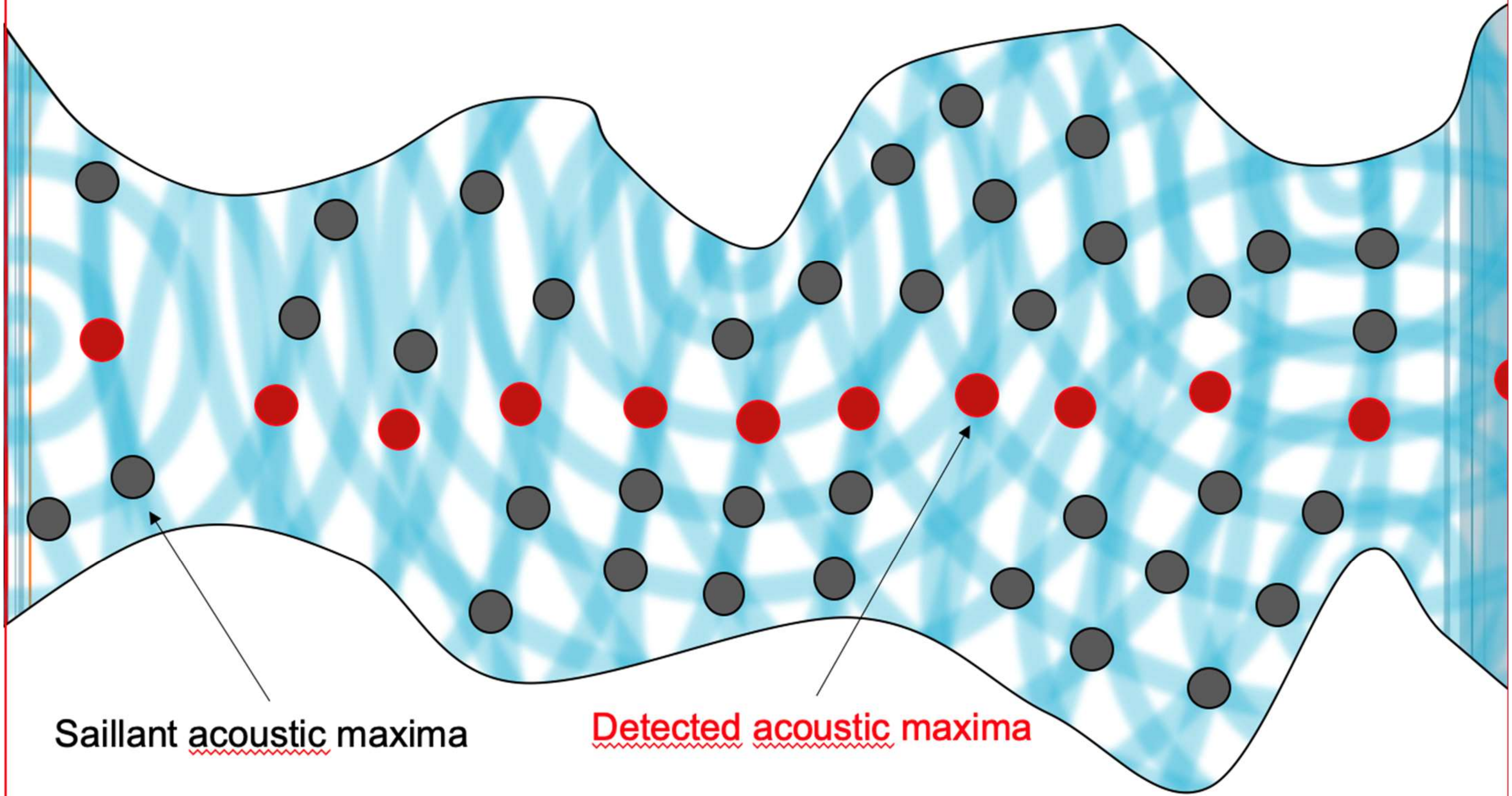
Karst Exploration : Unconventional Sensors

- **Acoustic Interference Paterns as Invariant Landmarks -> SLAM**



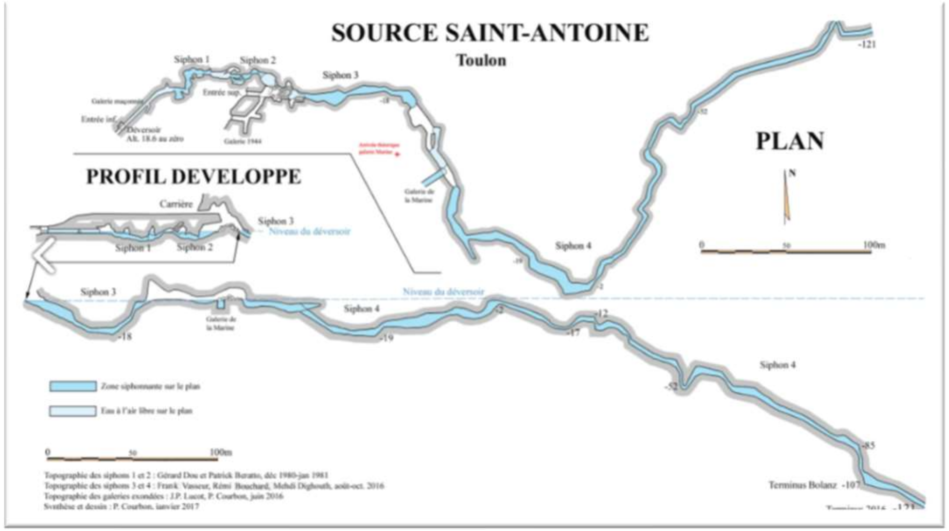
KARST EXPLORATION : UNCONVENTIONAL SENSORS

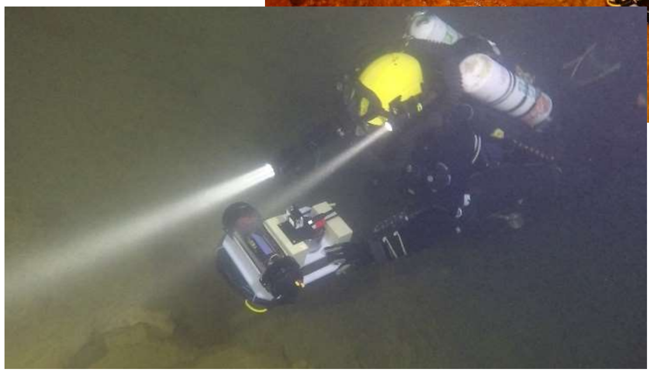
- **Acoustic Interference Paterns as Invariant Landmarks -> SLAM**

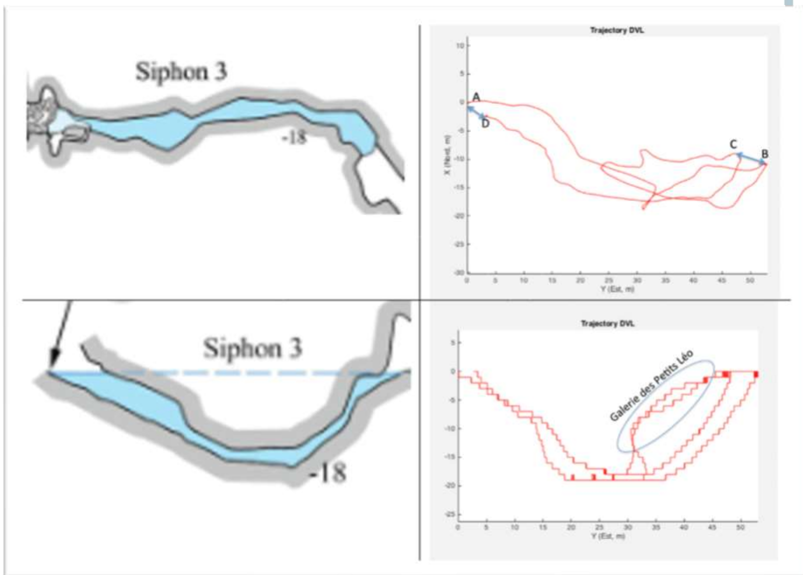


KARST EXPLORATION : NAVIGATION

- **Global Navigation System**
  - IMU (SBG Ellipse D)
  - DVL (Nortek 1000)
  - Pressure Sensor (Blue Robotics)

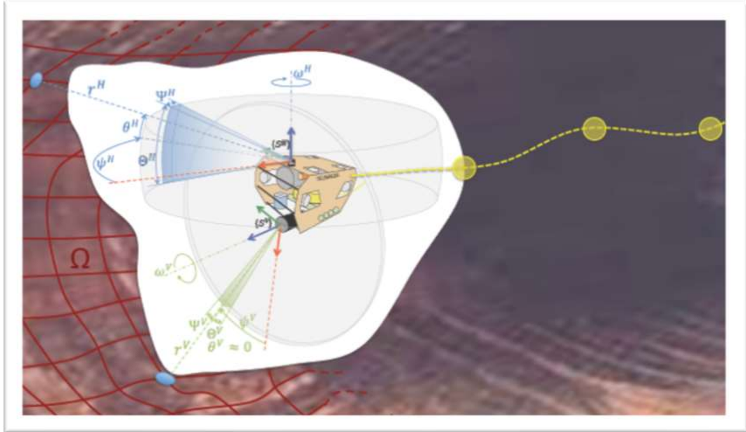


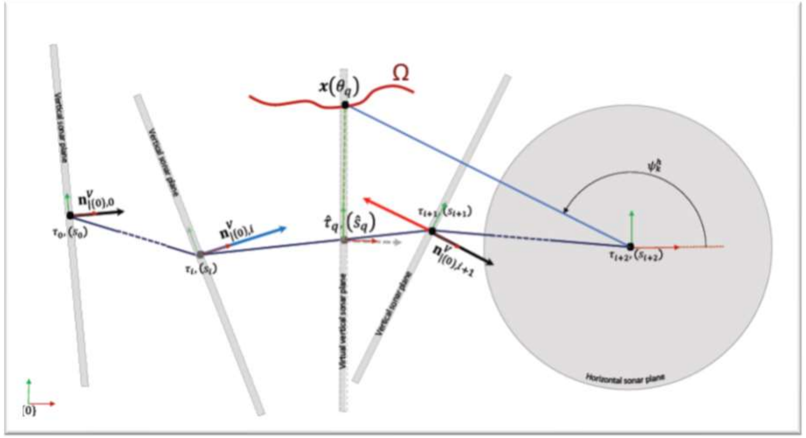


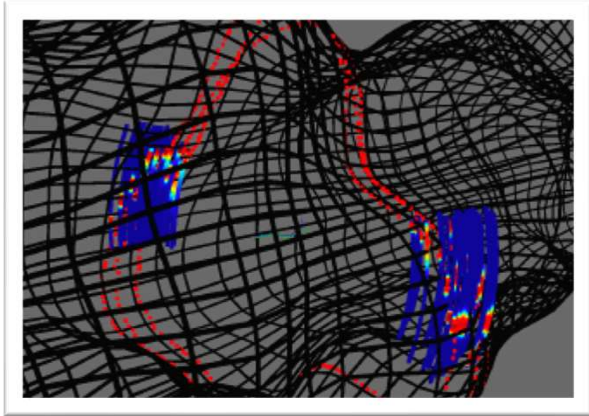


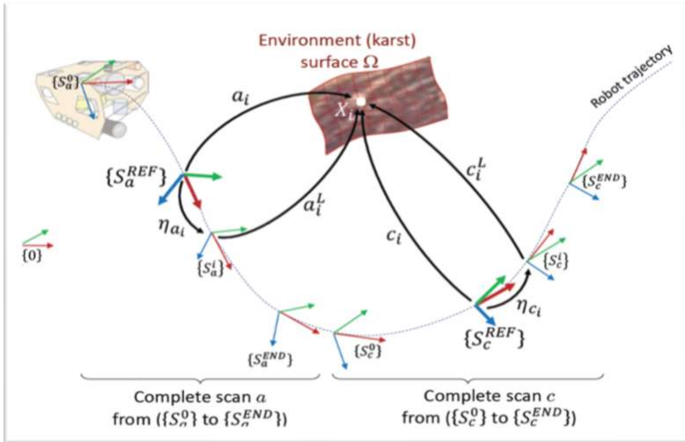
KARST EXPLORATION : NAVIGATION

- **Acoustic SLAM**
  - Vertical / Horizontal Scans Fusion
  - Scan Matching (point to point and point to plane)
  - Graph SLAM and loop closure detection





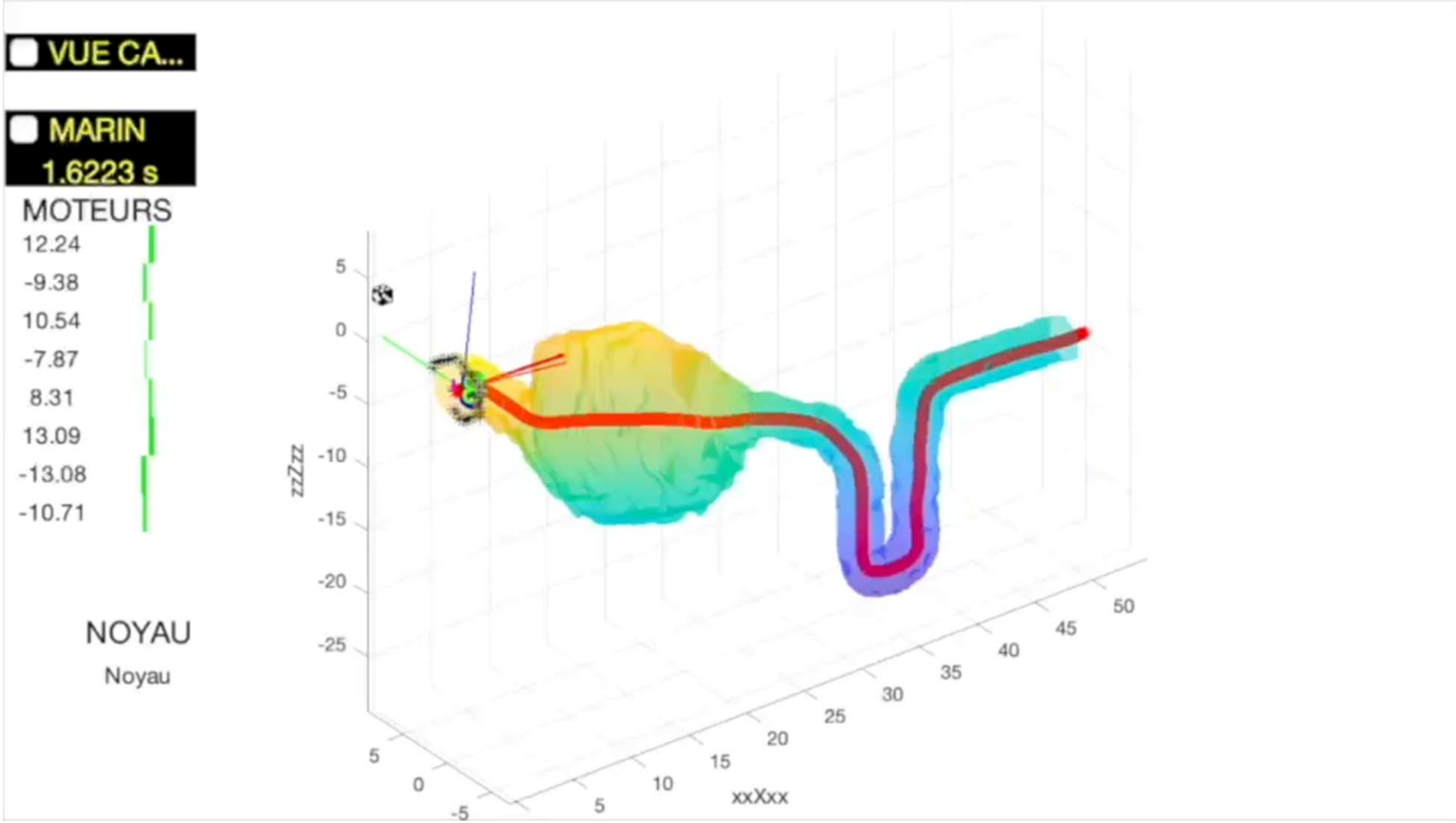




[J-22] Yohan Breux, Lionel Lapierre. 'Elevation Angle Estimations of Wide-Beam Acoustic Sonar Measurements for Autonomous Underwater Karst Exploration', Sensors, MDPI, 2020, 20 (14), pp.4028, https://doi.org/10.3390/s20144028

KARST EXPLORATION : NAVIGATION

- **Acoustic SLAM, with helicoidal constraints**



Karst Exploration : Navigation

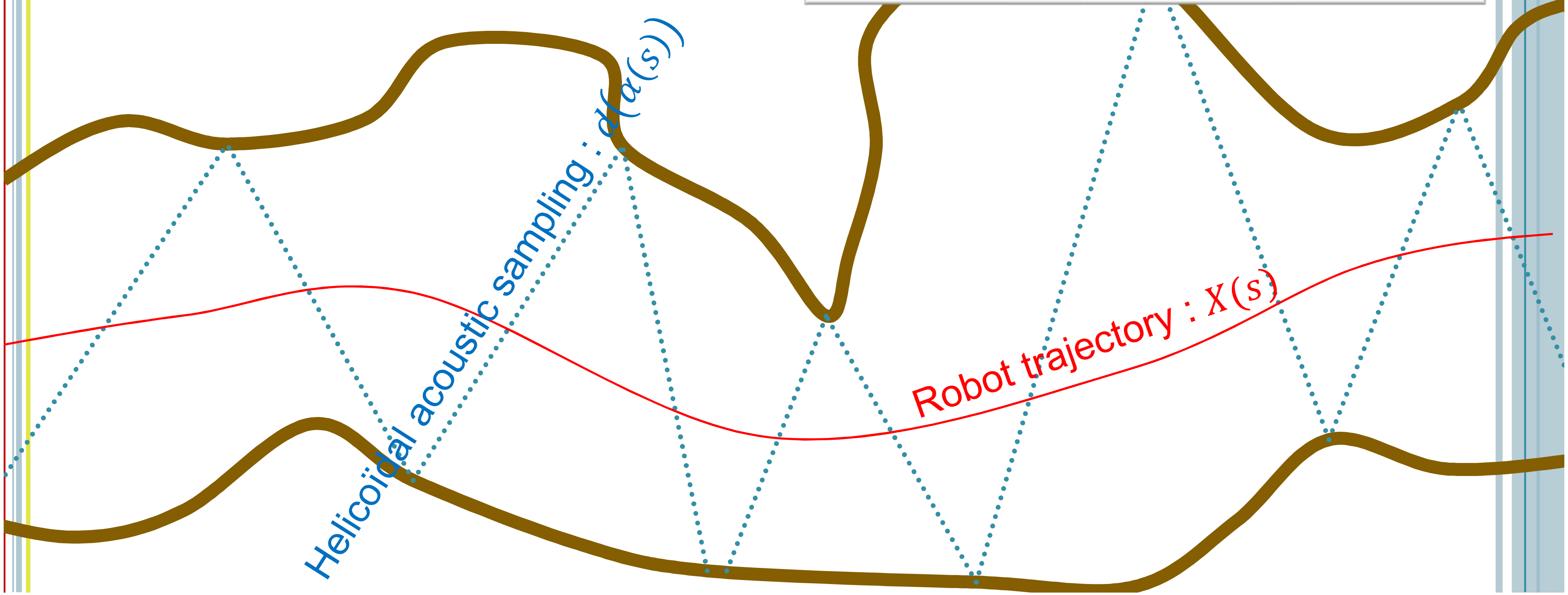
- **Clustering and Saliency Data Analysis**

$$f\left(\mathrm{t}^{\circ}, \mathrm{Cond}, \mathrm{V}_{10}, \mathrm{C}_{\mathrm{s}}, d(\alpha)\right)?$$

which maximizes

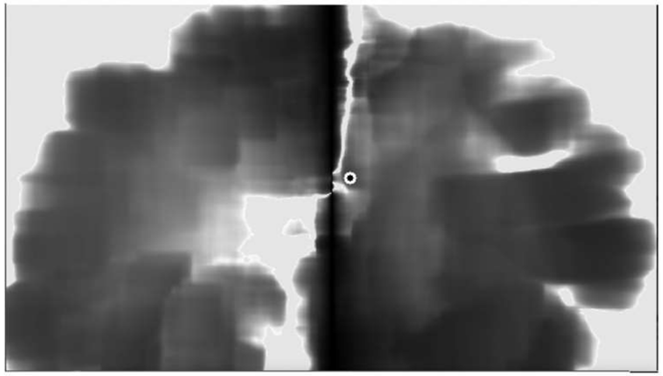
$SALS\left(f(s)\right)$ over S,

$\mathrm{s} \in \mathrm{S}$

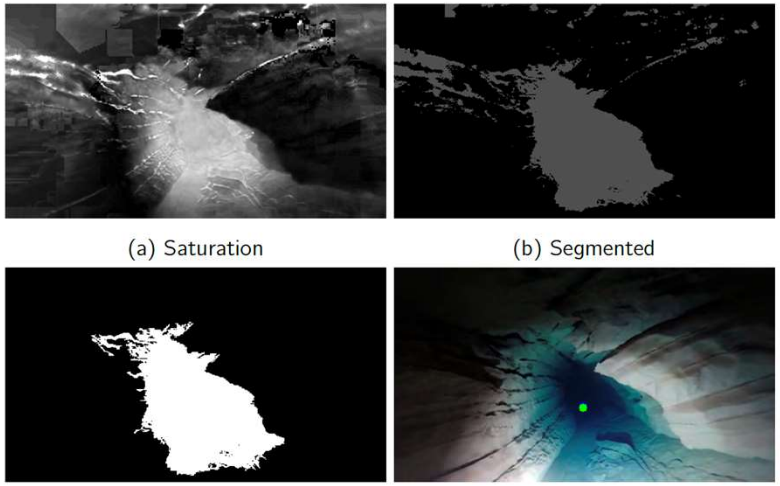


KARST EXPLORATION : GUIDANCE

- **Visual Analysis : Centering, Advancement Vector, SLAM, 3D reconstruction**



Depth map



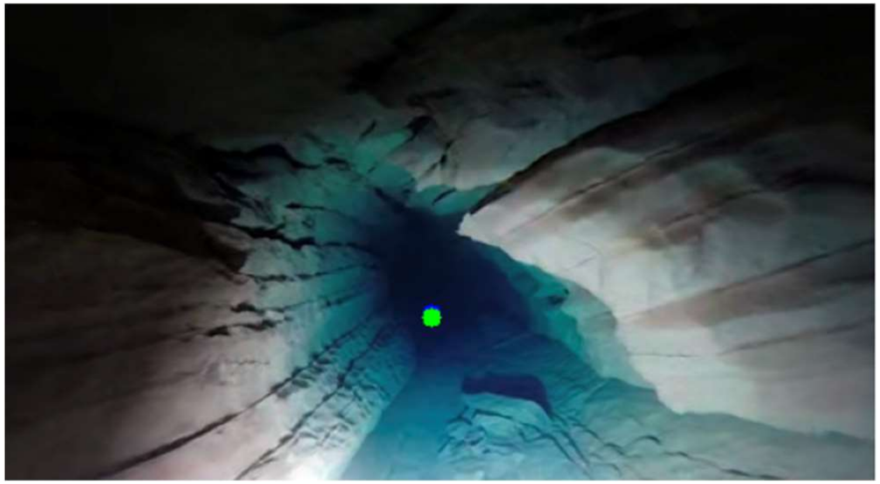
(a) Saturation (b) Segmented

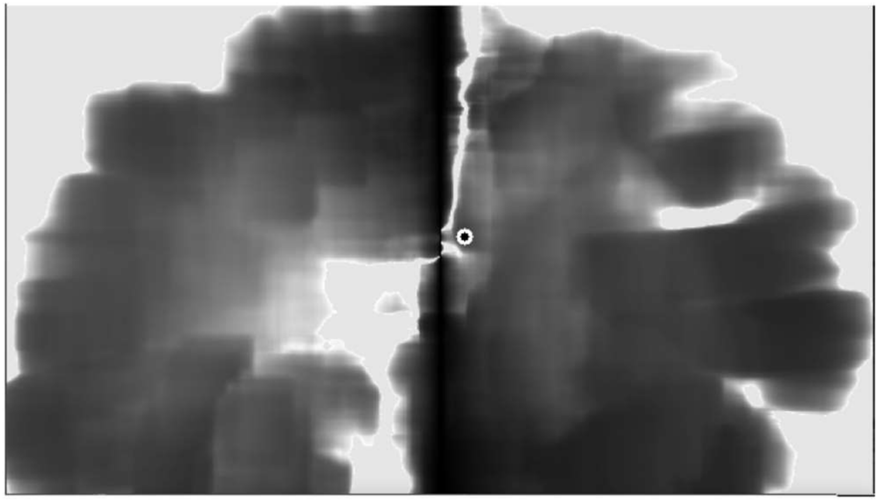
(c) Largest blob (d) Result

Dense Optical Flow

KARST EXPLORATION : GUIDANCE

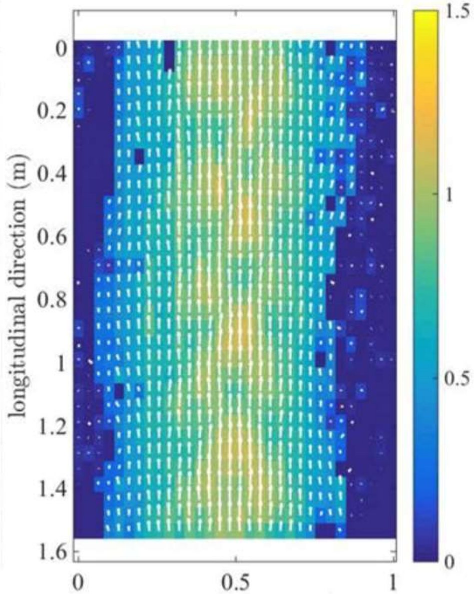
- **Vacancy Evidence Grid**





KARST EXPLORATION : GUIDANCE

- **Environmental Model Consideration**



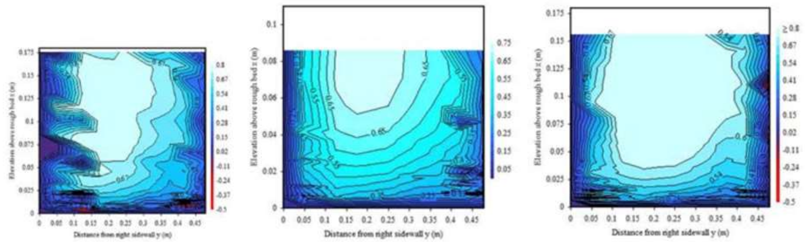
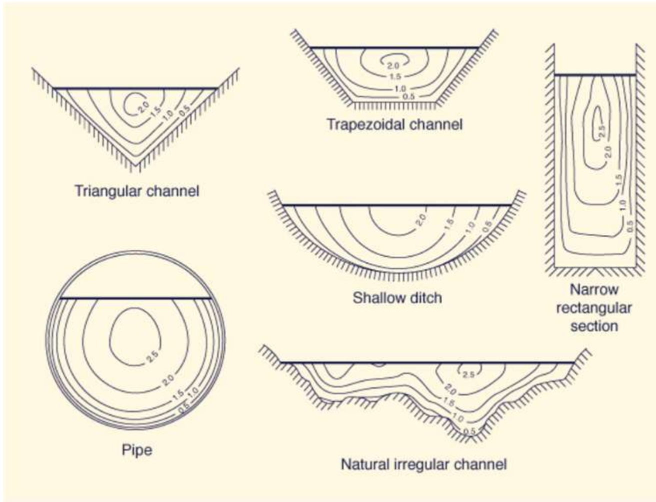
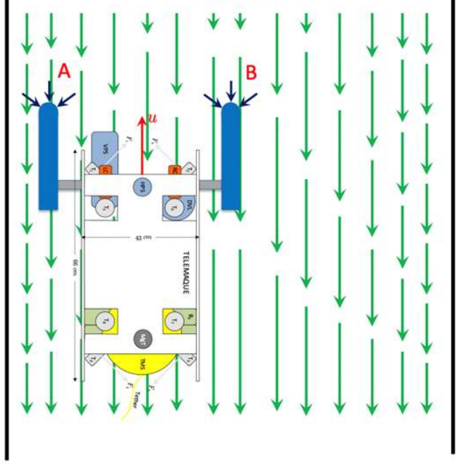


Fig. 12 Experimental velocity fields from Wang et al. [34] for $h = 0.175$ m and $Q = 0.0556$ l/s (left), $h = 0.085$ m. and $Q = 0.0261$ l/s (center) and $h = 0.155$ m and $Q = 0.0556$ l/s (right)

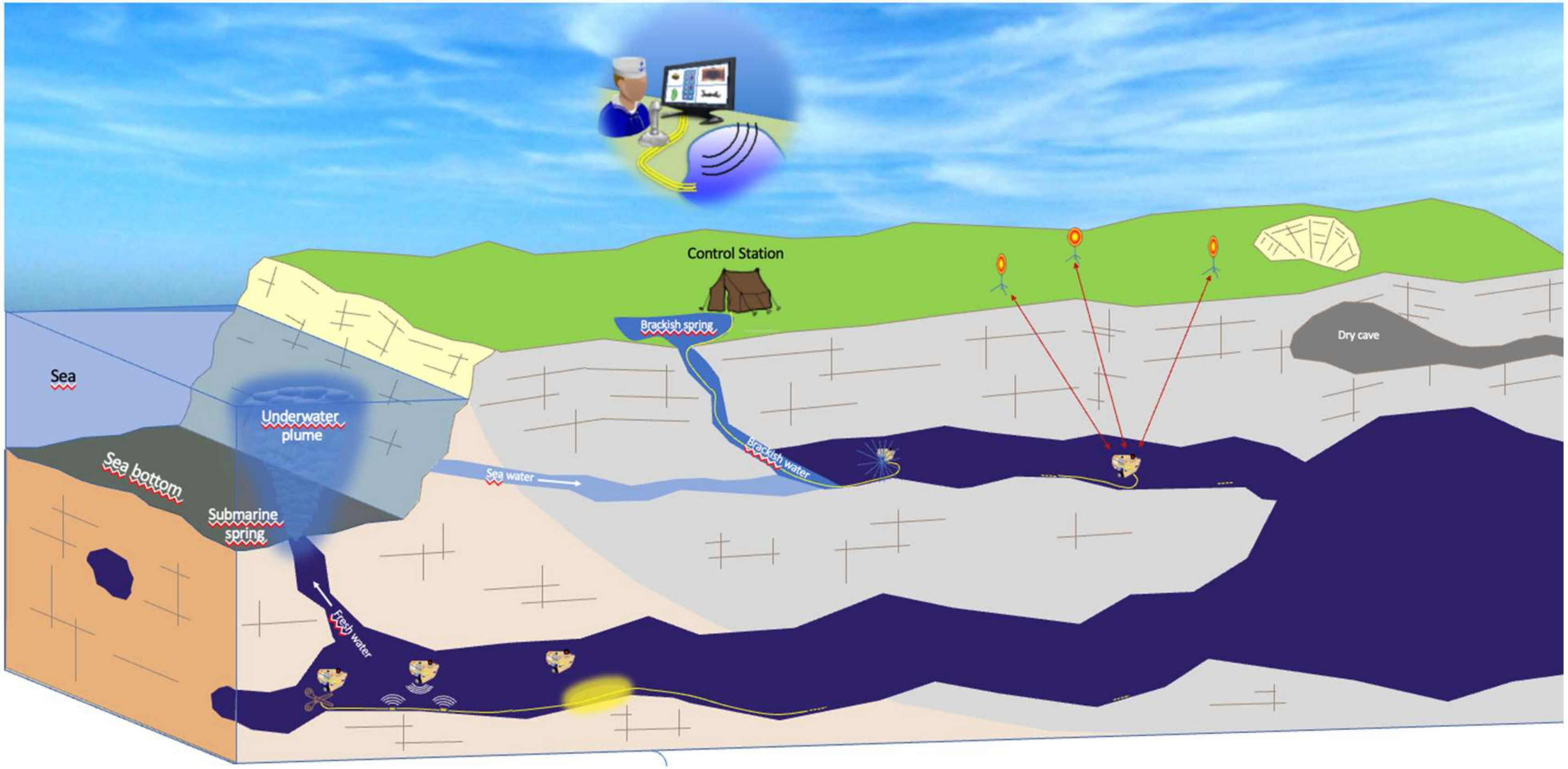


Can we measure a siginificative difference of pressure ? Kwowing u ? Or V ?



KARST EXPLORATION : CONTROL

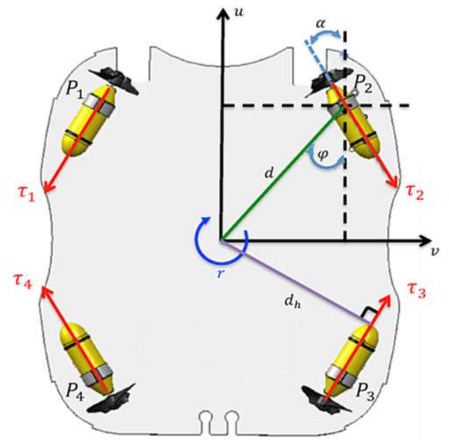
- **Co-control**



[C-39] Lasbouygues A., Louis S., Ropars B., Rossi L., Jourde H., Delas H., Balordi P., Bouchard R., Dighouth M., Dugrenot M., Jacquemin E., Vasseur F., Lapierre L. and Andreu D., 'Robotic mapping of a karst aquifer', IFAC World Congress 2017, demonstration paper.

KARST EXPLORATION : CONTROL

- **Open-Loop Stability**



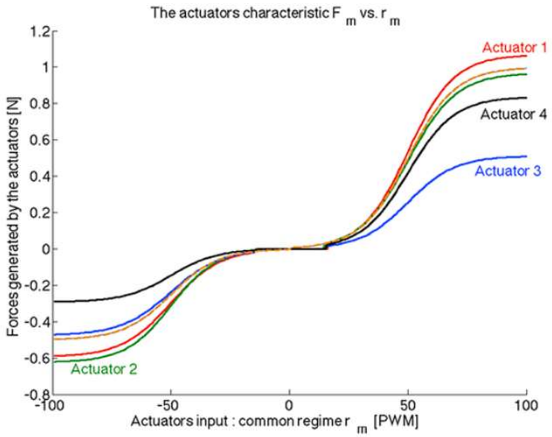


Fig. 6. Illustration of the actuators' characteristics disparity (simulation).

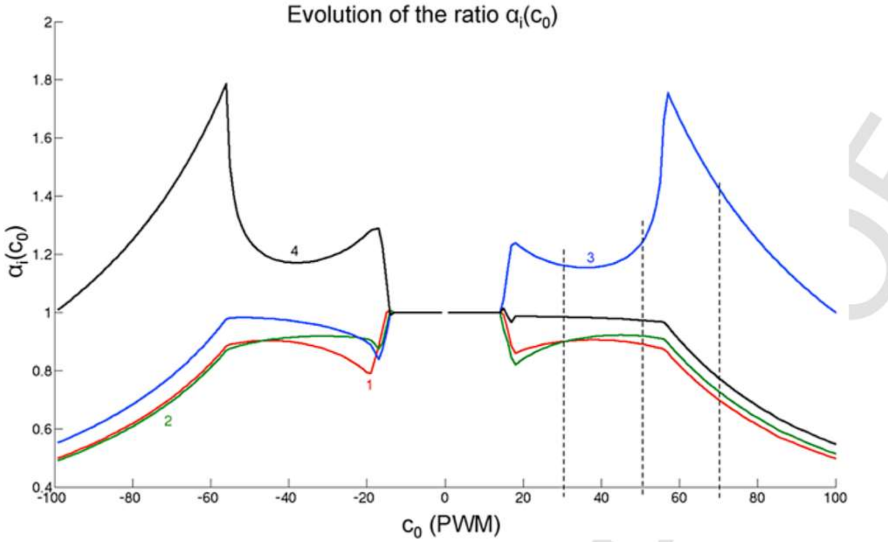


Fig. 10. Evolution of the corrective coefficient versus the common motor regime (simulation).

$$\mathbf{c}_m = \mathcal{Q}\left(\widehat{\mathcal{M}}^{-1}\left(\mathbf{A}^{+}\cdot\mathbf{F}_B^d\right) + c_0 \cdot 1_4\right)$$

[J-20] Ropars B., Lapierre L., Lasbouygues A., Andreu D and Zapata R. 'Redundant Actuation System of an Underwater Vehicle', in the Elsevier Journal of Ocean Engineering, Volume 151, March 2018, pp. 276-289, https://doi.org/10.1016/j.oceaneng.2017.12.025

KARST EXPLORATION : CONTROL

- **Autonomous Centering & Targeting**

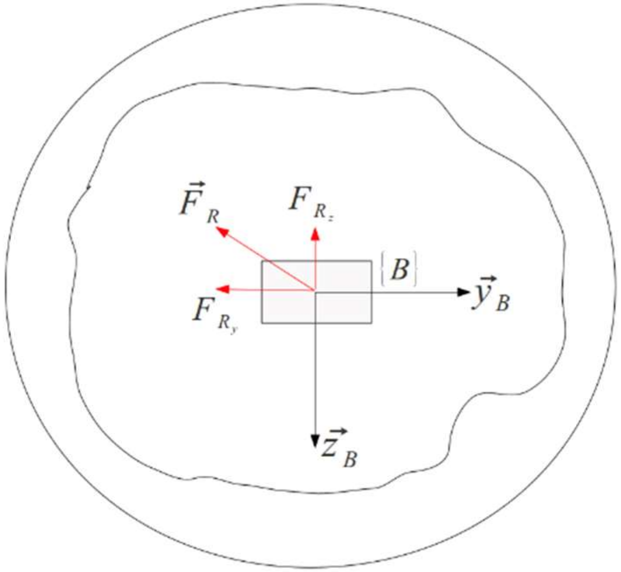
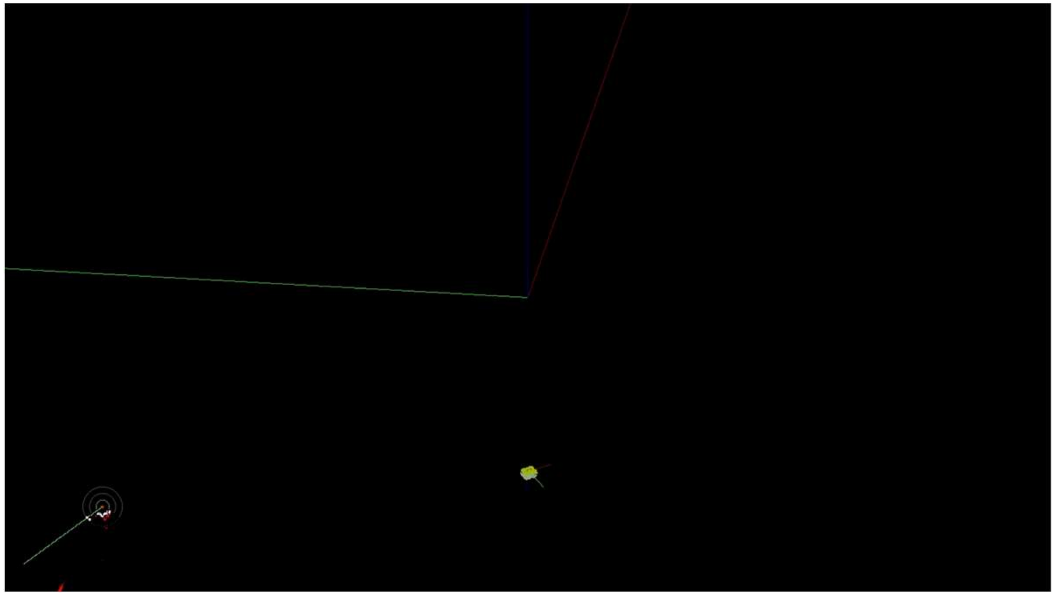


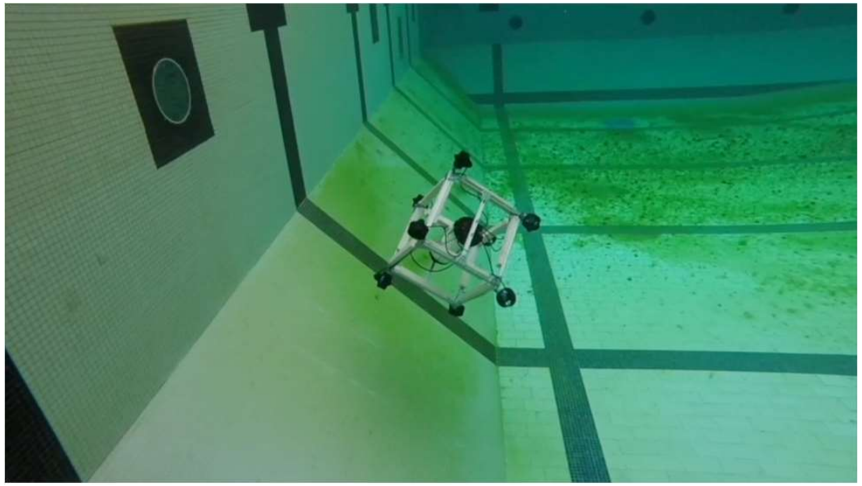
Fig. 6. Resulting force

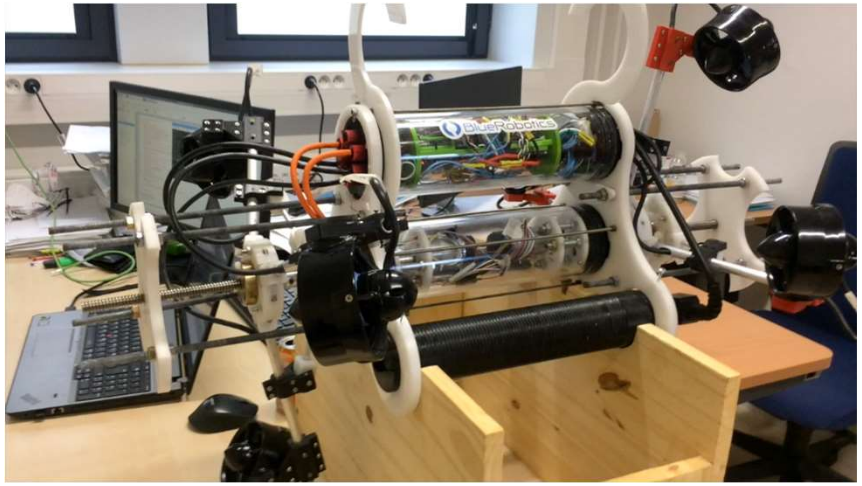


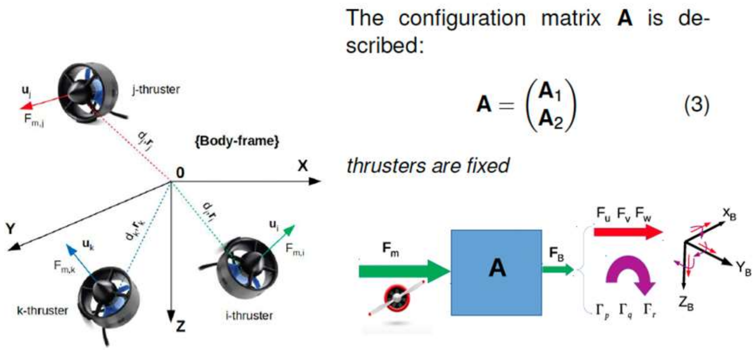
[C-39] Lasbouygues A., Louis S., Ropars B., Rossi L., Jourde H., Delas H., Balordi P., Bouchard R., Dighouth M., Dugrenot M., Jacquemin E., Vasseur F., Lapierre L. and Andreu D., 'Robotic mapping of a karst aquifer', IFAC World Congress 2017, demonstration paper.

Karst Exploration : Actuation

- **Reactive redundant Allocation System and Variable Actuation Geometry**







$$\mathbf{F}_B = \mathbf{A} \cdot \mathbf{F}_m$$

$$\mathbf{M}_m \in \ker(\mathbf{A}) \Leftrightarrow \mathbf{A} \cdot \mathbf{M}_m = \mathbf{0}$$

$$\mathbf{F}_m = [\mathbf{A}^+ \quad \mathbf{M}_m] \cdot \begin{bmatrix} \mathbf{F}_B^d \\ \mathbf{r}_m \end{bmatrix}$$

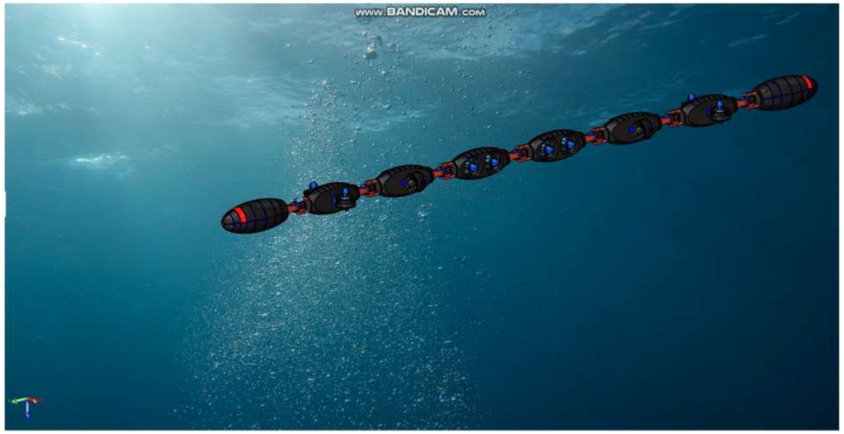
A *k*-dimensional space to explore redundant solutions

[J-30] Dang, T.; Lapierre, L.; Zapata, R.; Ropars, B. 'Energy-Efficient Configuration and Control Allocation for a Dynamically Reconfigurable Underwater Robot', Sensors 2023, 23(12), 5439; https://doi.org/10.3390/s23125439.

KARST EXPLORATION : ACTUATION

- **Anguilliform Locomotion & Underwater Swimming Manipulator**

ANR ElectroKarst



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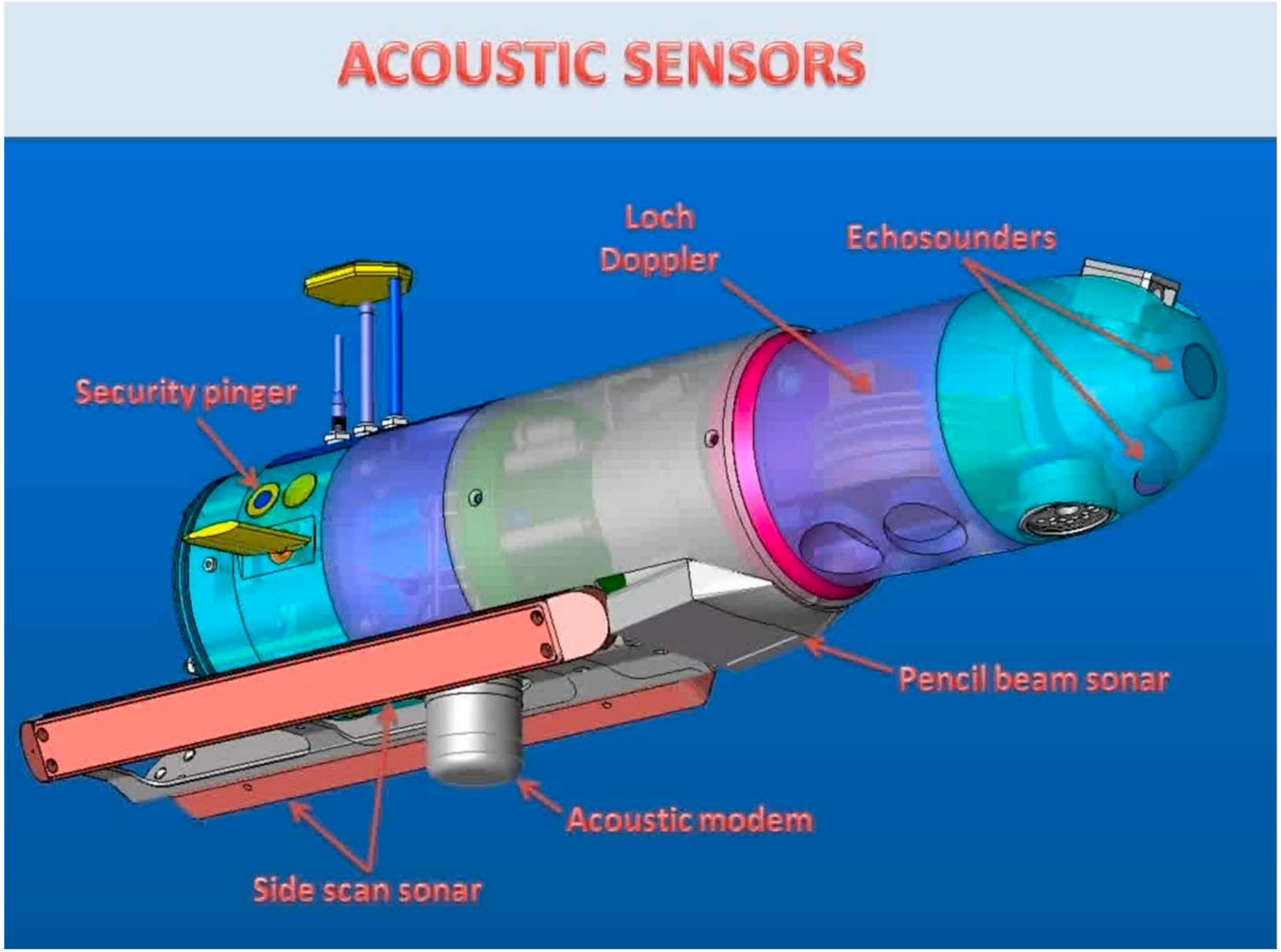
SLAM ?

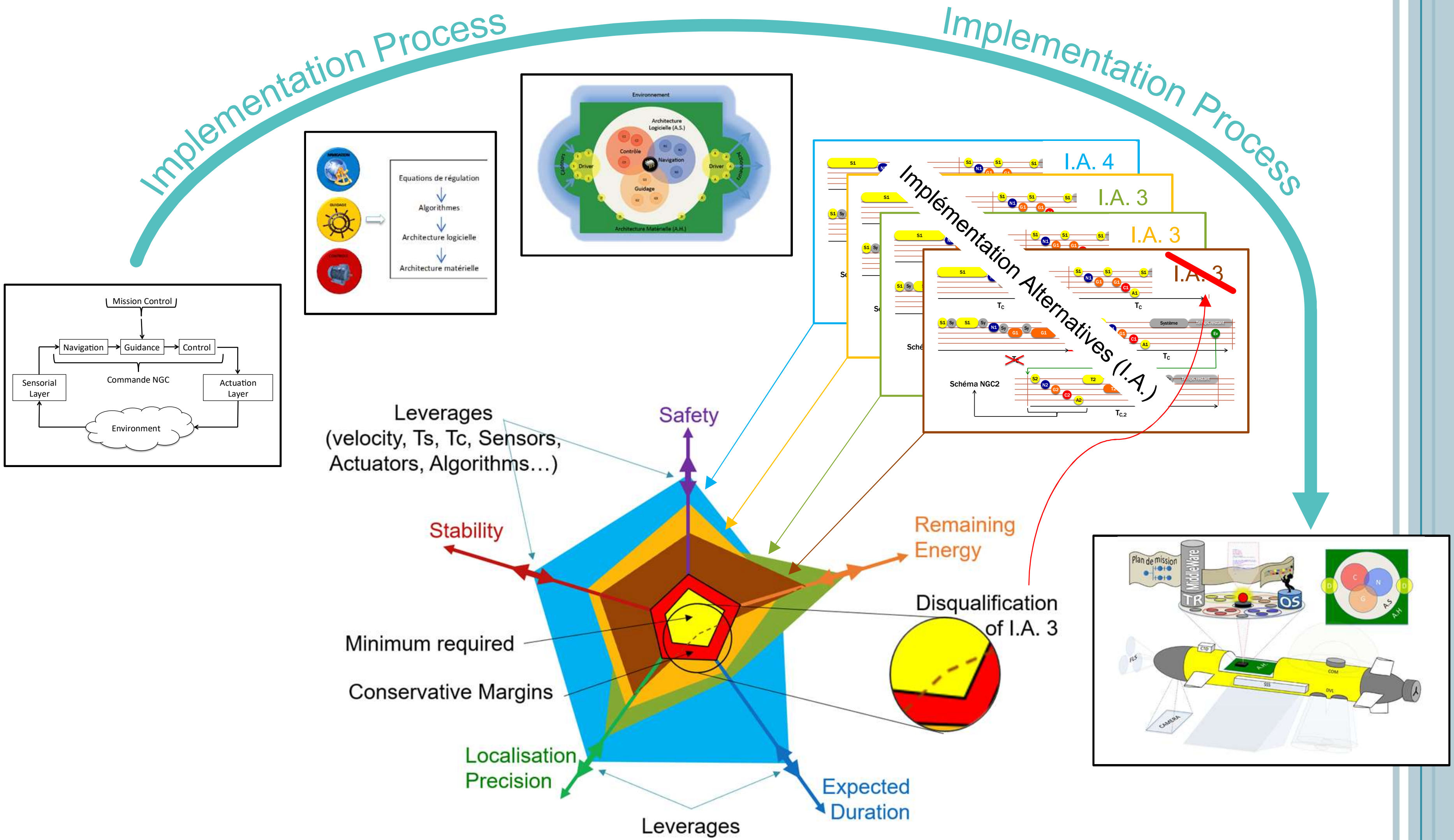
Karst Exploration : Mission Management

- **Management of interfering sensors (Acoustic sensors jamming)**



Karst Exploration : Mission Management

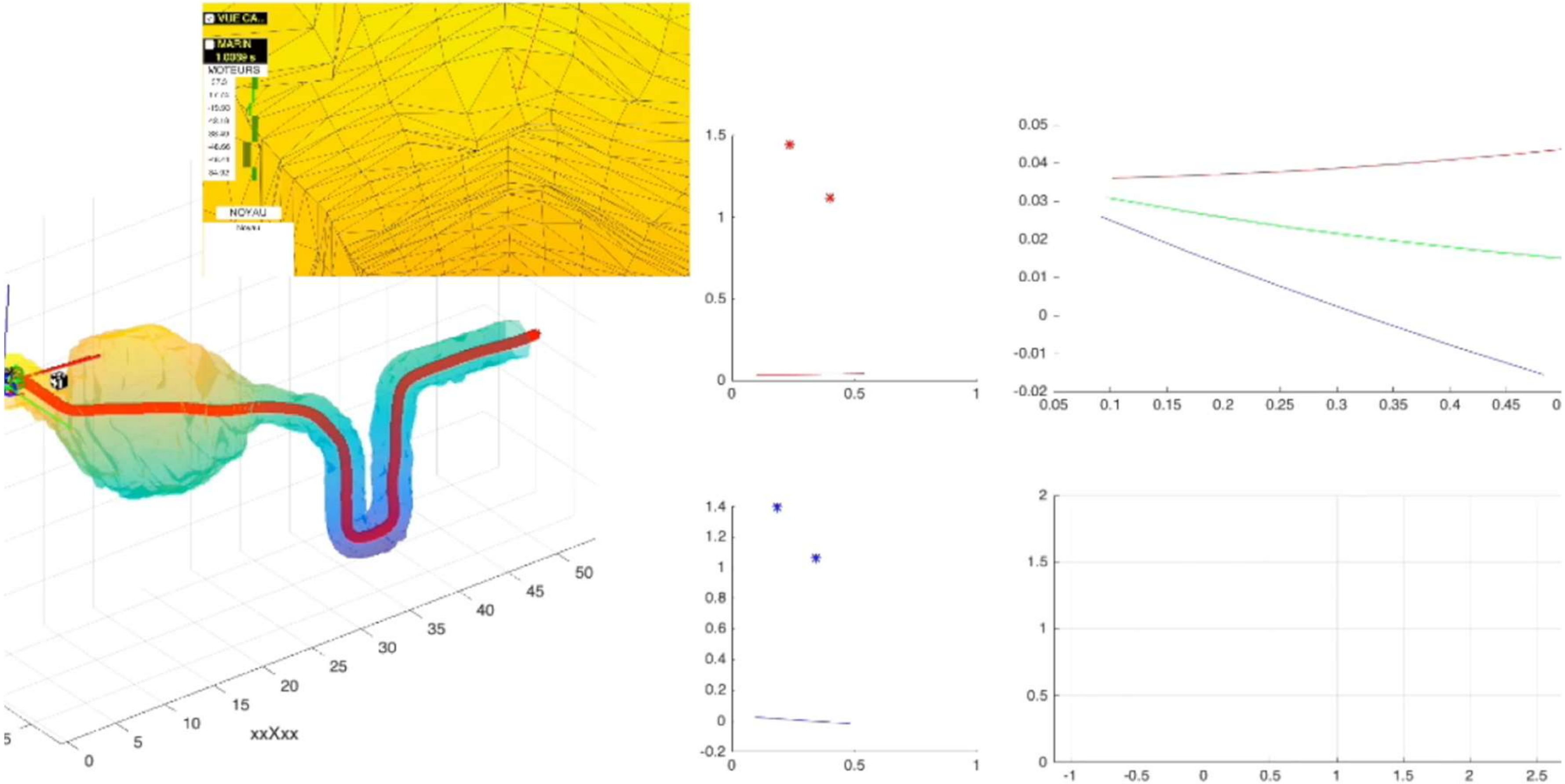
- **Adaptive Autonomy / Guarantees of Performance**



KARST EXPLORATION : MISSION MANAGEMENT

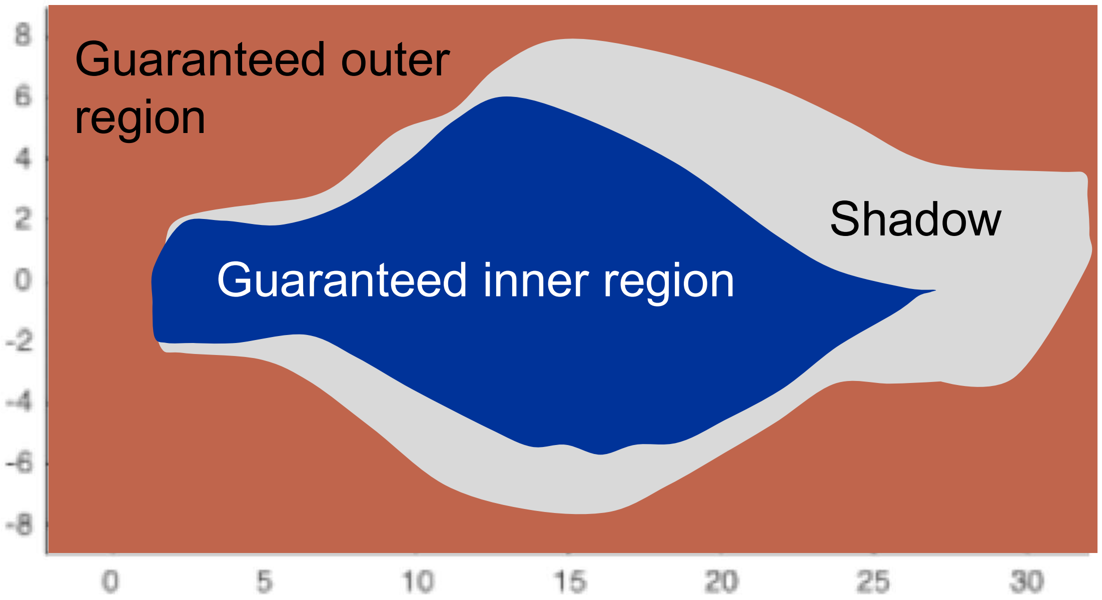
- **(Seeking) for Guarantees of Performance & Interval approach**

$$X, \tilde{X} \rightarrow [X]$$



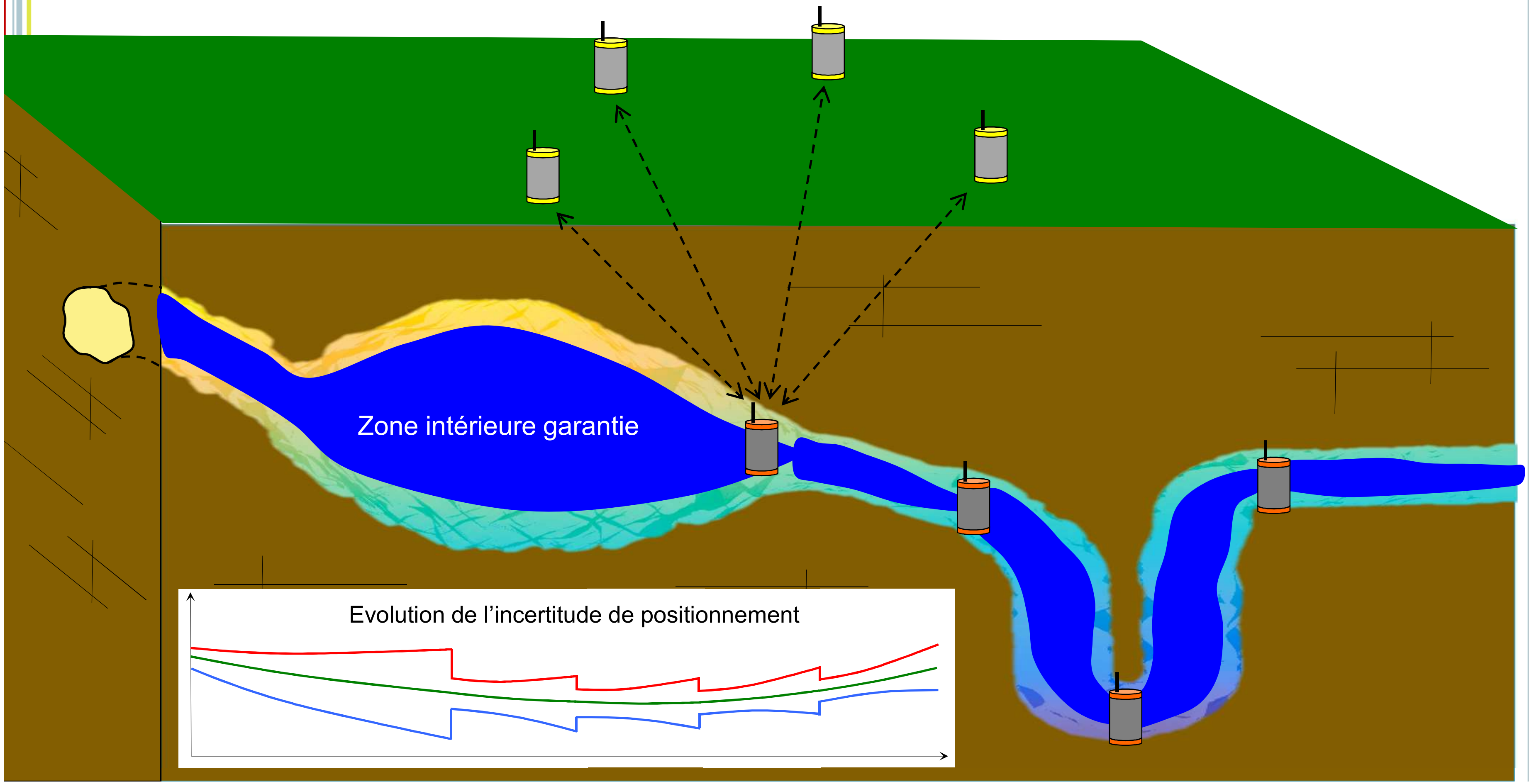
Karst Exploration : Mission Management

- **(Seeking) for Guarantees of Performance & Interval approach**



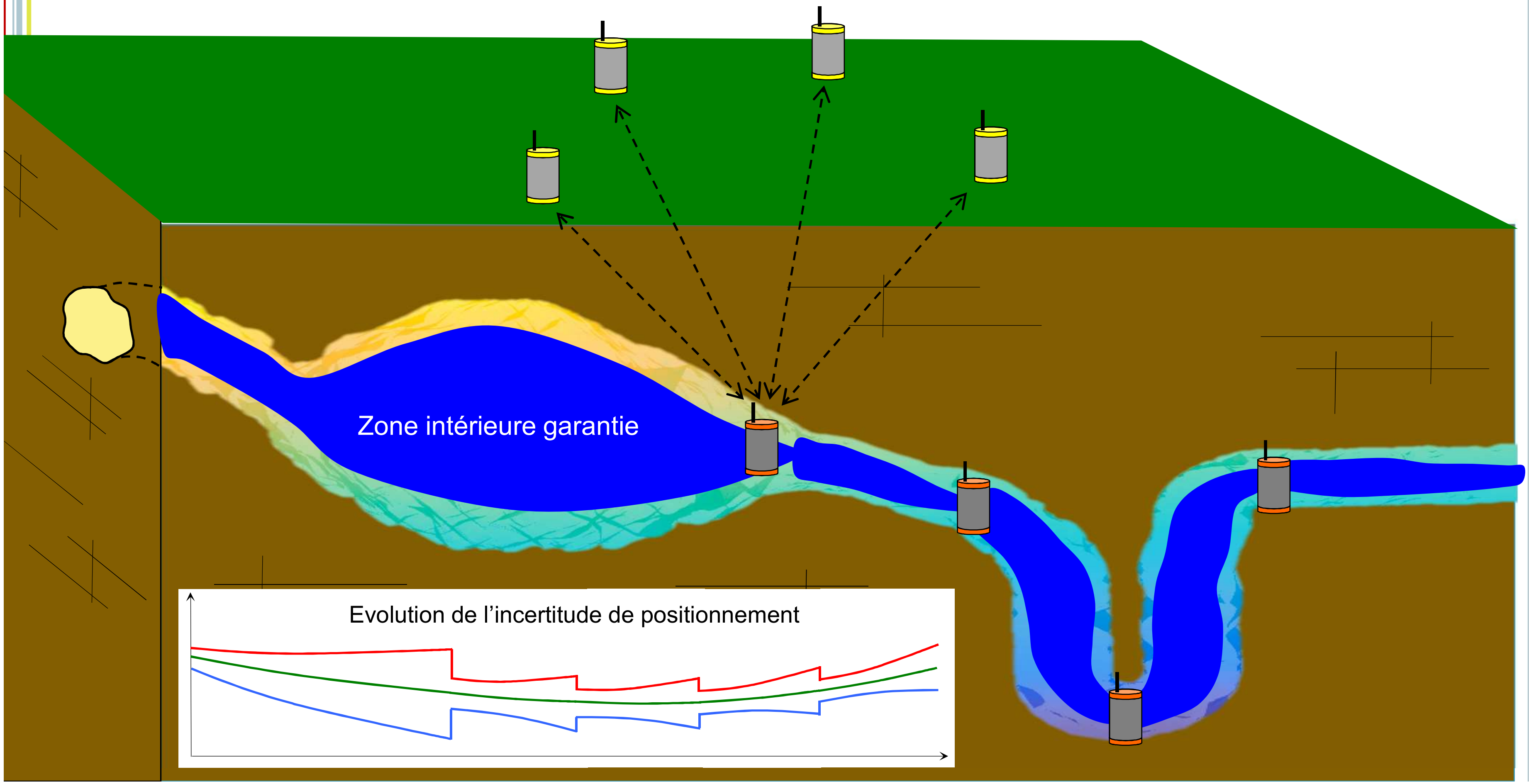
KARST EXPLORATION : MISSION MANAGEMENT

- **(Seeking) for Guarantees of Performance & Interval approach**
- **Global positioning using UGPS**



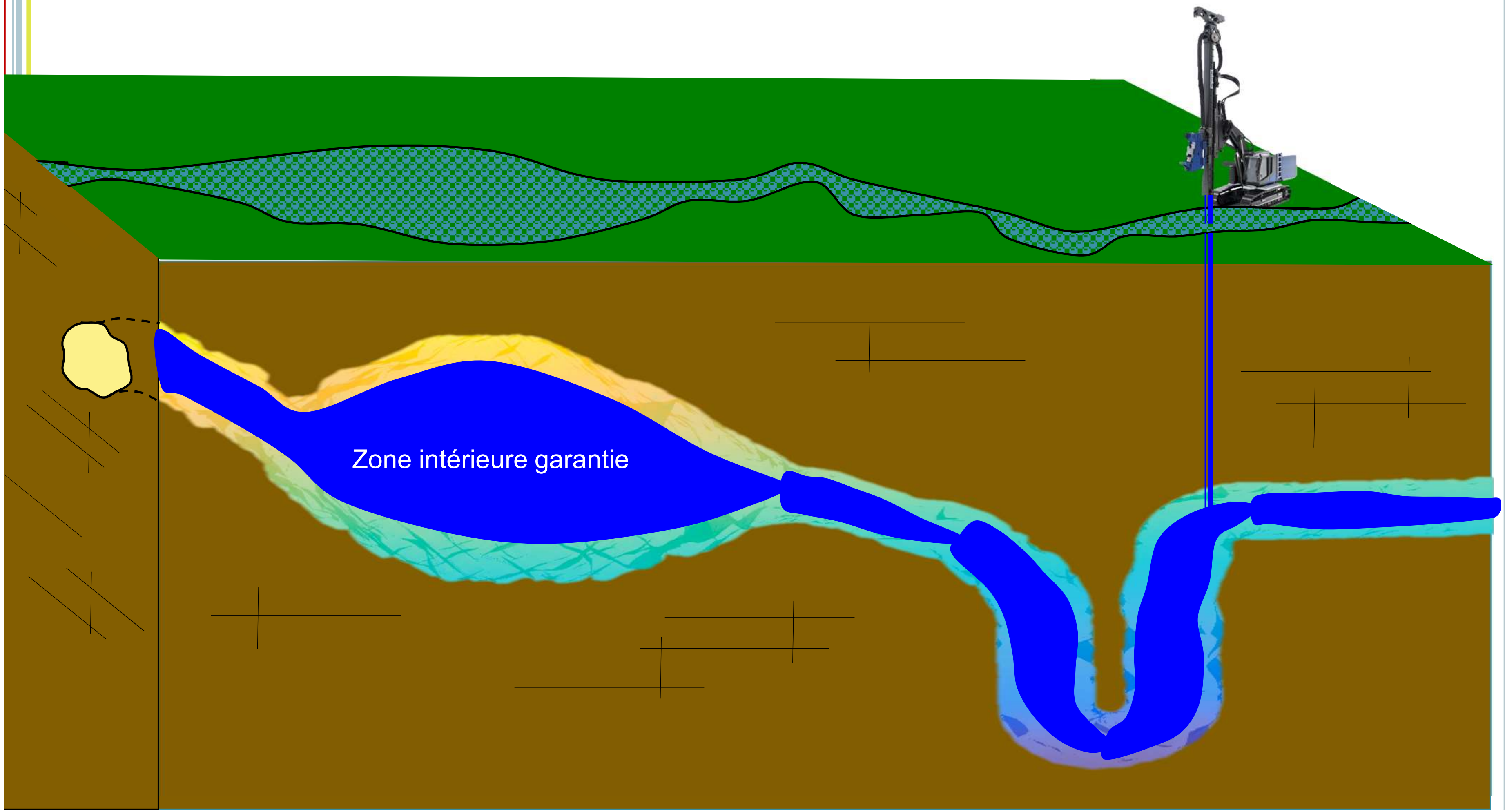
KARST EXPLORATION : MISSION MANAGEMENT

- (Seeking) for Guarantees of Performance & Interval approach
- Global positioning using UGPS
- Application to hydraulic drilling



THE RKE INITIATIVE : FORCES AT WORK (LIRMM, ENSTA)

- Cartographie garantie, analyse par intervalles
- Recalage par UG-GPS (ISSKA, localisation magnétique)
- Application au forage hydraulique



KARST EXPLORATION : TERRAIN RESULTS

- Ulysse

Co-contrôle Réactif

Exploitation de la Redondance d'actionnement

Commande Orientée Modèles d'Environnement

Commande S-NGC-A

Polyvalence et Robotique

Autonomie Adaptative

Garanties de Service

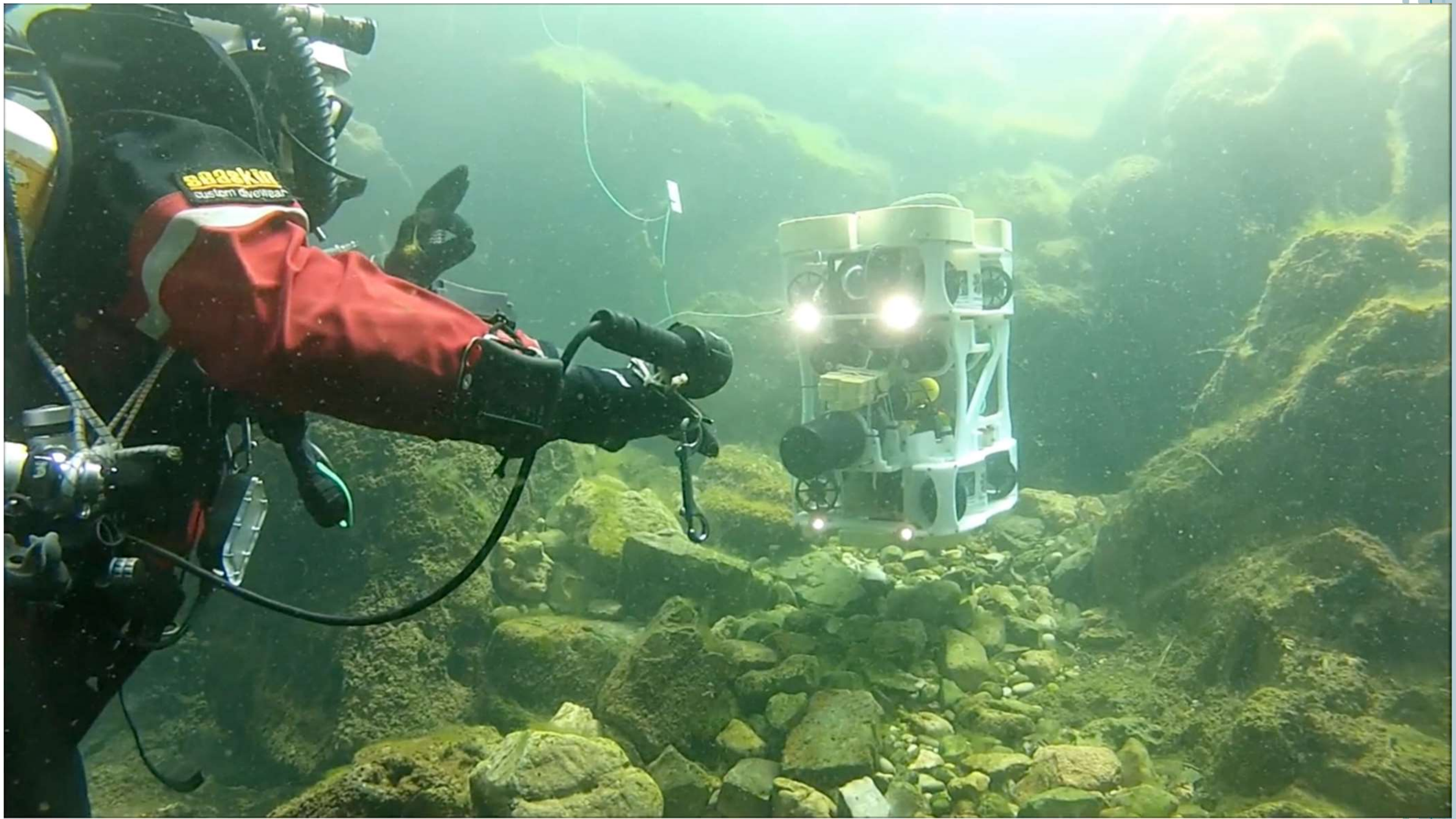
Garanties de Performance

Décomposition Atomique de la Commande

Gestion des Commutations de Modes

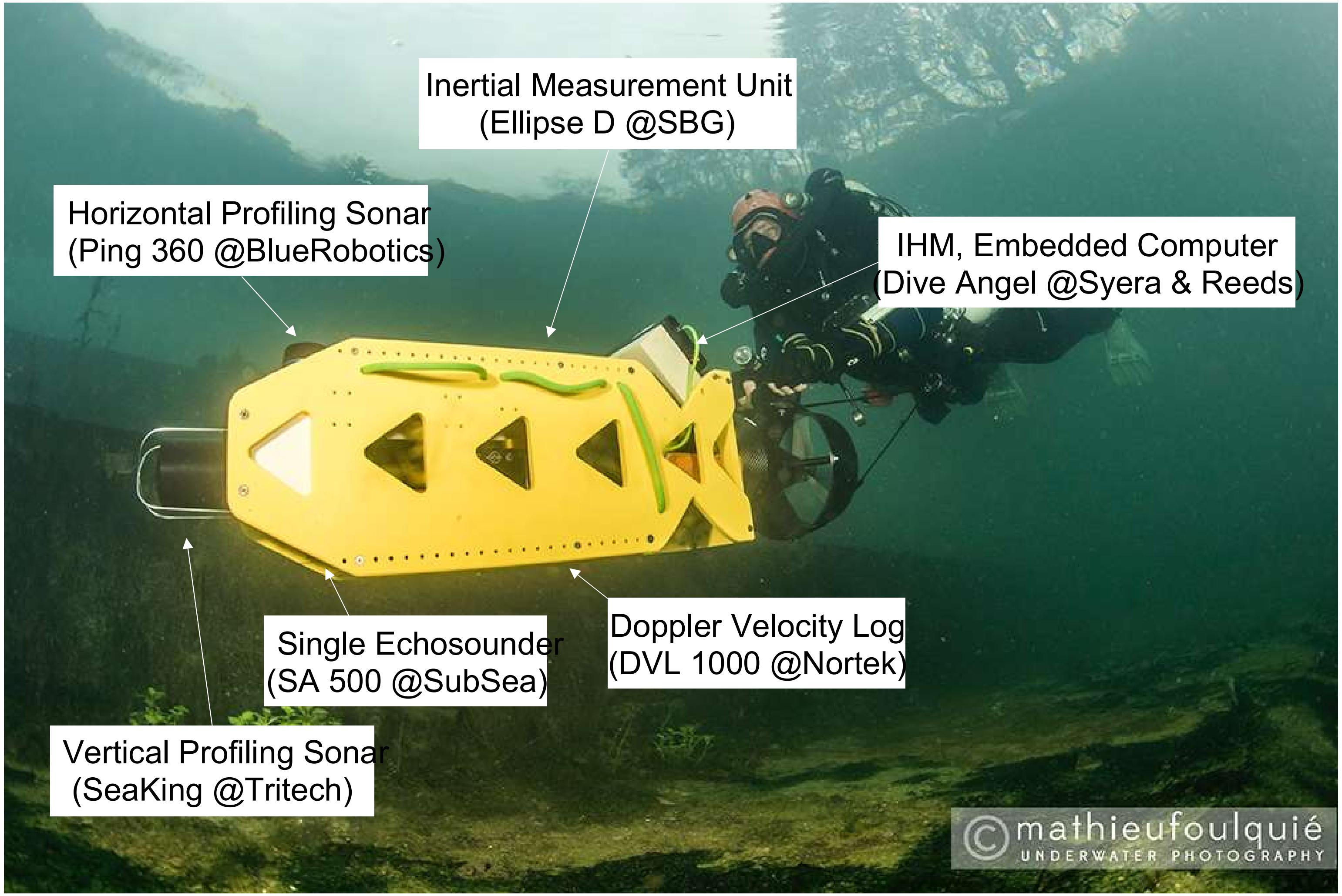
KARST EXPLORATION : TERRAIN RESULTS

- Ulysse, Gourneyras, France



KARST EXPLORATION : TERRAIN RESULTS

- NavScoot 2

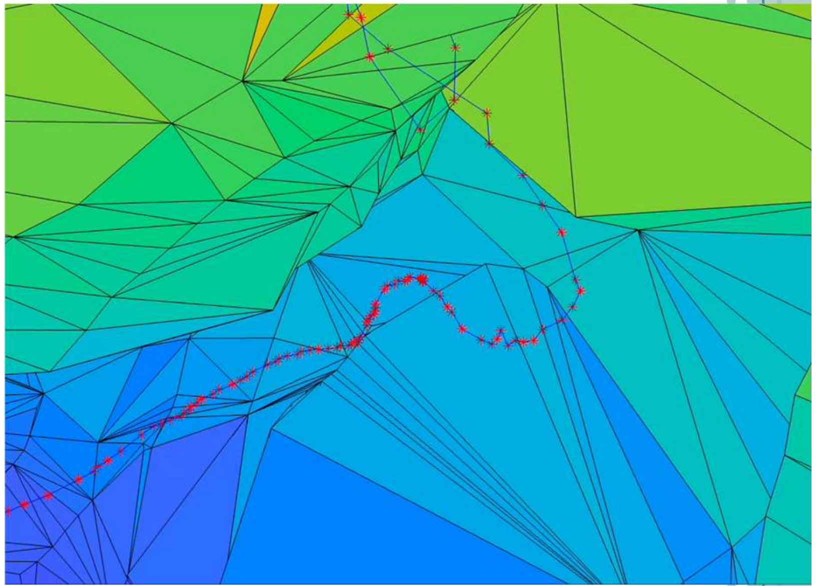


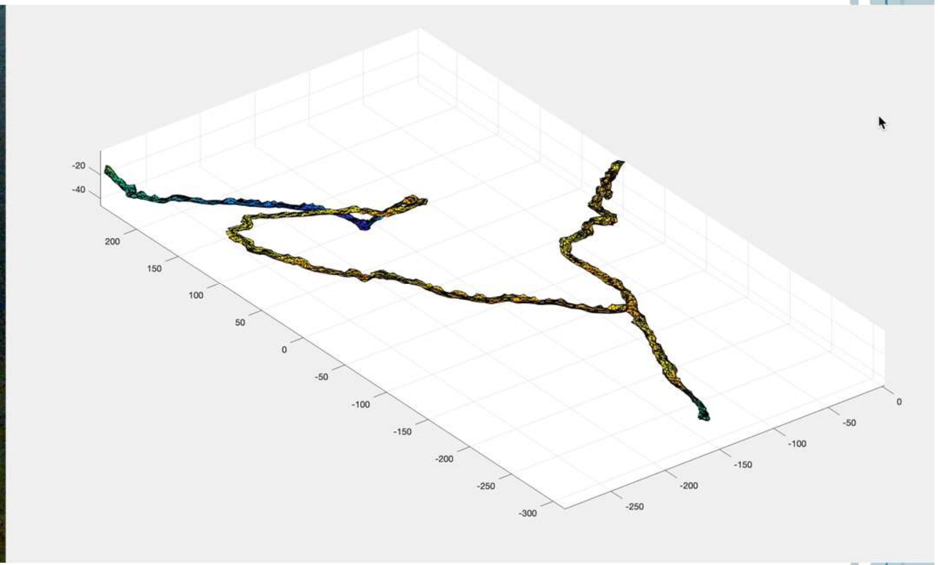
Terrain Results: Fontaine de Nîmes, 8/03/2023

PLONGEURS
Frank VASSEUR
Mathieu FOULQUIE
Doriane MORATE
Damien VIGNOLE
Denis PAILLO

Eq. TECHNIQUE
Lionel LAPIERRE
Hervé JOURDE
Pierre FISCHER
Benoit ROPARS
Mohammed ALIOUACHE

MAIRIE DE NIMES
Guillaume PLA

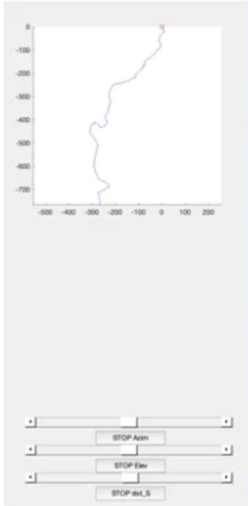


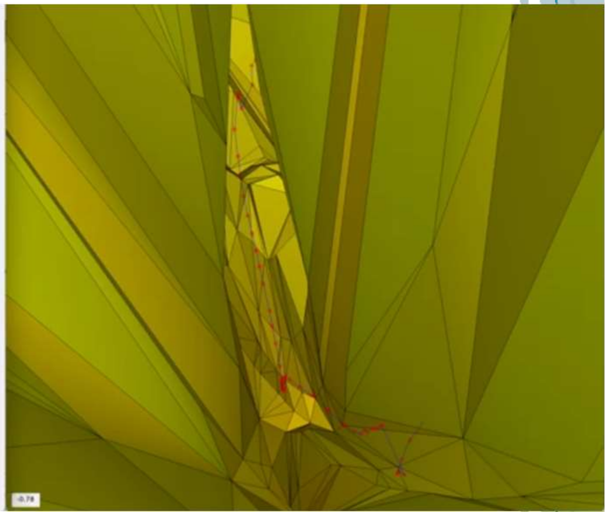


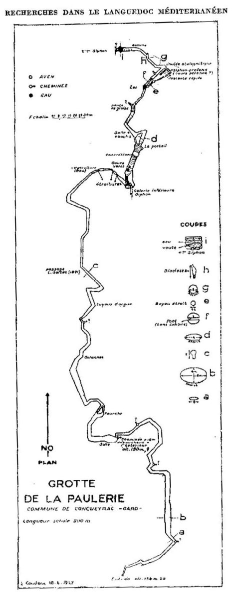
TERRAIN RESULTS: FONTAINE DE SAUVE, 24/05/2023

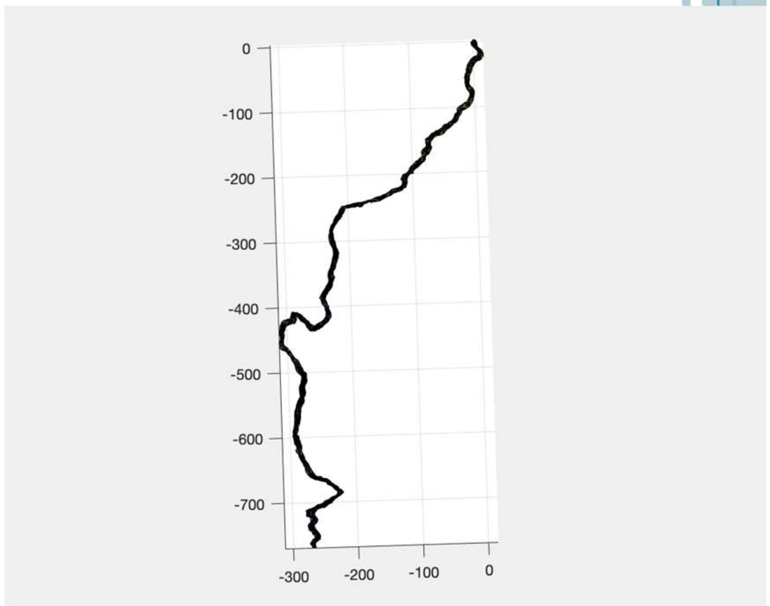
PLONGEURS
Frank VASSEUR
Doriane MORATA
Dominique VIGNOLE

Eq. TECHNIQUE
Benoit ROPARS

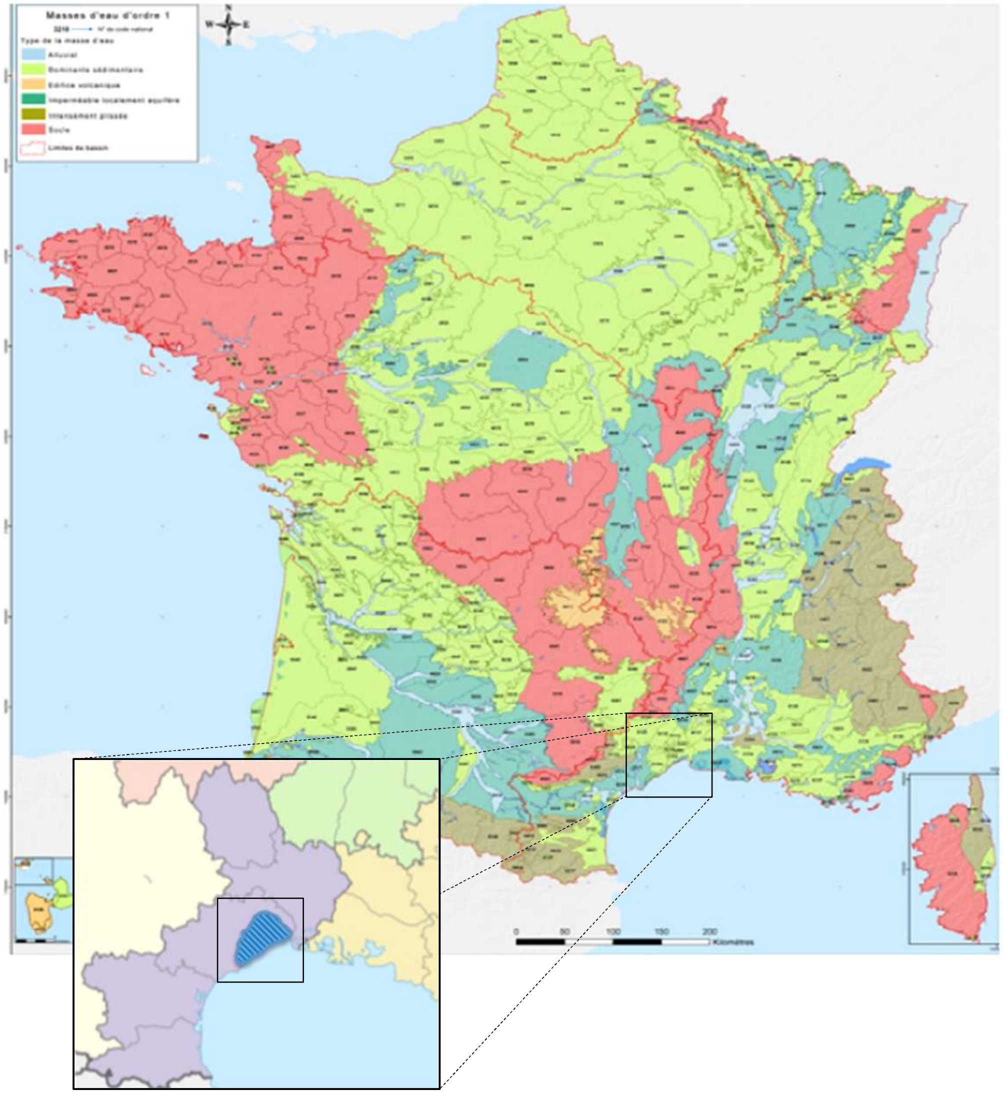




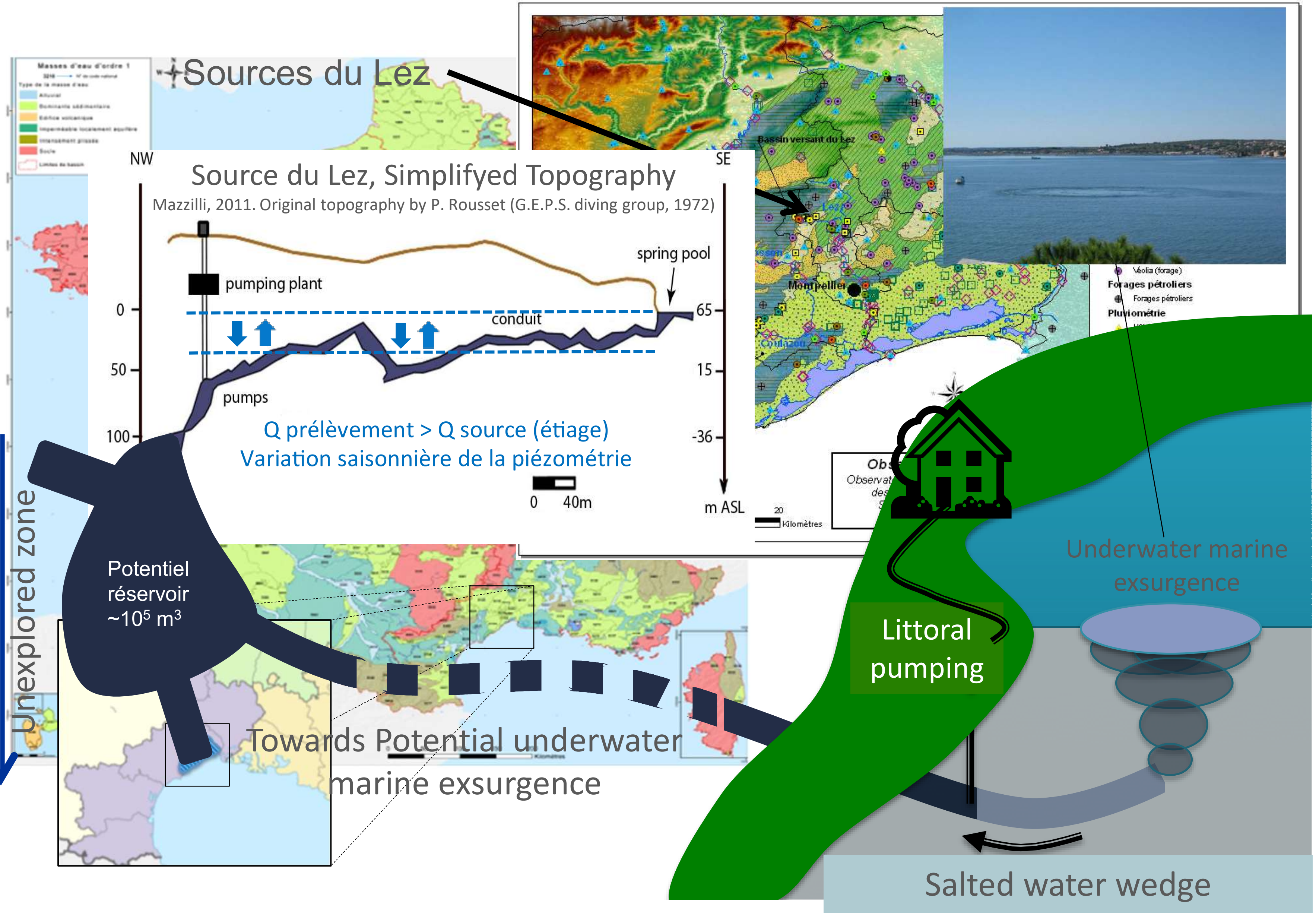




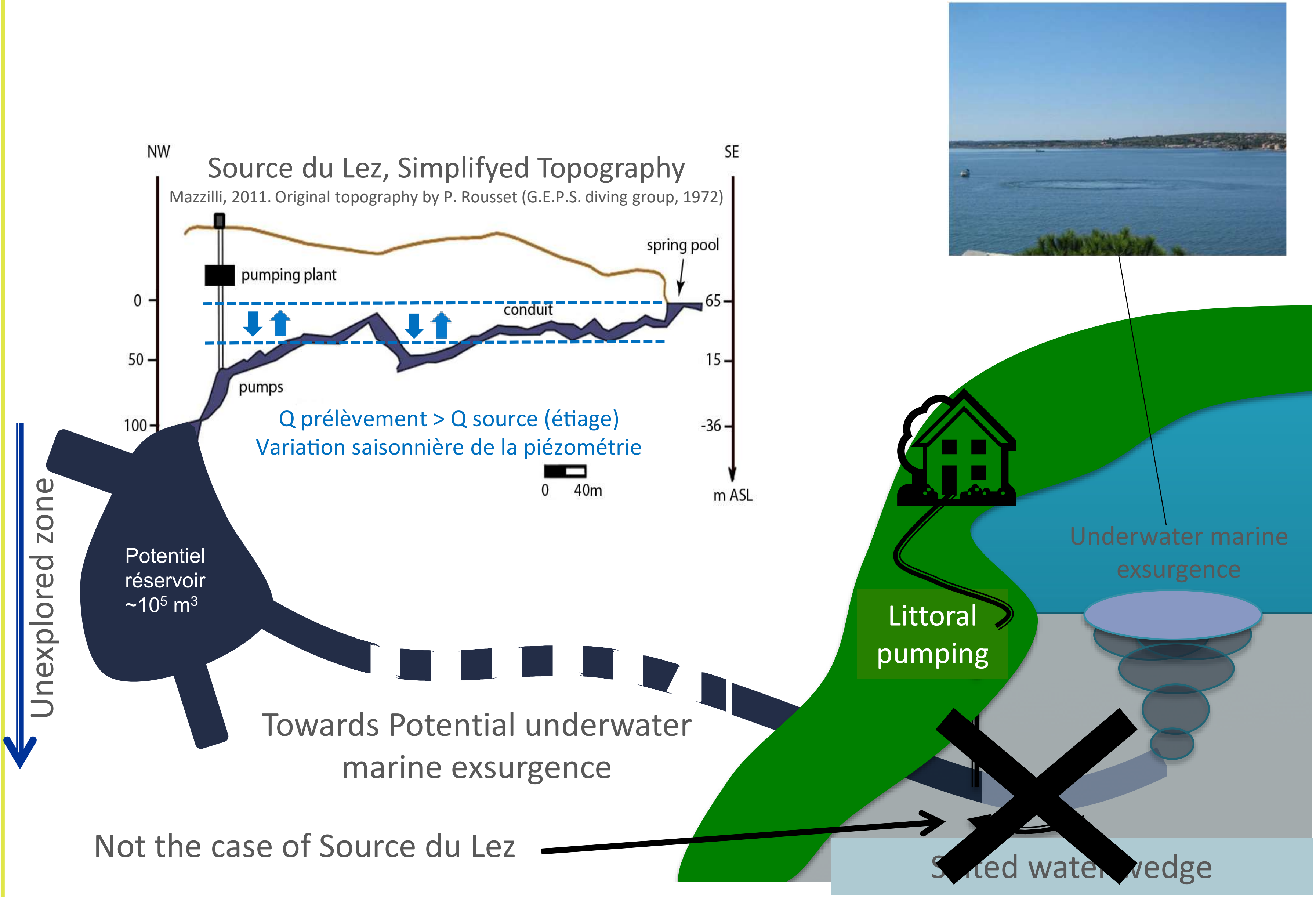
TERRAIN RESULTS: SOURCE DU LEZ, 15/03/2023



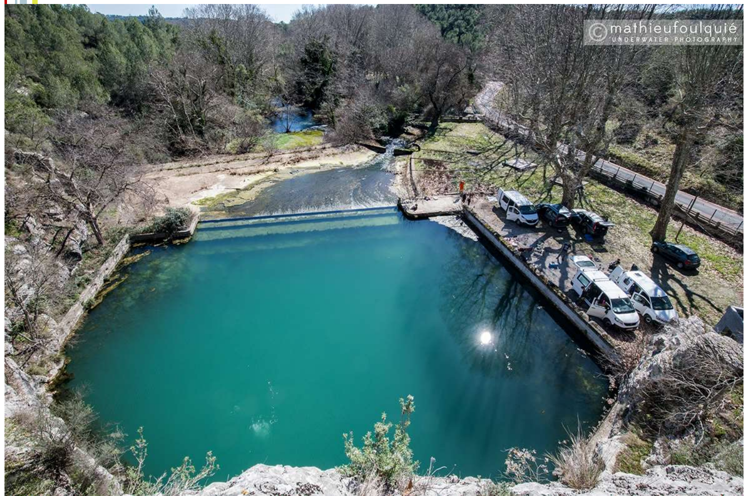
Sources du Lez : a Seminal Case Study



Sources du Lez : Active Management of GW Resource



TERRAIN RESULTS: SOURCE DU LEZ, 15/03/2023



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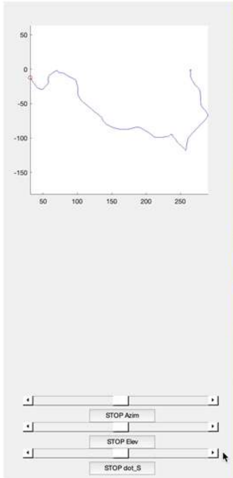

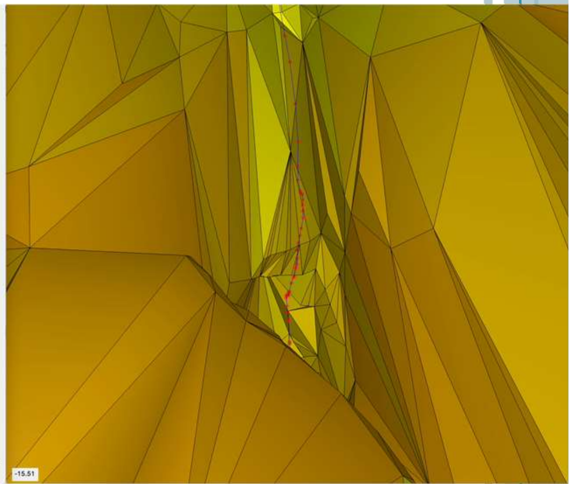

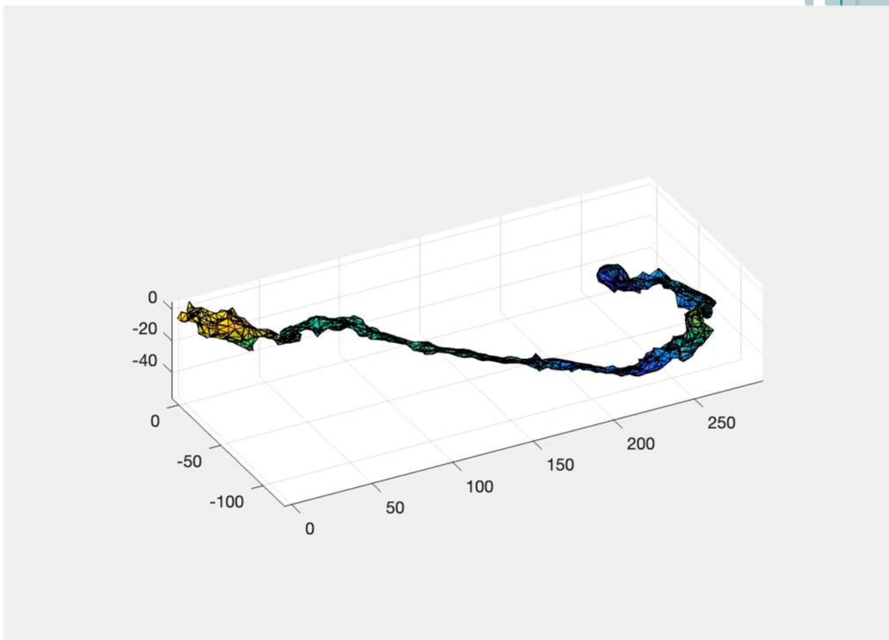

TERRAIN RESULTS: FONTANILLES, 15/03/2023

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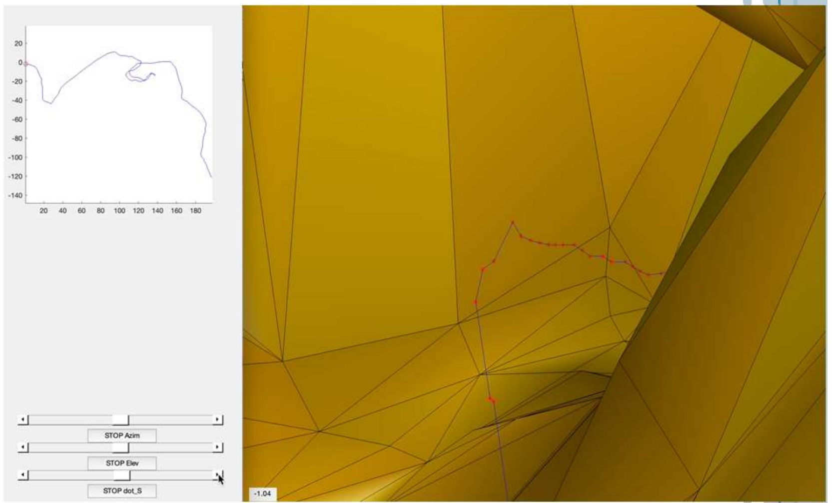
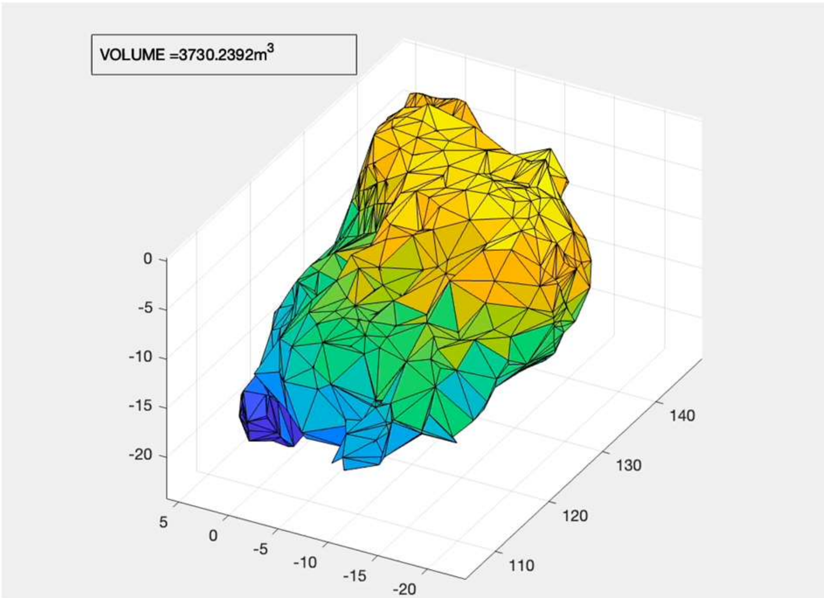
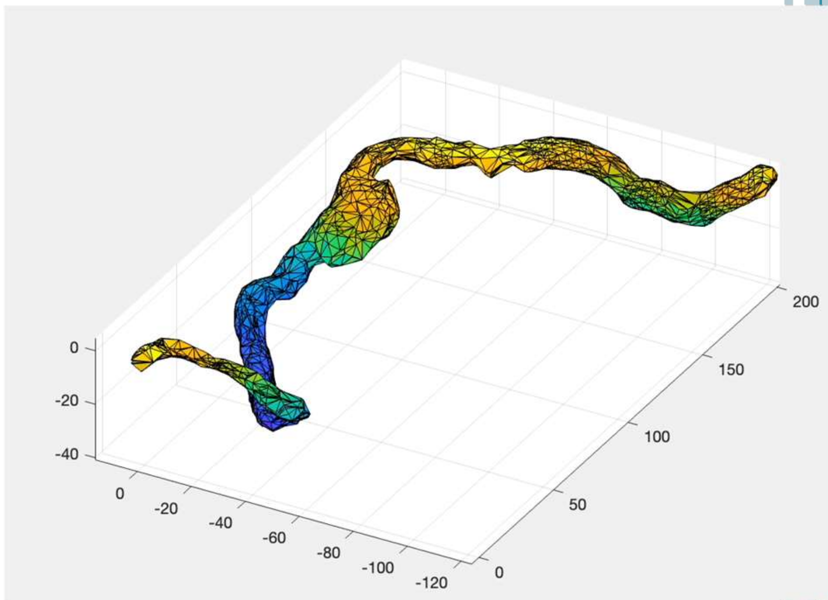
Mathieu FOULQUIE
Doriane MORATA
Dominique VIGNOLE
Denis PAILLO

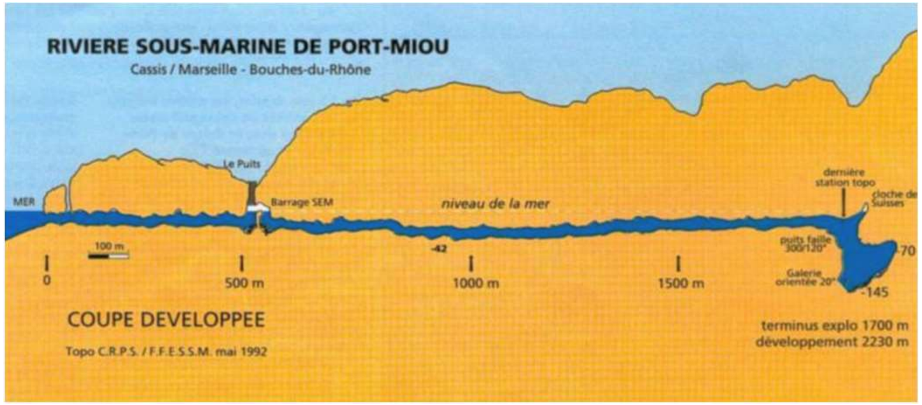
Eq. TECHNIQUE
Benoit ROPARS







A VENIR : PORT MIOU, UN SITE PILOTE



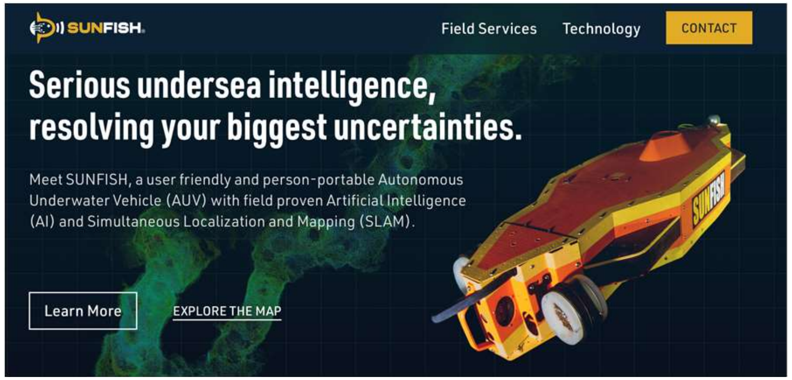
IngéBlue
institut
interdisciplinaire

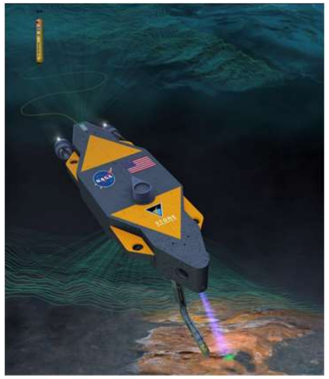
ENSTA BRETAGNE

UNIVERSITÉ DE TOULON

CASSIS rivières mystérieuses

BILL STONE AND THE SUNFISH





Exploring Karst with Robots

Exploration Robotics for Confined, Unstructured Subaquatic Environment

FARO, 26-27 novembre 2024, LIX, Polytechnique, Palaiseau

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