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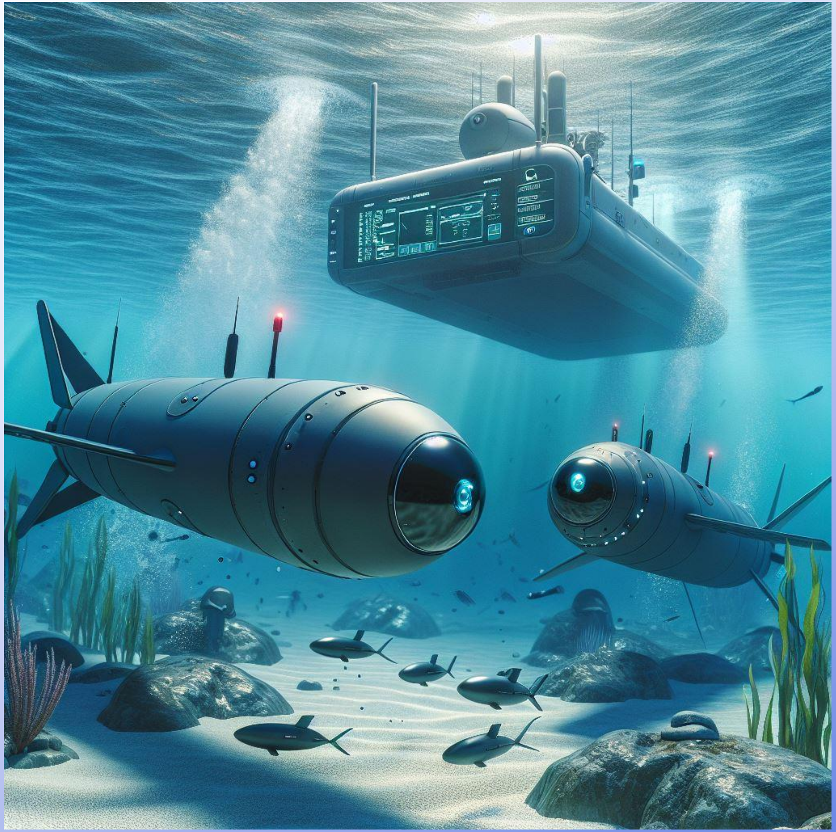

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Navigation, Communication & actuation devices

Navigation meaning in marine robotics

- Robot navigation means the robot's ability to determine its own position in its frame of reference.
- Navigation does not include motion planning, guidance and control

Sensor classes

- **Proprioceptive sensors**
  - measure values internal to the robot, e.g. orientation, position and speed
- **Exteroceptive sensors**
  - acquire information from the robot environment, e.g. distance measurement, light intensity

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Proprioceptive sensors: attitude

- Clinometers
- Inertial Measurement Unit
  - 3 orthogonal gyroscopes (angular)
  - 3 orthogonal accelerometers (linear)

Proprioceptive sensors: heading

- Magnetic compass
- Fiber Optic Gyro
- Dual antenna GPS

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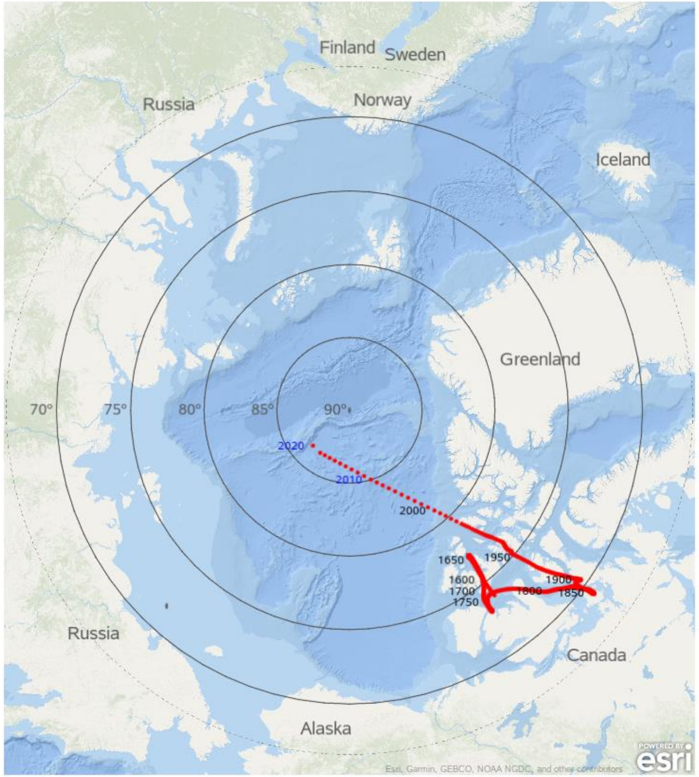
Proprioceptive sensors: magnetic compass

- Magnetic pole does not coincides with geographic pole
  - local offset
  - **magnetic North is not the True North**

Shift in magnetic north pole (yearly position, 1590-2020)



Data source: https://www.ngdc.noaa.gov/geomag/GeomagneticPoles.shtml

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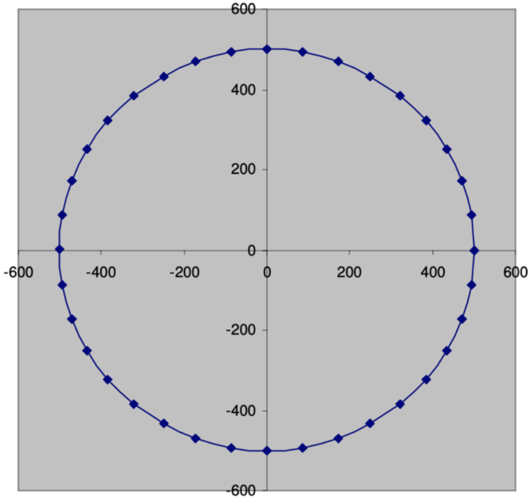
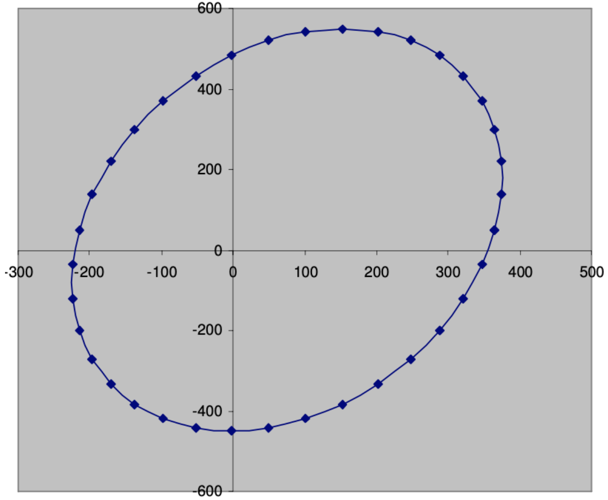
Proprioceptive sensors: magnetic compass

- Deformation of the magnetic field induced by robot structure and electronics





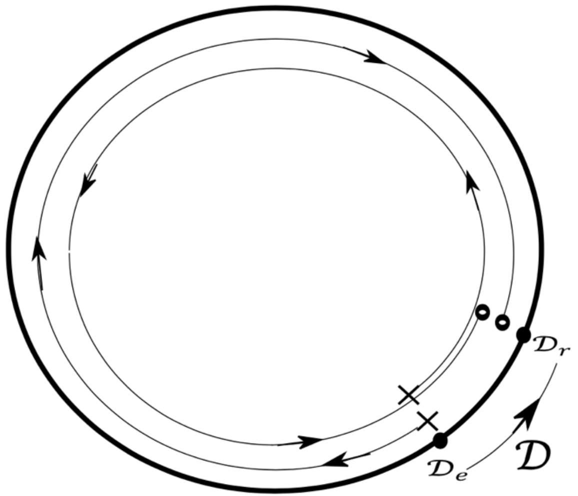
PNI White Paper

Local Magnetic Distortion Effects on 3-Axis Compassing

- **always auto calibrate magnetic compass**

Proprioceptive sensors: how to determine True North

- **Sagnac effect** (1899)
    - Principle: “let us imagine two balls rolling at the same speed but in opposite directions at the circumference of a disc. If the disc is static, an external observer would see both balls crossing each other after half a turn and again at the start point. If the disc is put into rotation, the balls will not reach the start point relative to an inertial frame at the same time. The delay is therefore proportional to the disc rotation speed.”



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Proprioceptive sensors: how to determine True North

- “FOG-based sensors use a similar principle: two light beams traveling at the same speed along an optical fibre are injected from each end. The phase shift between the two optical waves gives the sensor rotation speed.”

Geosci. Instrum. Method. Data Syst., 6, 439–446, 2017
https://doi.org/10.5194/gi-6-439-2017

Geoscientific Instrumentation Methods and Data Systems
Open Access
EGU

Fog-based automatic true north detection for absolute magnetic declination measurement

Alexandre Gonsette, Jean Rasson, Stephan Bracke, Antoine Poncelet, Olivier Hendrickx, and François Humbled
Dourbes magnetic observatory, Royal Meteorological Institute of Belgium, Dourbes, 5670, Belgium

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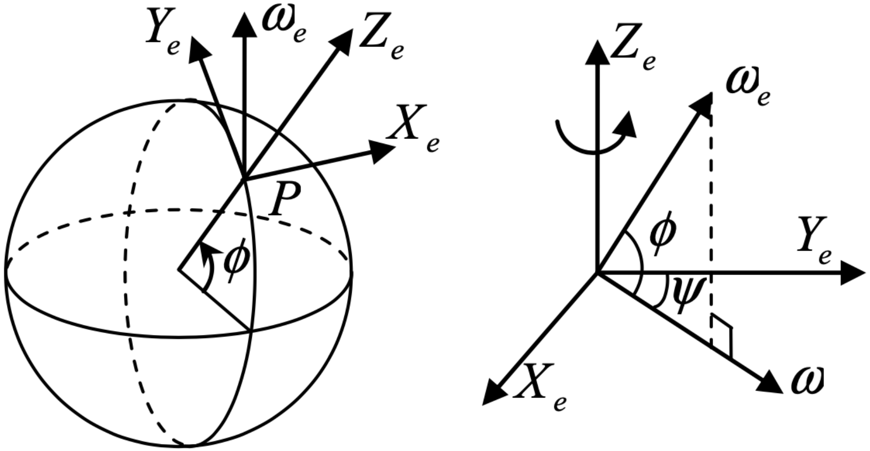
Proprioceptive sensors: how to determine True North

- ψ : angle between the initial direction of the gyroscope sensitive axis and true North
- ω_e : Earth rotation rate
- ω : Earth rotation rate towards the direction of gyroscope sensitive axis
- $\omega_1 = \omega_e \cos\phi \cos\psi + \epsilon(t_1)$
- 180 deg rotation
- $\omega_2 = -\omega_e \cos\phi \cos\psi + \epsilon(t_1)$



$$\psi = arccos\left(\frac{\omega_1 - \omega_2}{2\omega_e \cos\phi}\right)$$

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Proprioceptive sensors: measuring heading

- **Magnetic compass**
  - True North is not determined
  - auto-calibration manoeuvre is required
  - cheap
  - low cost
    - AHRS < 1K€
    - AHRS 3-4K€
- **Fiber Optic Gyro**
  - True North is determined
  - warm up
  - very small drift: 0.01 deg/min
  - expensive
    - 40-60K€

Proprioceptive sensors: IMU - AHRS - INS

- **Inertial Measurement Unit**
  - An **inertial measurement unit** (**IMU**) is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body, using a combination of accelerometers, gyroscopes, and sometimes magnetometers
- **Attitude Heading Reference System**
  - An **attitude and heading reference system** (**AHRS**) consists of sensors on three axes that provide attitude information for aircraft, including roll, pitch, and yaw. These are sometimes referred to as **MARG** (Magnetic, Angular Rate, and Gravity) sensors and consist of either solid-state or microelectromechanical systems (MEMS) gyroscopes, accelerometers and magnetometers. They are designed to replace traditional mechanical gyroscopic flight instruments.

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source: Wikipedia

Proprioceptive sensors: IMU - AHRS - INS

- The **main difference between an IMU and an AHRS** is the addition of an on-board processing system in an AHRS, which provides attitude and heading information. This is in contrast to an IMU, which delivers sensor data to an additional device that computes attitude and heading.
- **Inertial Navigation System**
  - An **inertial navigation system** (**INS**; also **inertial guidance system**, **inertial instrument**) is a navigation device that uses motion sensors (accelerometers), rotation sensors (gyroscopes) and a computer to continuously calculate by dead reckoning the position, the orientation, and the velocity (direction and speed of movement) of a moving object without the need for external references. Often the inertial sensors are supplemented by a barometric altimeter and sometimes by magnetic sensors (magnetometers) and/or speed measuring devices.

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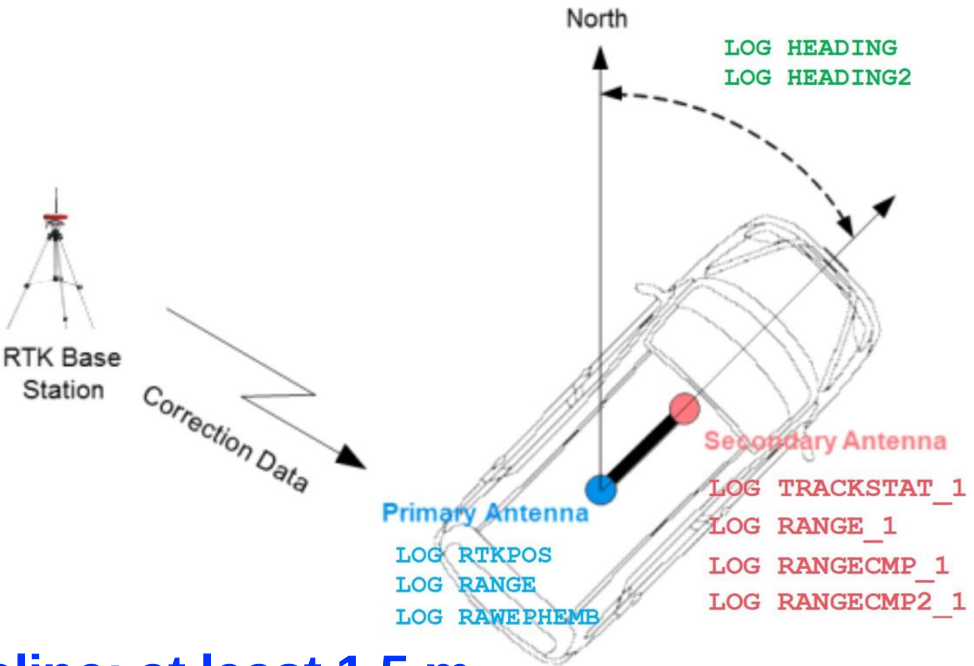
source: Wikipedia

Proprioceptive sensors: how to determine True North

- Surface Vehicles: dual antenna GPS



suggested baseline: at least 1.5 m

Proprioceptive sensors: measuring depth

- depth gauge: pressure sensor
  - the pressure increases by 1 atmosphere for every 33 feet (10.06 m) you go down
  - $P = \rho g z$

$$\rho_{fresh} = 997.0474\, kg/m^3$$ (for freshwater)

$$\rho_{salt} = 1023.6\, kg/m^3$$ (for saltwater)

$$g = 9.80665\, m/s^2$$

- **A/D converters and max range**
  - n bit converter
  - 2^n levels
  - resolution = max range / 2^n
    - 10m,16bit → 0.15mm; 10m, 8bit → 3.9cm
    - 1000m, 16bit → 1.5cm; 1000m, 8bit → 3.9m

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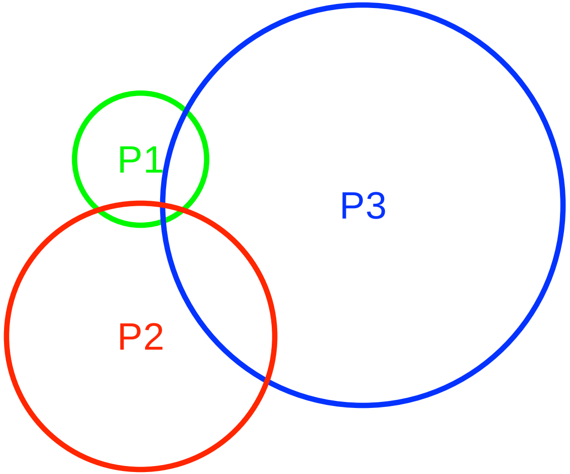
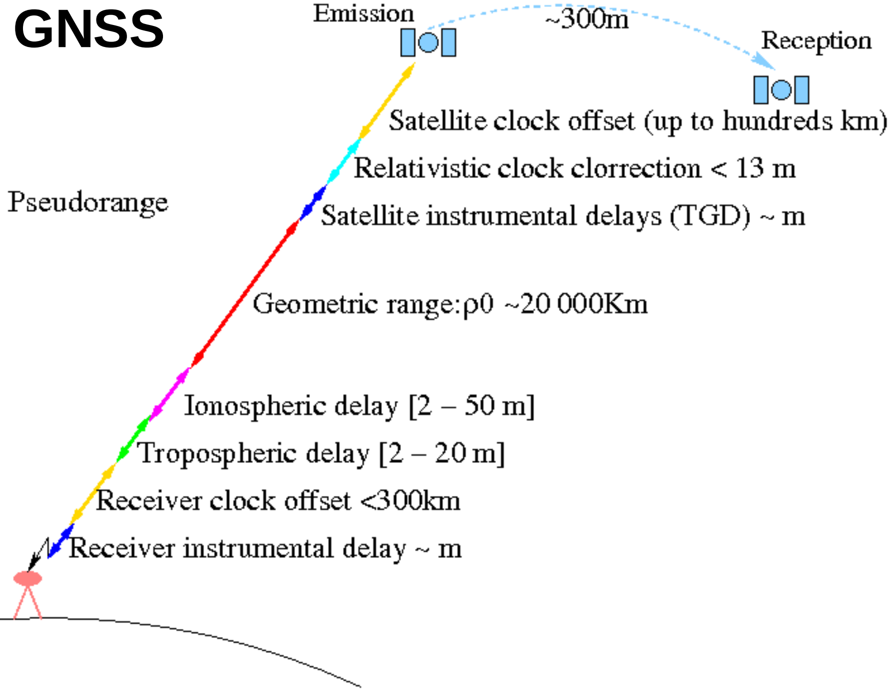
Proprioceptive sensors: position from triangulation



GNSS



- Time-Of-Flight
- At least 3 known **transmitters**

$$\rho_j = \sqrt{(x_j - x_u)^2 + (y_j - y_u)^2 + (z_j - z_u)^2} + ct_u$$

Bancroft algorithm

$$\rho_j = \sqrt{(x_j - x)^2 + (y_j - y)^2 + (z_j - z)^2)} + ct \ , \ b = ct$$

$$(x_j^2 + y_j^2 + z_j^2 - \rho_j^2) - 2(x_j x + y_j y + z_j z - b\rho_j) + (x^2 + y^2 + z^2 - b^2) = 0$$

$$\langle \mathbf{p}, \mathbf{q} \rangle = p_1 q_1 + p_2 q_2 + p_3 q_3 - p_4 q_4$$

$$\mathbf{u} = [x \ , \ y \ , \ z \ , b]^t \qquad \mathbf{s}_j = [x_j \ , \ y_j \ , \ z_j \ , \rho_j]^t$$

$$\langle \mathbf{s}_j, \mathbf{s}_j \rangle - 2\langle \mathbf{s}_j, \mathbf{u} \rangle + \langle \mathbf{u}, \mathbf{u} \rangle = 0$$

$$\mathbf{a} = \frac{1}{2} \left[\langle \mathbf{s}_1, \mathbf{s}_1 \rangle, \ldots, \langle \mathbf{s}_N, \mathbf{s}_N \rangle \right]^T \quad B = \begin{bmatrix} x_1 & y_1 & z_1 & -\rho_1 \\ \ldots & \ldots & \ldots & \ldots \\ x_N & y_N & z_N & -\rho_N \end{bmatrix} \qquad \Lambda = \frac{1}{2} \langle \mathbf{u}, \mathbf{u} \rangle \qquad \mathbf{e} = [1 \ , \ , \ldots \ , \ 1]^T$$

$$\mathbf{a} - B\mathbf{u} + \Lambda \mathbf{e} = \mathbf{0} \ , , \ i.e. \ B\mathbf{u} = \mathbf{a} + \Lambda \mathbf{e}$$

$$\mathbf{u} = \left(B^T B \right)^{-1} B^t \left(\mathbf{a} + \Lambda \mathbf{e} \right) \Longrightarrow$$ Quadratic expression in Λ

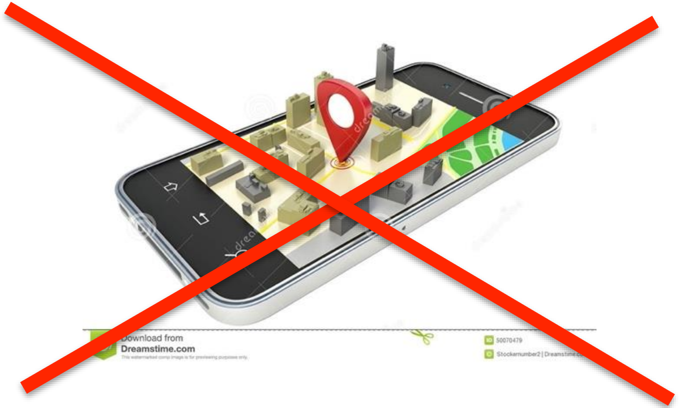
Proprioceptive sensors: horizontal position

- Surface Vehicles: GPS
  - accuracy
    - 5m in 2000 when selective availability was lifted
    - 0.3m in 2018 using L5 band
    - centimetre-level using RTK (Real-Time Kinematic positioning) that relies on a single reference station or interpolated virtual station

Electromagnetic wave propagation underwater

- because of water’s high permittivity and electrical conductivity, wave attenuation is very high compared to air and increases rapidly with frequency
  - no GNSS and wifi
  - limited performance of optical sensors

Where am I?



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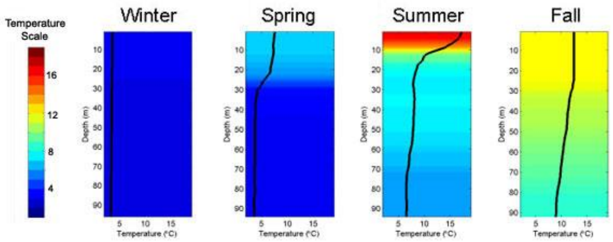
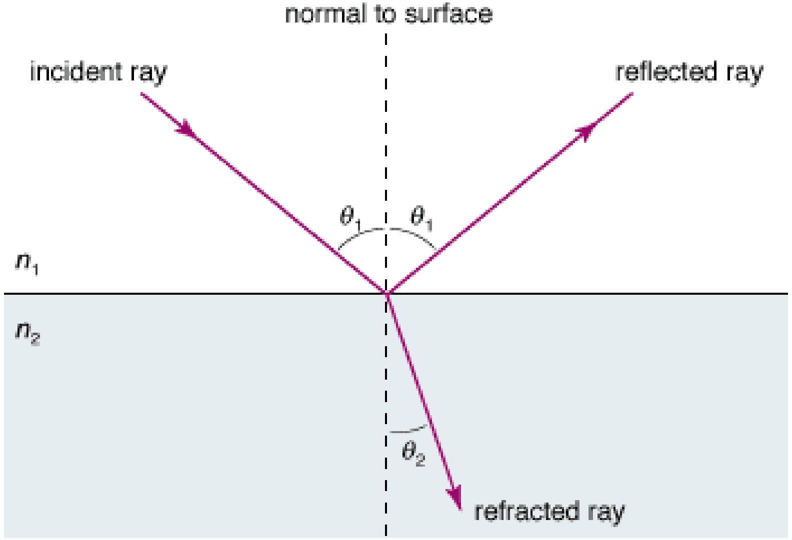
Acoustic wave propagation underwater

- sound speed in salt water is about 1500 m/s, and increases with temperature, pressure and salinity
  - **acoustic localisation & comms**
- **Underwater acoustic propagation**
- Boundary interactions
  - surface & bottom
    - reflection
  - water layers
    - reflection & refraction





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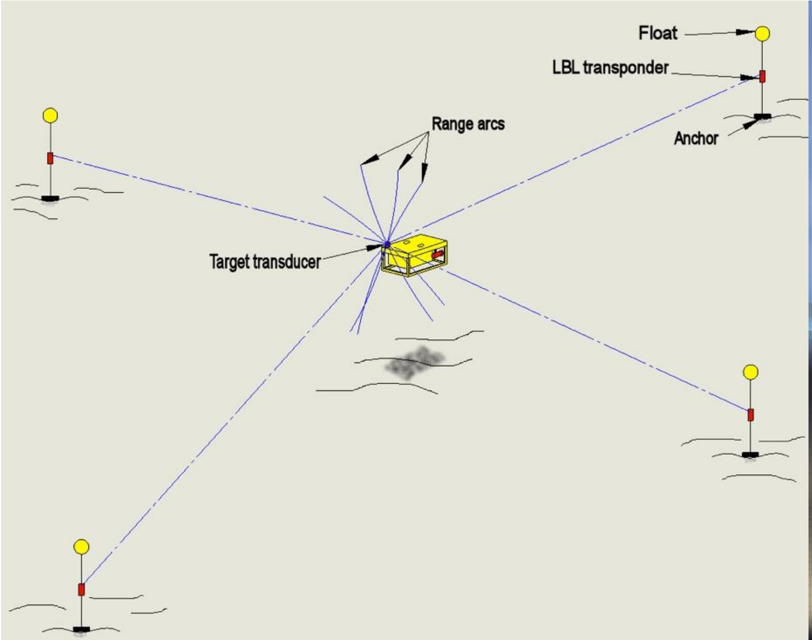
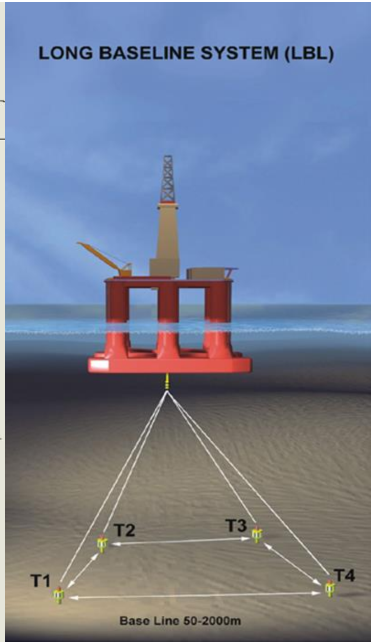
Proprioceptive sensors: positioning underwater

- build a polygon of acoustic transponders on the seabed: **Long Base Line** acoustic positioning





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Proprioceptive sensors: LBL baseline calibration

- the distances between the transponders, their depth information, the ranges from an interrogator on the host vessel and GPS position of the host vessel itself are used to calibrate the array and set up a local inertial frame (use a Sound Velocity Profiler to perform accurate calibration)
- **baseline deployment and calibration requires time and suitable logistics**

	Frequency Range	Maximum range	Typical relative, static accuracy*
Low frequency (LF)	8kHz to 16kHz	$\backsim$ 10km	2m to 5m
Medium frequency (MF)	18kHz to 36kHz	2km to 3.5km	0.25m to 1m
High frequency (HF)	30kHz to 60kHz	1,500m	0.15m to 0.25m
Extra high frequency (EHF)	50kHz to 110kHz	$< 1,000$m	< 0.05m
Very high frequency (VHF)	200kHz to 300kHz	< 100m	< 0.01m

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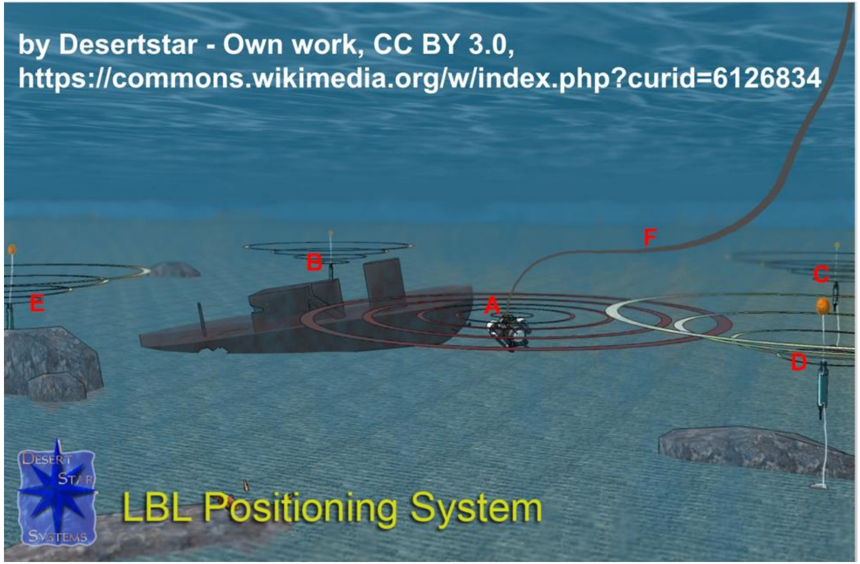
Proprioceptive sensors: LBL positioning underwater



The interrogator pings the baseline transponders in sequence

AA: **interrogator**, mounted on the vehicle to be tracked

B,C,D,E: baseline transponders

- The **interrogator** transmits an acoustic signal that is received by the georeferenced **baseline transponders**
- The reply of the **baseline transponders** is received again by the **interrogator**, that measures the signal **time-of-flight** and computes the corresponding distances A-B, A-C, A-D, A-E
- acoustic distance measurements may be **augmented** by **depth sensor** data

this requires time!

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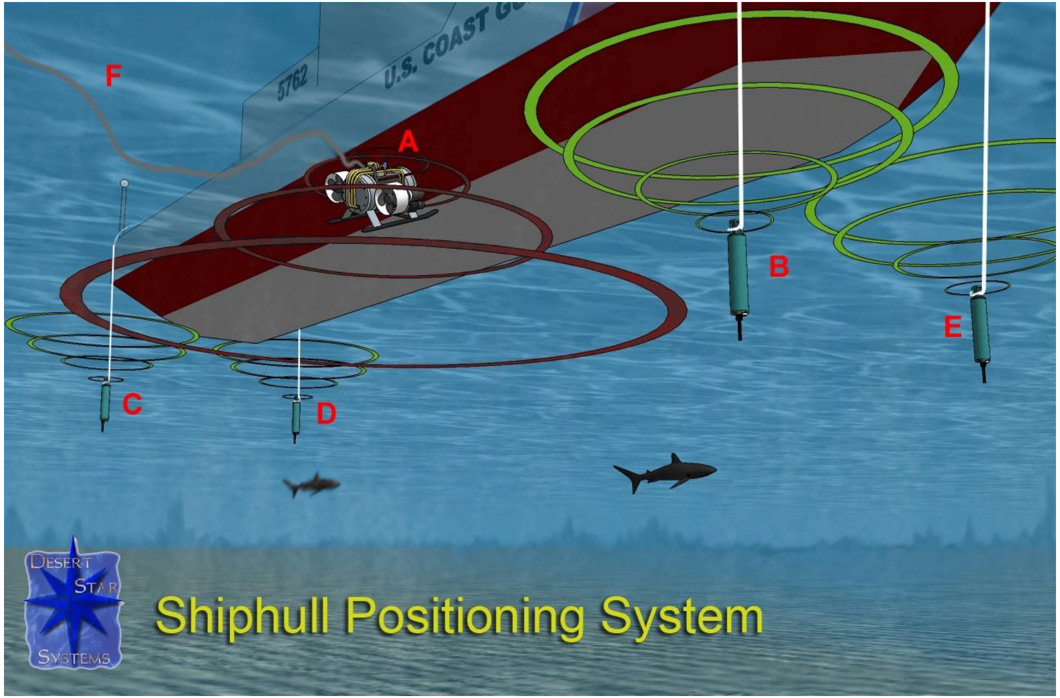
Short Base Line acoustic positioning system

- to reduce time and logistics: build the baseline on the ship hull



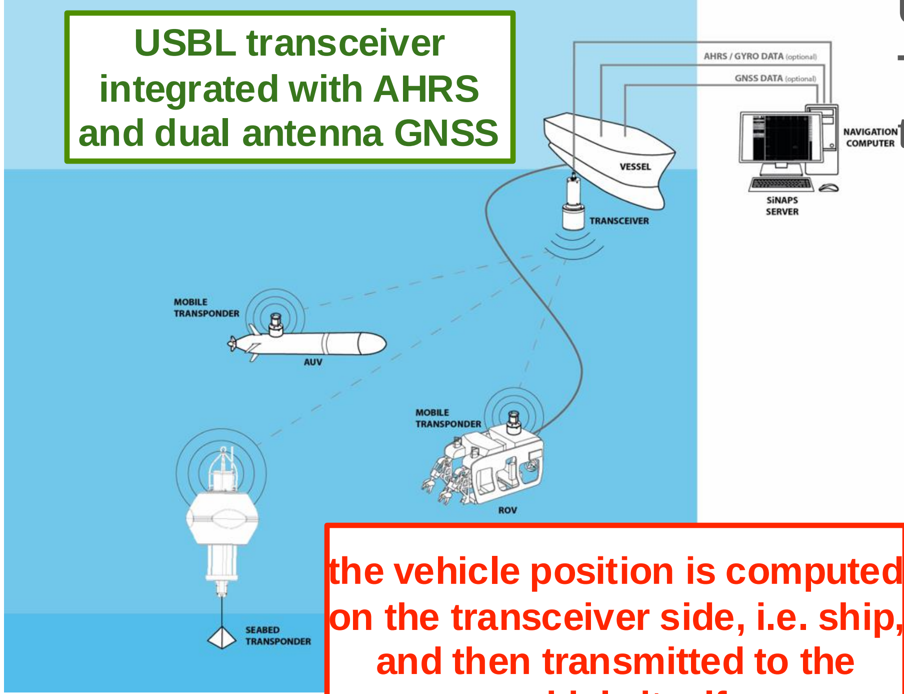
Ship position and attitude have to be measured

the vehicle position is computed on the ship side and then transmitted to the vehicle itself

Ultra Short Base Line acoustic positioning system

- to adapt to any vessel

USBL transceiver integrated with AHRS and dual antenna GNSS



the vehicle position is computed on the transceiver side, i.e. ship, and then transmitted to the vehicle itself

USBL transceiver is mounted on the vessel
Transponders are mounted on the objects to be tracked

- The **transceiver** transmits an acoustic signal that is received by the **transponder**
- The reply of the **transponder** is received again by the **transceiver**
  - time-of-flight → range
  - phase-difference → bearing
- acoustic distance measurements may be **augmented** by **depth sensor** data

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Inverted Ultra Short Base Line (iUSBL)

- USBL transceiver is mounted on the vehicle (AUV/ROV), where position is computed
- transponders are mounted in fixed points, e.g. docking station

the vehicle position is computed on the transceiver side, i.e. onboard vehicle itself

- Examples of applications
  - AUV docking and position re-initialisation
  - AUV beneath extensive ice sheets
  - ROV positioning single transponder tracking instead of a full LBL array

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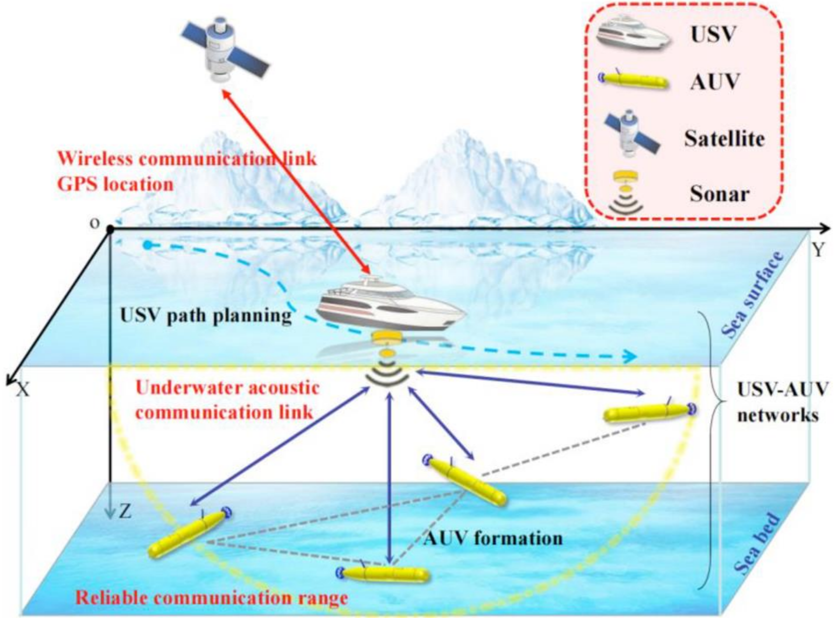
Cooperative robotics: USBL with multiple vehicles

- **The transceiver pings the vehicle transponders in sequence: this requires time!**
- **passive inverted Ultra-Short-BaseLine (piUSBL)**
- each vehicle is equipped with a iUSBL
- one single acoustic beacon (transponder) for all the vehicles
- **time-synchronised** USBL array
- **one way travel time (OWTT)** range and bearing between each vehicle and the acoustic beacon



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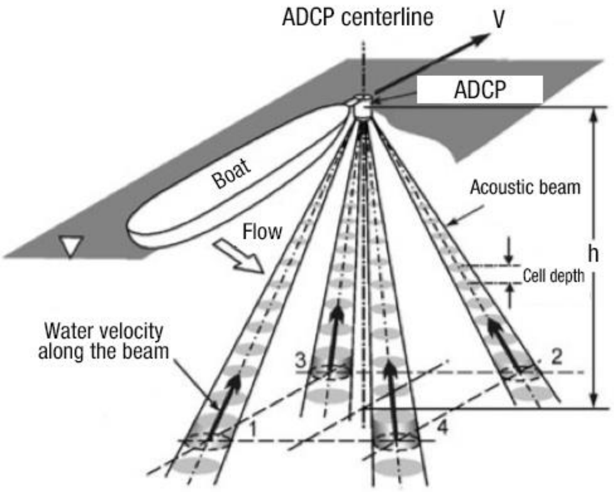
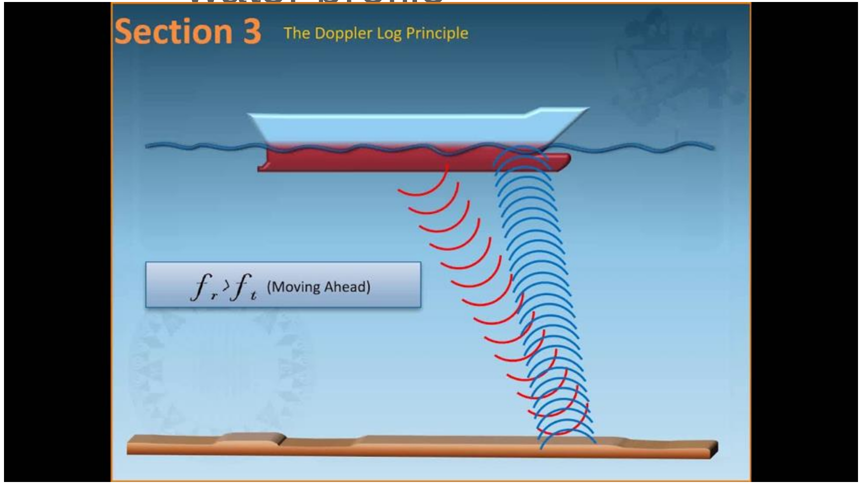
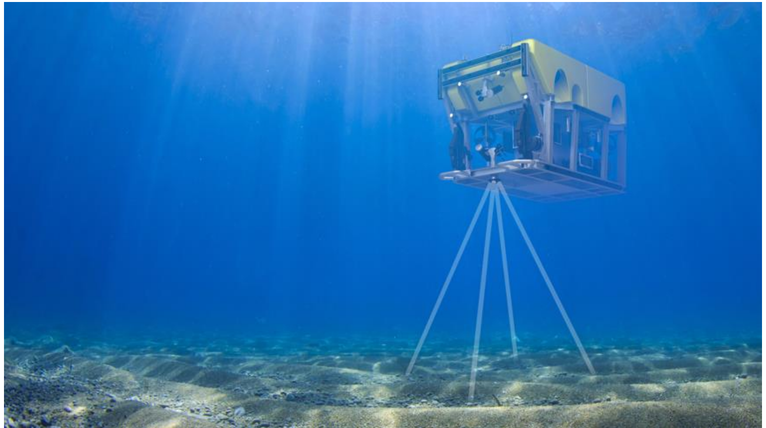
Proprioceptive sensors: linear speed



Doppler Velocity Logger (DVL)

- Range and speed along 4 beams
  - u, v, w linear speeds
  - 4 range measurements from the seabed
  - water profile





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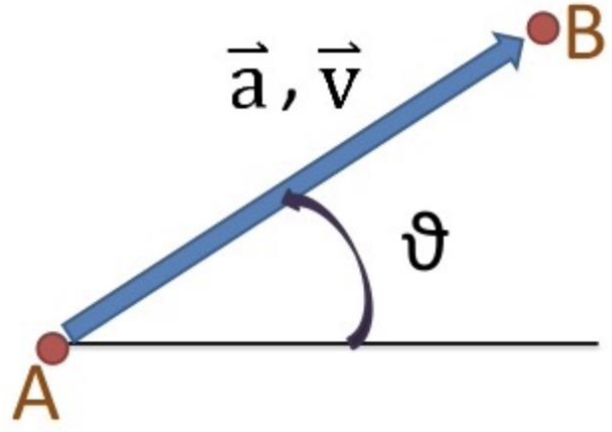
Position computation: dead-reckoning

- Process of calculating one's current position by using a previously determined position.



- compass
- velocimeter

on long distance the main error is given by orientation

- Dead-Reckoning may be improved with OWTT single beacon navigation

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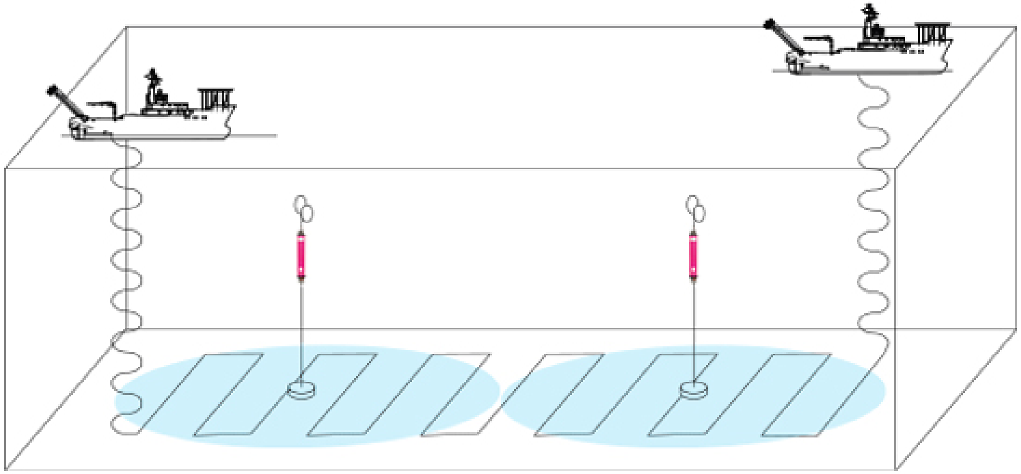
Sparse LBL aided INS

- Dead-reckoning + one/two LBL beacon(s)
  - improve precision by constraining estimate drift and covariance
- **Challenges**
  - single beacon navigation/comms + atomic clock



Accurate georeferenced positioning

Example: e-URoPe ROV

- Position & orientation of the surface acoustic head
  - dual antenna GPS (position + heading): 10 K€
  - inclinometers (pitch & roll) - included in USBL head
- Position with respect to the surface acoustic head
  - USBL: 30 K€
- Short range dead-reckoning
  - Fiber Optic Gyro: 40 K€
  - DVL: 30 K€
- **High accuracy underwater geolocation costs!**

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Exteroceptive sensors: range

- DVL measures range and speed with respect to specific features within the operating environment, e.g. seabed
- Range from an underwater object is typically measured by acoustic time-of-flight sensors, denoted as **echosounders**
- increasing frequency
  - decreasing max range
  - increasing accuracy

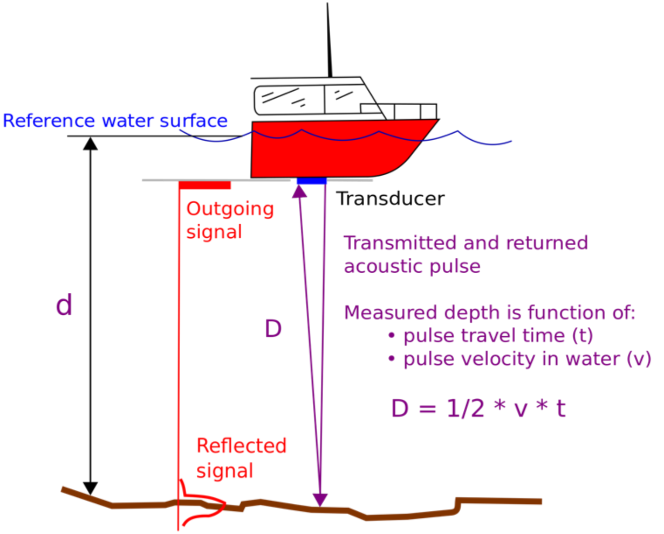

Figure 9-1. Acoustic depth measurement

By Brandon T. Fields (cdated) via the US Army Corps of Engineers - EM 1110-2-1003, Manual of Hydrographic Surveying, based upon Principle_of_SBES.jpg by en:User:Mredmayne. This W3C-unspecified vector image was created with Inkscape ., Public Domain, https://commons.wikimedia.org/w/index.php?curid=23357601

Underwater acoustics: random or physics?

- “Many times we model these phenomena as random, but if you look the data with attention, you see that’s repeatable, it is acoustic propagation: it’s physics!” (Marcus Cardew, making experiments in Horta, Azores, 2003)

Underwater acoustics: random or physics?

- Exploring the keel of the Campbell ice tongue in Antarctica with Romeo ROV

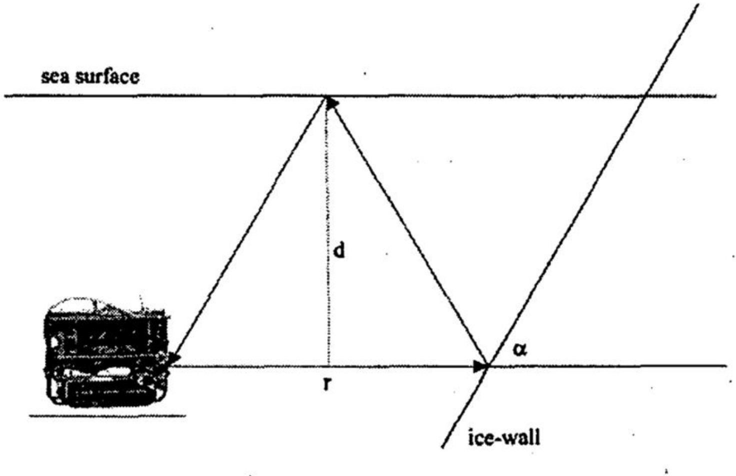

Fig. 7. Model of acoustic multi-path between the ice-wall and the sea surface.

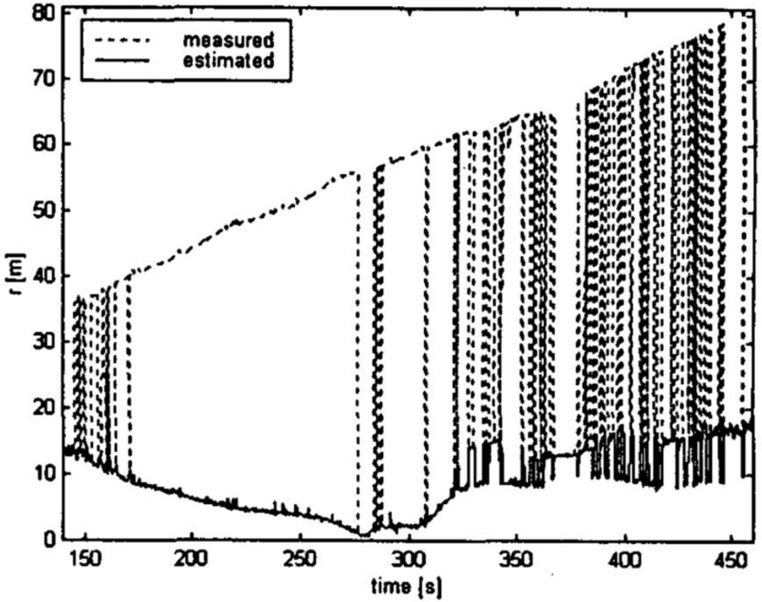

Figure 9. Measured and reconstructed obstacle avoidance sonar range.

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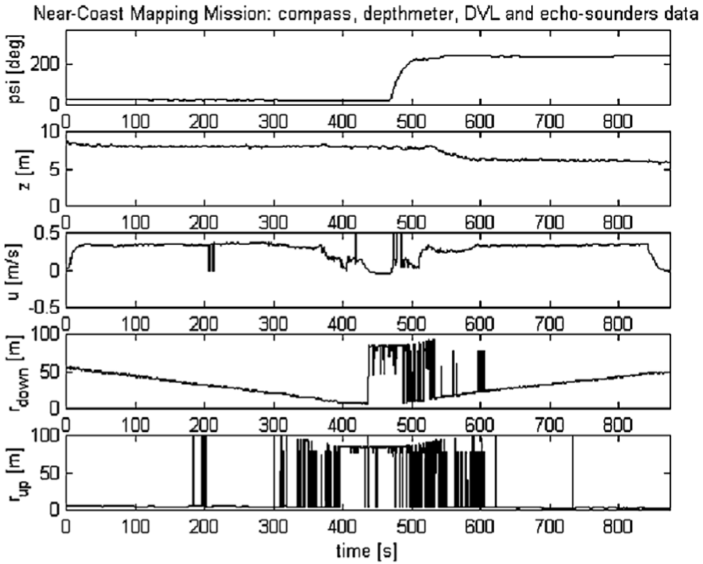
Underwater acoustics: random or physics?

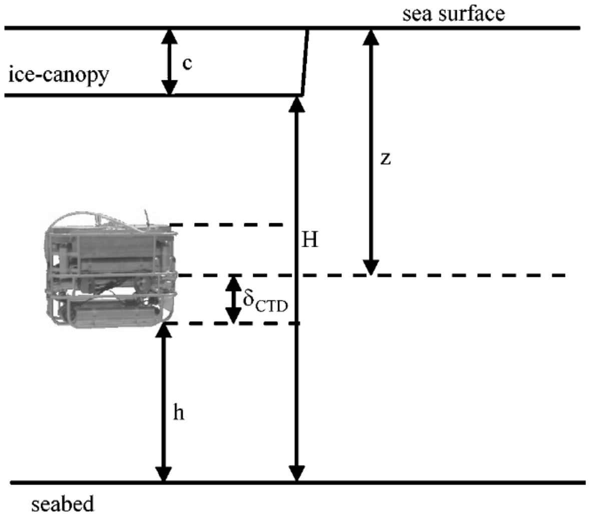
- under ice shallow water near coast exploration



$$\varepsilon_n(t) = h(\rho(t),\ n(t)) - \hat{h}(t/t - \Delta t)$$

minimum range decision maker

$$\hat{h}(t) = h(\hat{n}(t)) \colon \hat{n}(t) = \arg\min_n |\varepsilon_n(t)|$$



$$\rho = h + nH = h + n(h + \delta_{CTD} + z - c)$$

Underwater acoustic modems performance: a COTS example

Underwater acoustic modems sorted by frequency and operating ranges

HIGH SPEED MID-RANGE DEVICES

18/34

Fast devices for mid-range horizontal transmissions. All-round performer

Frequency: 18 - 34 kHz
Acoustic Connection: up to 13.9 kbit/s
Operating Range: 3500 m
Directivity: several versions available

42/65

High-speed devices for mid-range vertical and slant transmissions

Frequency: 42 - 65 kHz
Acoustic Connection: up to 31.2 kbit/s
Operating Range: 1000 m
Directivity: wide-angle (100 degrees)

48/78

High-speed devices for mid-range horizontal transmissions

Frequency: 48 - 78 kHz
Acoustic Connection: up to 31.2 kbit/s
Operating Range: 1000 m
Directivity: horizontally omnidirectional

HS

High-speed devices for short-range transmissions in shallow waters

Frequency: 120 - 180 kHz
Acoustic Connection: up to 62.5 kbit/s
Operating Range: 300 m
Directivity: omnidirectional

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Underwater acoustic modems performance: a COTS example

DEPTH-RATED LONG-RANGE DEVICES

15/27

Depth-rated devices for long-range vertical or slant transfers

Frequency: 15 - 27 kHz
Acoustic Connection: up to 9.2 kbit/s
Operating Range: 6000 m
Directivity: wide-angle (120 degrees)

12/24

Depth-rated devices for long-range vertical or slant transfers

Frequency: 13 - 24 kHz
Acoustic Connection: up to 9.2 kbit/s
Operating Range: 6000 m
Directivity: conical (70 degrees)

7/17

Depth-rated devices for long-range horizontal, vertical or slant transfers

Frequency: 7 - 17 kHz
Acoustic Connection: up to 6.9 kbit/s
Operating Range: 8000 m
Directivity: several versions available

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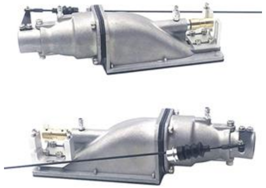
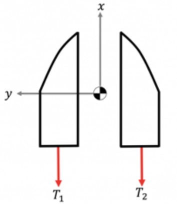
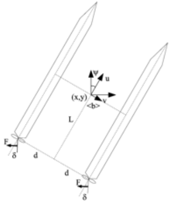
Unmanned Marine Vehicles actuation systems

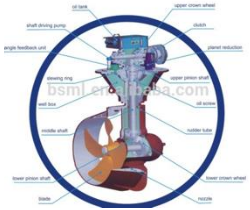
- Forward speed
  - propellers, jets



- Steering mode
  - differential thrusts, rudders, azimuth thrusters

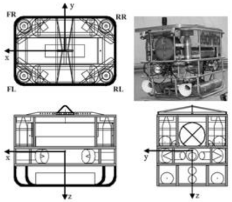


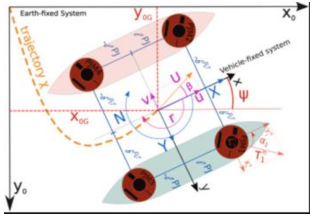




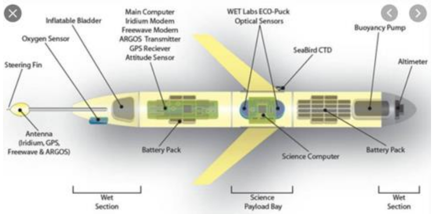
Unmanned Marine Vehicles actuation systems

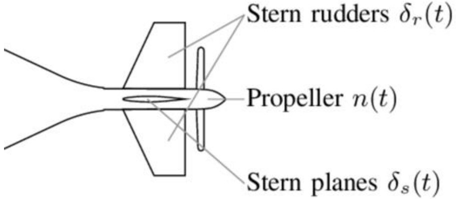
- Station keeping
  - fixed thruster configuration, azimuth thrusters





- Vertical motion
  - mass displacements, planes, vertical thrusters





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