MITMECHE

MIT 2.S01 Introduction to Autonomous Underwater Vehicles

Lecture 6: Underwater Navigation

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MIT Sea Grant AUV Lab

MIT Marine Autonomy Lab

Navigation of AUVs

What is navigation:

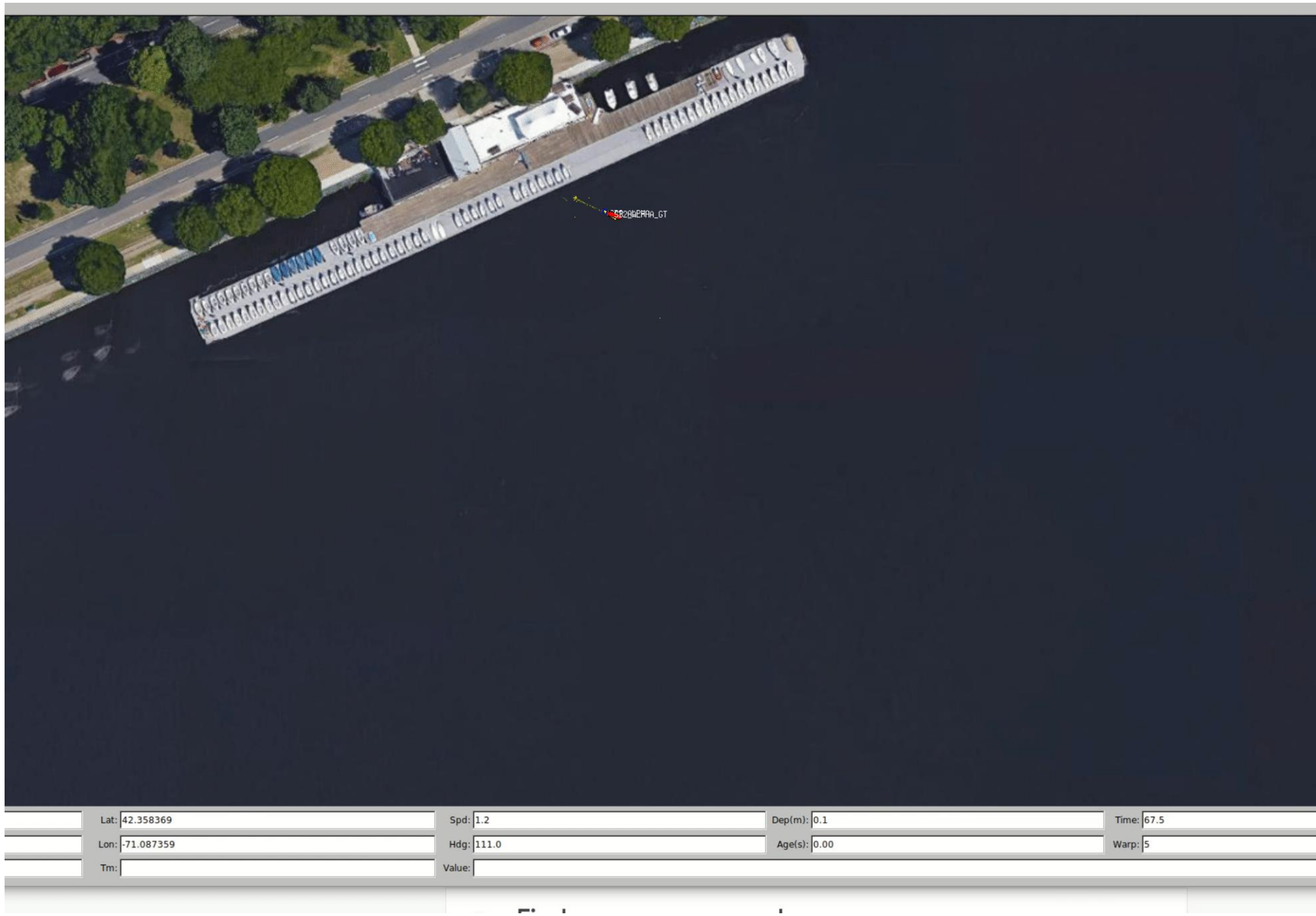
- AUV continuously estimating its own position while it is underway.

What is navigation accuracy:

- How well does the AUV know its own position.

Why is navigation accuracy important?

- To transit to a given location.
- To avoid known obstacles; e.g., to avoid going under the dock.
- To accurately geo-locate (or geo-tag) the data measurements.

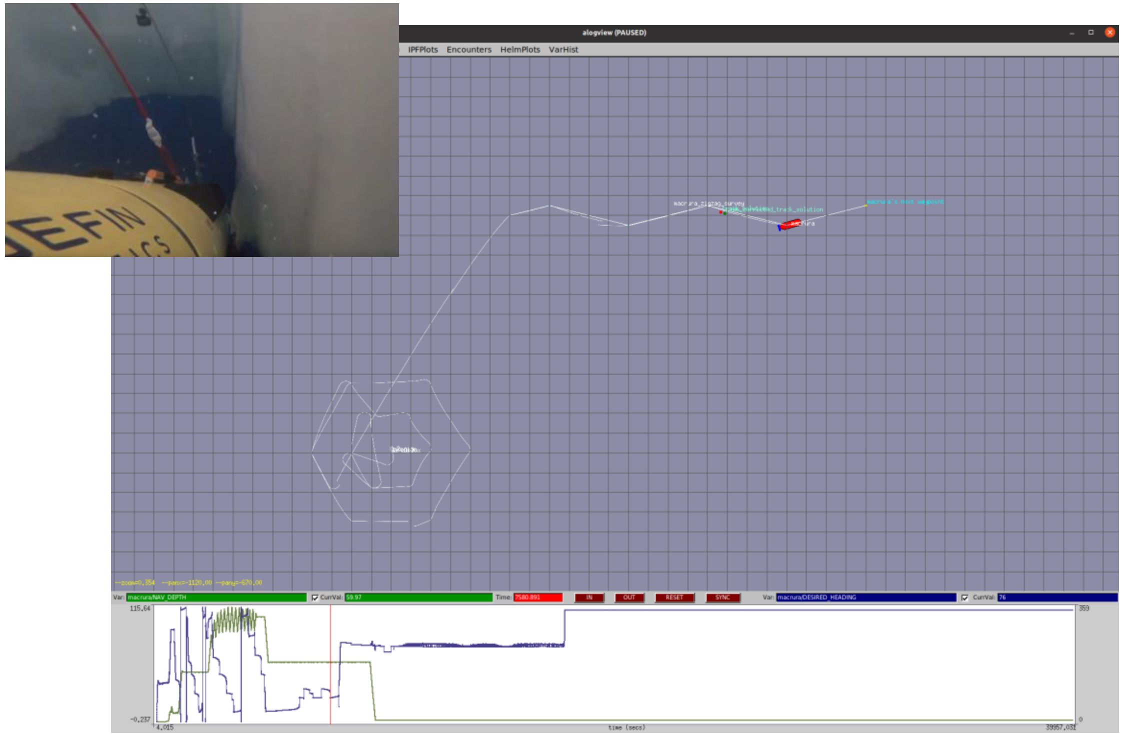


Lat: 42.358369
Spd: 1.2
Dep(m): 0.1
Time: 67.5
Lon: -71.087359
Hdg: 111.0
Age(s): 0.00
Warp: 5
Tm:
Value:

Navigation vs. Tracking

Navigation

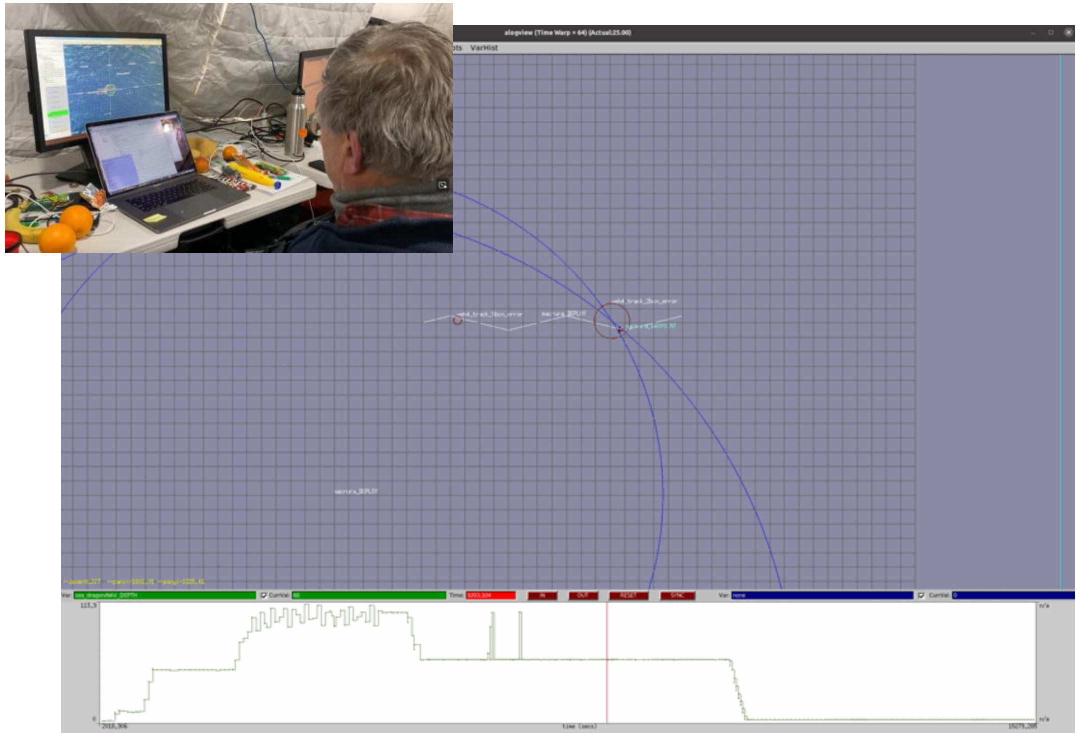
If you are the AUV, finding your own position is navigation



The Macrura AUV's navigation solution (i.e. own position estimate) while it is conducting a zig-zag pattern survey mission under the ice in the Arctic.

Tracking

If you are the AUV operator, finding the position and status of your AUV is tracking



Prof. Henrik Schmidt and his team are tracking the Macrura AUV in the Arctic during ICEX2020, while the AUV is conducting a zig-zag pattern survey leg under the ice.

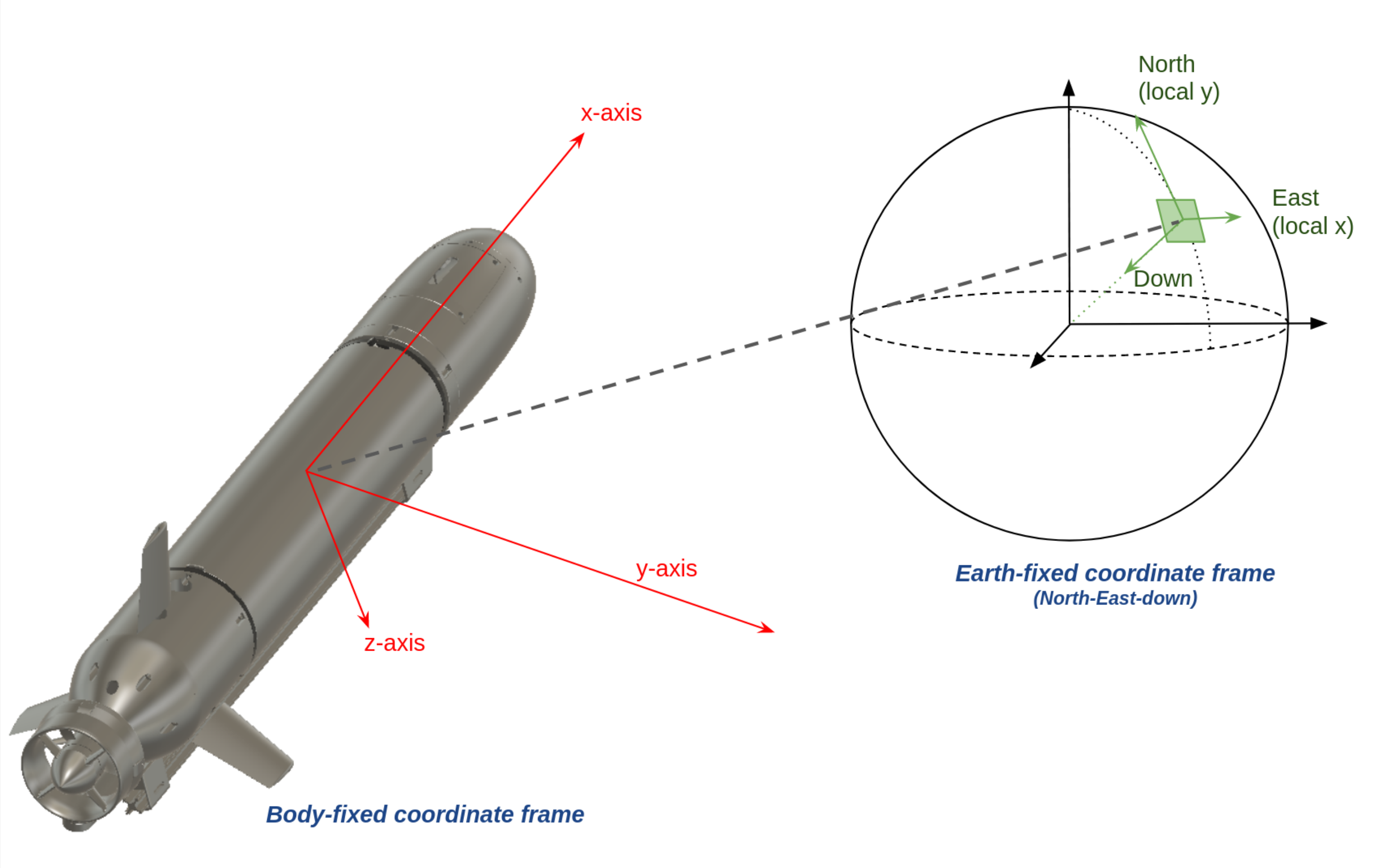
Body-fixed and earth-fixed coordinate systems

Body-fixed coordinate frame:

- Fixed to the vehicle.
- The coordinate system translates and rotates with the vehicle.
- Used to describe the motion and orientation of the vehicle.

Earth-fixed coordinate frame:

- A geo-centric coordinate frame used describe the position of the vehicle geodetic coordinates



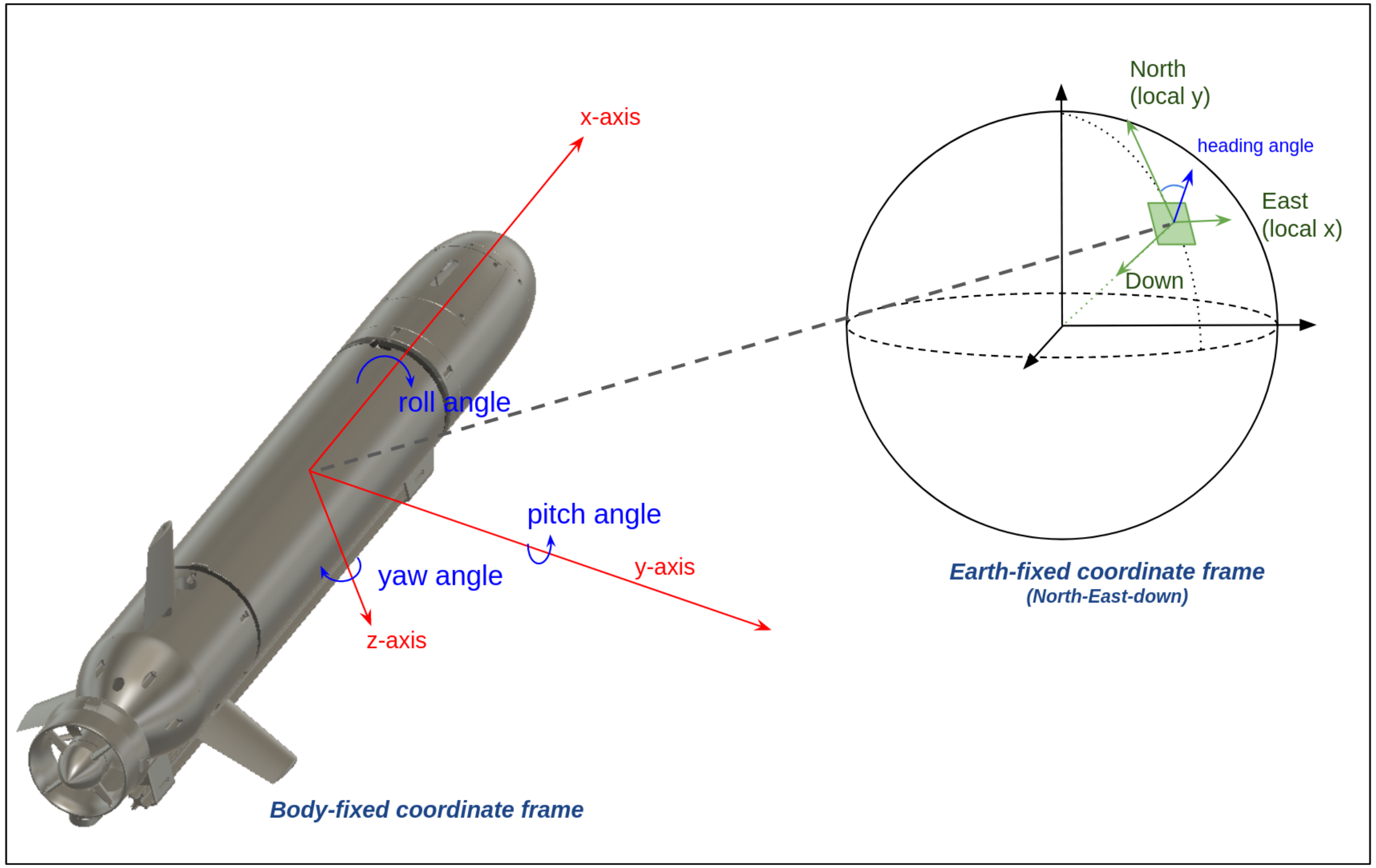
Body-fixed coordinate frame

Earth-fixed coordinate frame
(North-East-down)

Components of the navigation solution

Attitude:

- Roll angle
- Pitch angle
- Yaw angle
- Heading angle



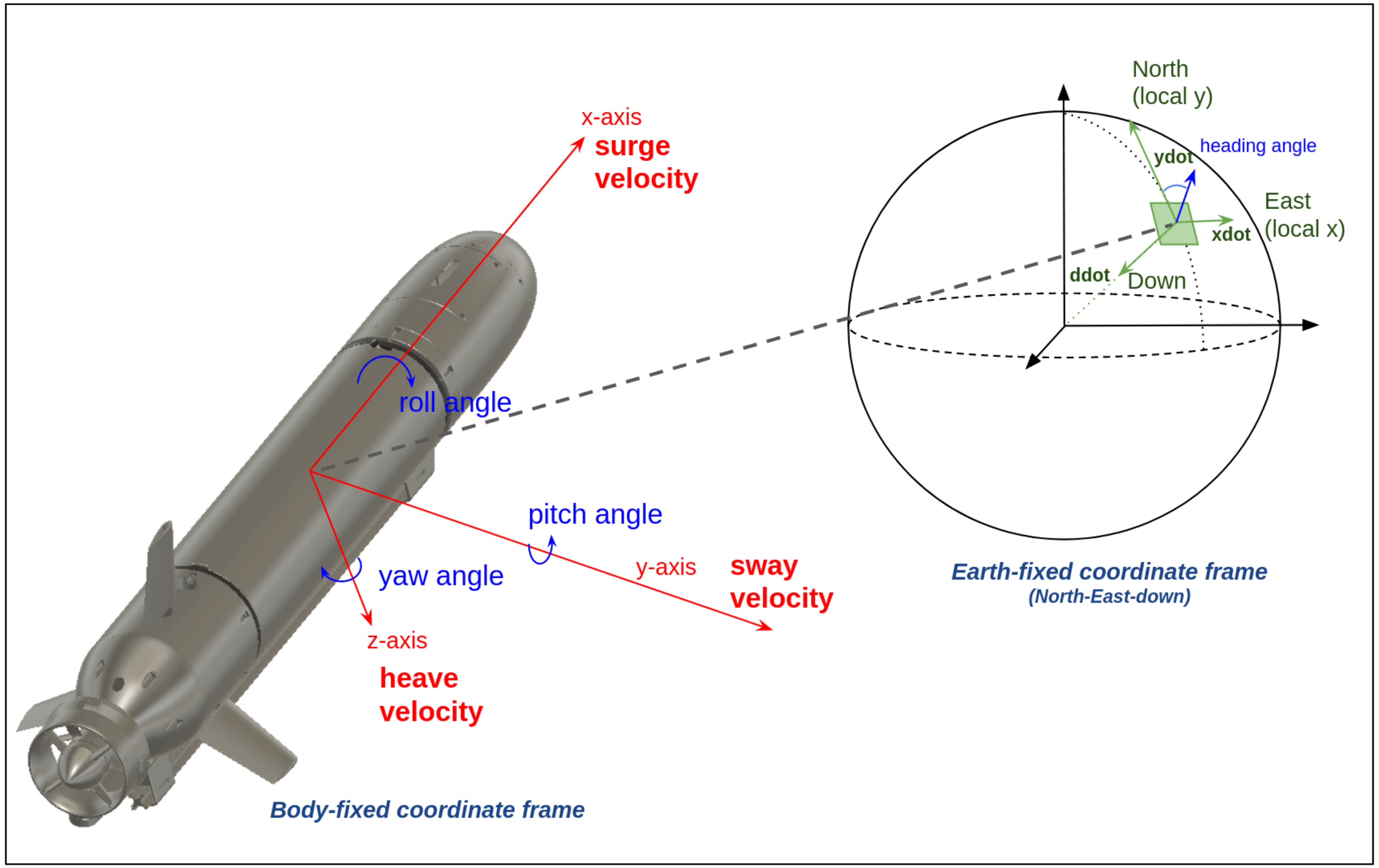
Components of the navigation solution

Attitude:

- Roll angle
- Pitch angle
- Yaw angle
- Heading angle

Velocity:

- Body-fixed
  - Surge velocity (u)
  - Sway velocity (v)
  - Heave velocity (w)
- Earth-fixed
  - Velocity along north-axis (ydot)
  - Velocity along east-axis (xdot)
  - Velocity along downwards-axis (ddot)



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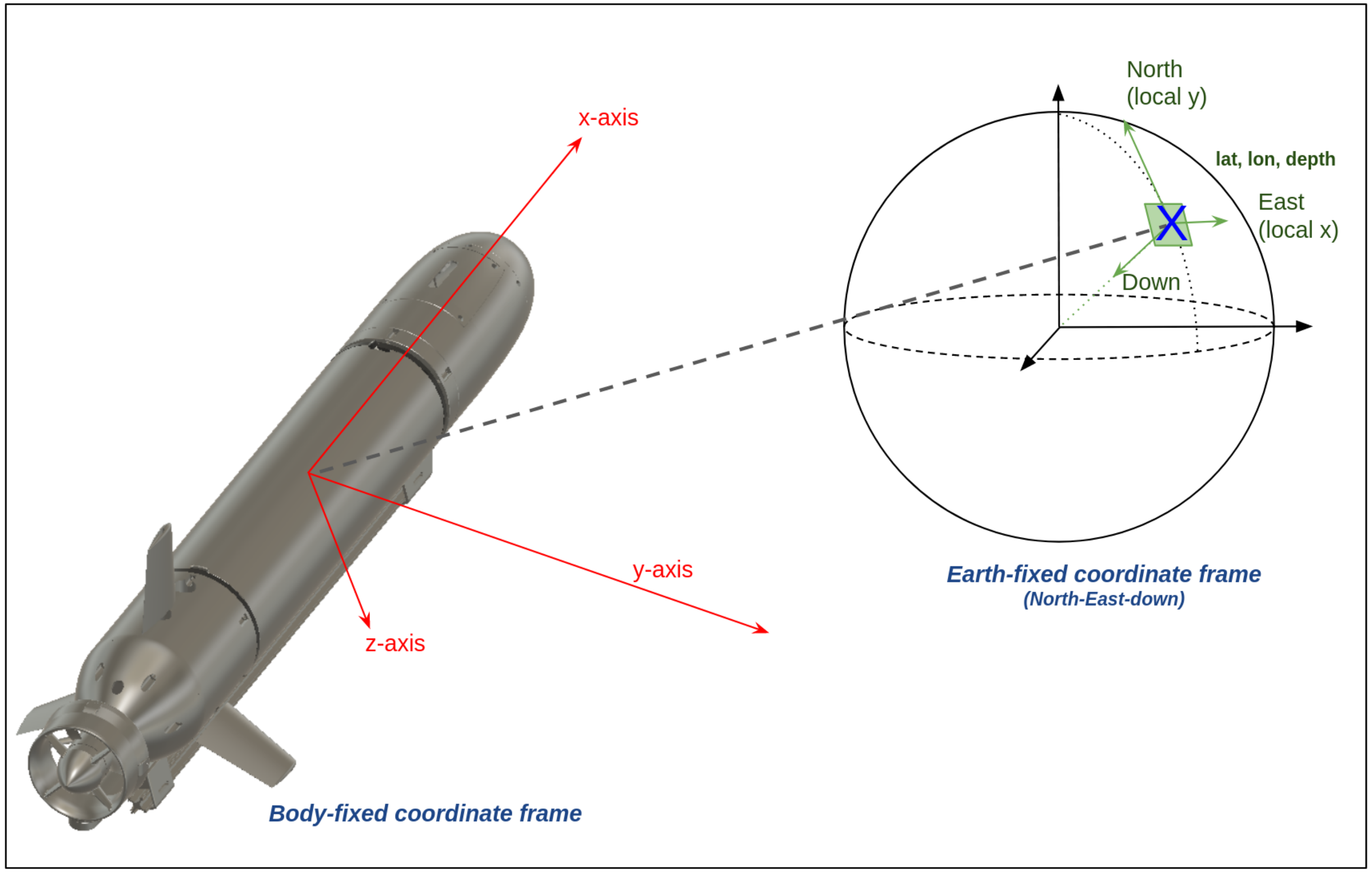
Position:

- Geodetic Coordinates
  - Latitude, longitude and depth
- Local coordinates
  - Local-x, local-y and depth

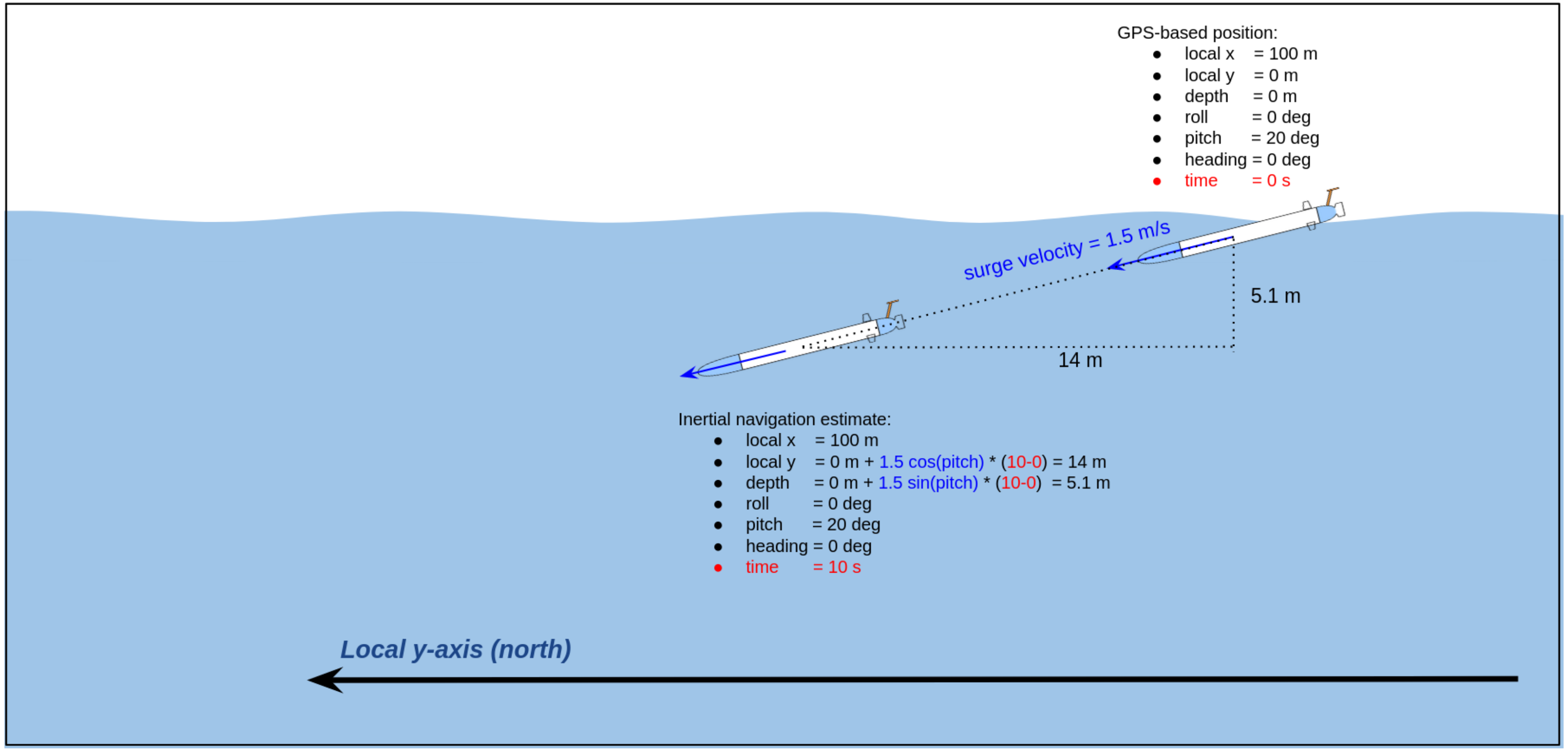


Body-fixed coordinate frame

Earth-fixed coordinate frame
(North-East-down)

Inertial navigation with velocity-aiding

- On the surface:
  - (Re)initialize the position using GPS
- Underwater:
  - Measure body-fixed velocity.
  - Convert the body-fixed velocity to earth-fixed using attitude measurements.
  - Integrate the earth-fixed velocity over time to obtain position delta (i.e., movement of the AUV from last position).
  - Add position delta to the last position estimate. **Repeat until the AUV re-gains GPS..**



GPS-based position:

- local x = 100 m
- local y = 0 m
- depth = 0 m
- roll = 0 deg
- pitch = 20 deg
- heading = 0 deg
- time = 0 s

Inertial navigation estimate:

- local x = 100 m
- local y = 0 m + 1.5 cos(pitch) * (10-0) = 14 m
- depth = 0 m + 1.5 sin(pitch) * (10-0) = 5.1 m
- roll = 0 deg
- pitch = 20 deg
- heading = 0 deg
- time = 10 s

Inertial navigation with velocity-aiding

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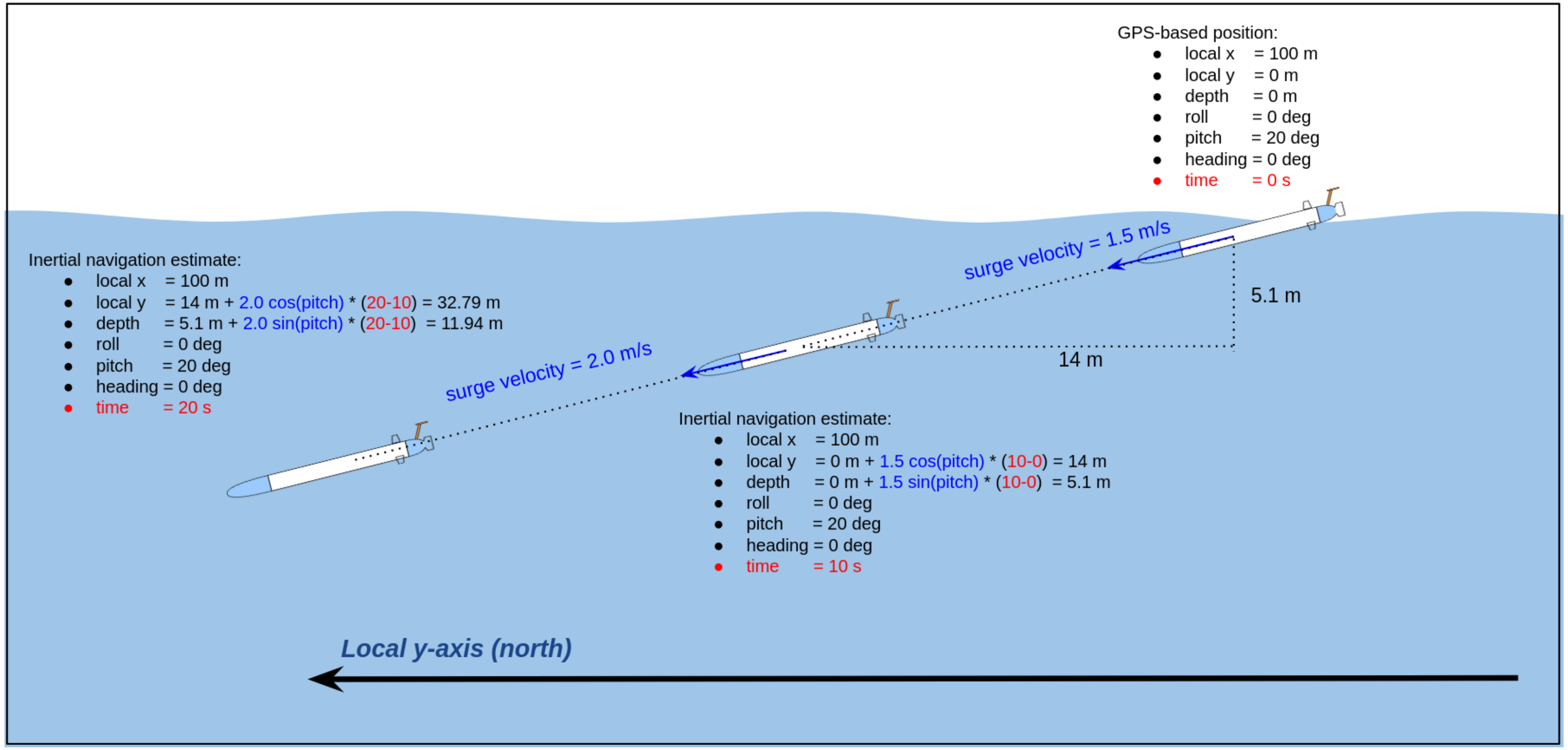

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- depth = 0 m + 1.5 sin(pitch) * (10-0) = 5.1 m
- roll = 0 deg
- pitch = 20 deg
- heading = 0 deg
- time = 10 s

Inertial navigation estimate:
- local x = 100 m
- local y = 14 m + 2.0 cos(pitch) * (20-10) = 32.79 m
- depth = 5.1 m + 2.0 sin(pitch) * (20-10) = 11.94 m
- roll = 0 deg
- pitch = 20 deg
- heading = 0 deg
- time = 20 s

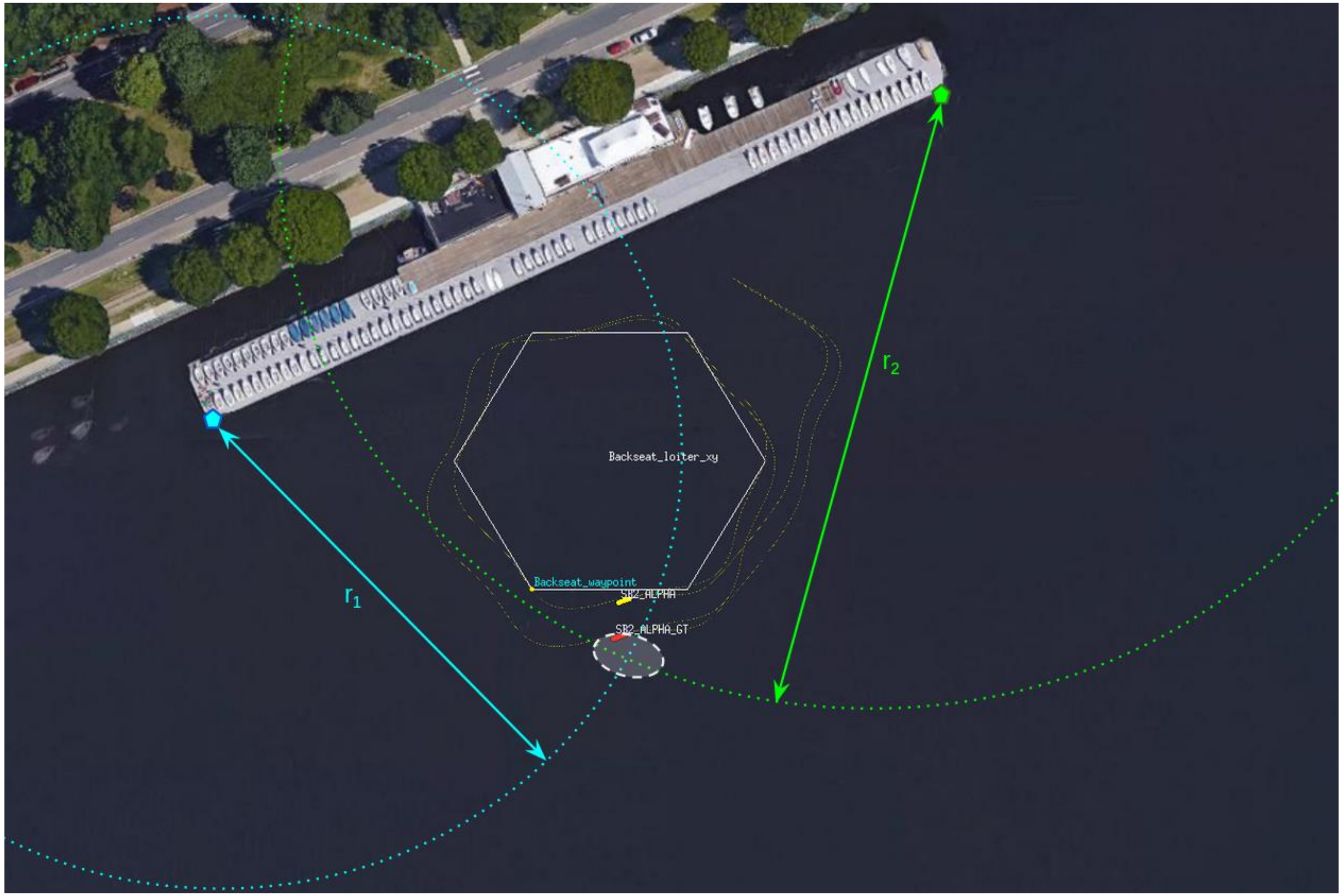
Position-aiding

- If/when an under-water position update is received (e.g., acoustic position update), the AUV can fuse it with its inertial navigation solution.

- When fusing, it will consider:
  - The current inertial navigation solution and its uncertainty.
  - The position of the acoustic update and its uncertainty.

- SeaBeaver AUVs use HydroMAN as the navigation fusion engine.

- HydroMAN uses an extended-Kalman filter for fusion and filtering.



Underwater navigation aiding sensors

Attitude aiding:

- Micro-electro-mechanical systems (MEMS) inertial measurement units (IMU)
- Fiber-optic gyroscopes (FOG)

Velocity aiding:

- Doppler velocity log (DVL)
- Vehicle dynamic models

Position aiding:

- Depth sensor
- Global positioning system (GPS) - only on the surface
- Long baseline (LBL) systems and their derivatives
- Ultra-short baseline (USBL) systems and their derivatives
- Terrain-aided navigation (TAN)

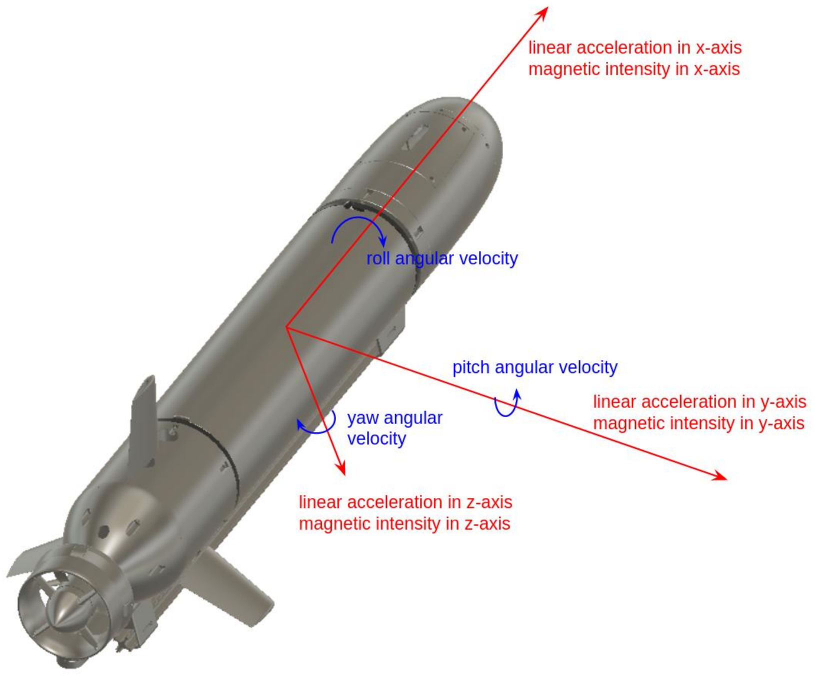
Micro-electro-mechanical systems (MEMS) inertial measurement units (IMU)

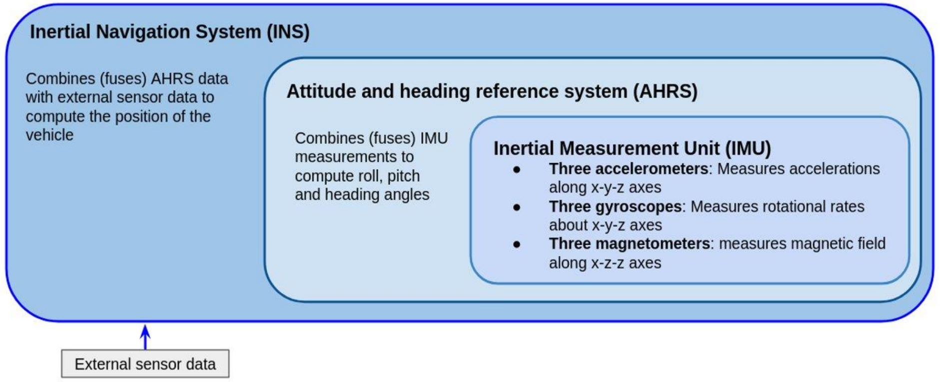
MEMS IMU typically contains 9 embedded sensors in a single chip:

- Three accelerometers measuring the 3D linear accelerations along body-fixed x, y and z axes.
- Three gyroscopes measuring the 3D angular velocities along body-fixed x, y and z axes.
- Three magnetometers measuring the 3D magnetic intensities along body-fixed x, y and z axes.

Attitude and heading reference system:

- An algorithm that combines the 9-axis measurements made by the IMU to compute:
  - Roll angle
  - Pitch angle
  - Heading angle





Inertial Navigation System (INS)

Combines (fuses) AHRS data with external sensor data to compute the position of the vehicle

Attitude and heading reference system (AHRS)

Combines (fuses) IMU measurements to compute roll, pitch and heading angles

Inertial Measurement Unit (IMU)

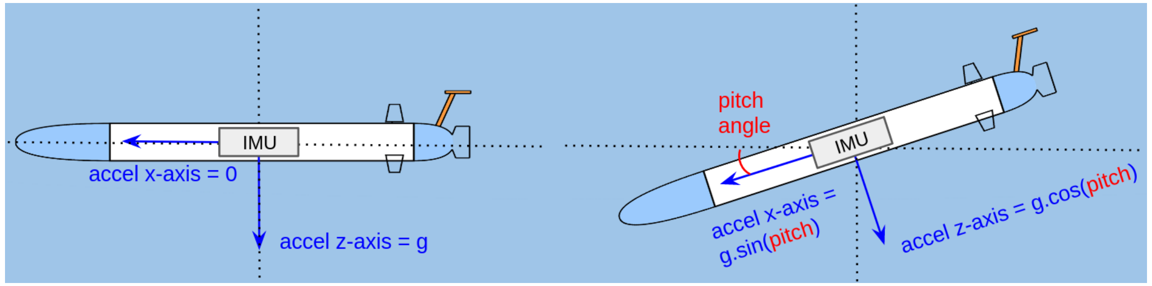
- **Three accelerometers**: Measures accelerations along x-y-z axes
- **Three gyroscopes**: Measures rotational rates about x-y-z axes
- **Three magnetometers**: measures magnetic field along x-z-z axes

External sensor data

Micro-electro-mechanical systems (MEMS) inertial measurement units (IMU)

Accelerometers help measure the roll and pitch angles:

- The accelerometers measurements include the gravitational acceleration.
- If z-axis accelerometer reports a value close to gravity, and others report zero, then it is likely that the z-axis is pointing downwards.
- If the vehicle is pitched, the components of the gravity will be distributed among x and z axes, according to the angle.



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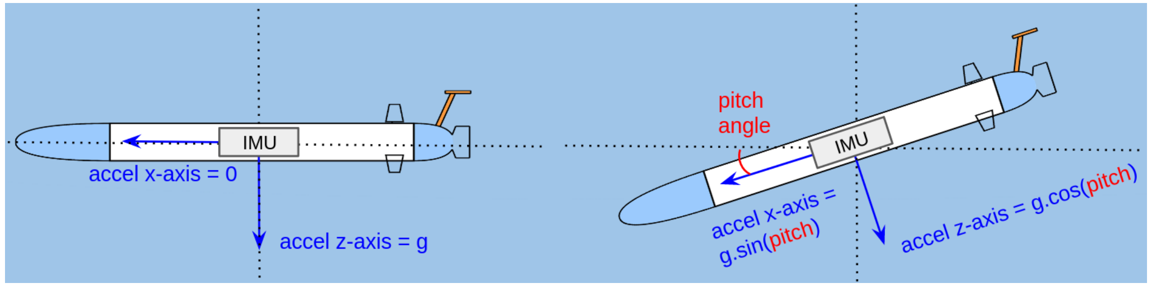
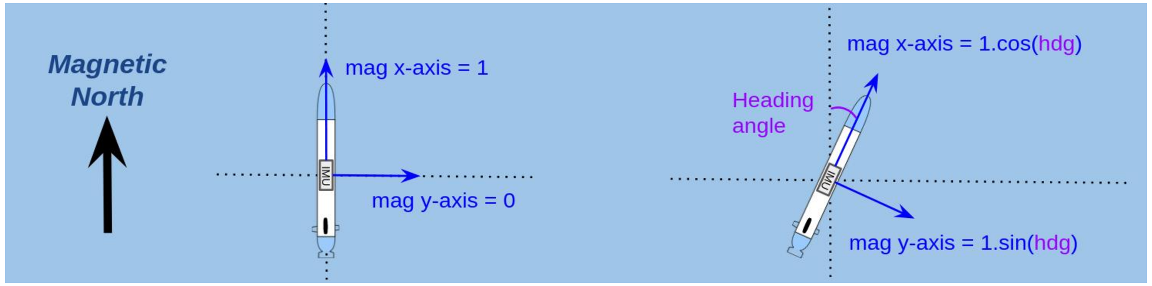


Magnetometers help measure the magnetic heading angle:

- Measures the normalized 3D magnetic intensity.
- If x-axis mag reports 1, while other two are zero, the x-axis is facing north.
- After the measurement, magnetic heading must be converted to true heading.



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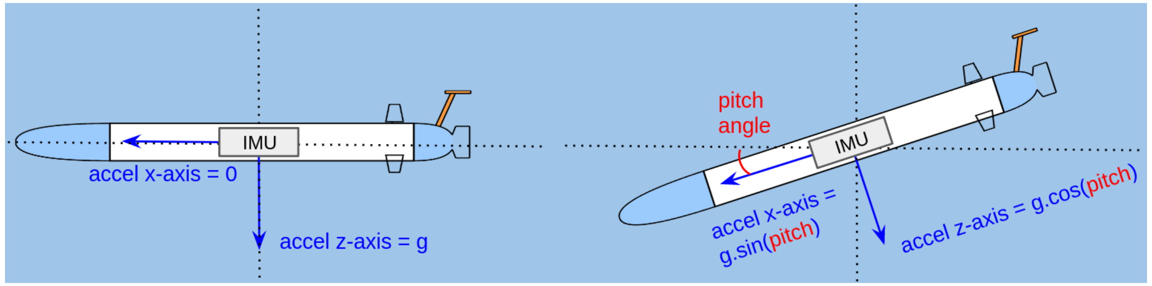

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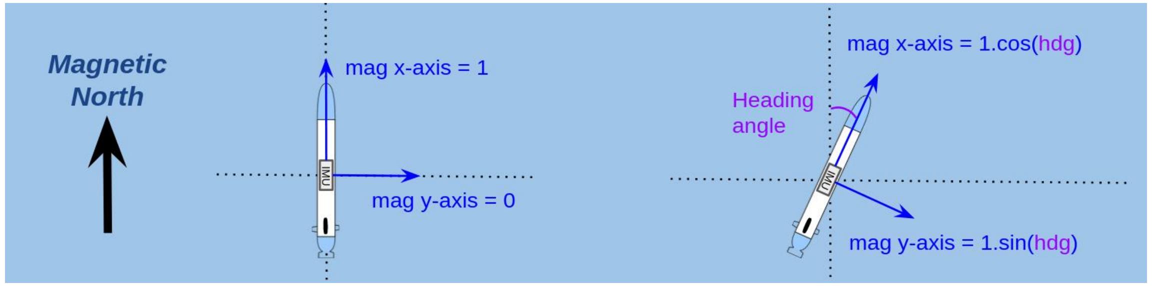
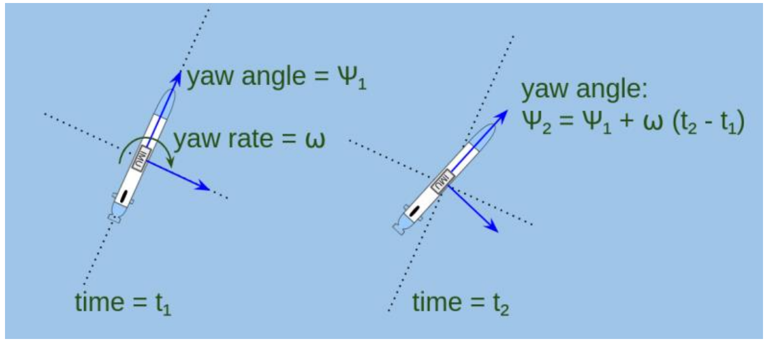


Gyroscopes provide additional angular measurements to be fused with mag and accelerometer outputs:

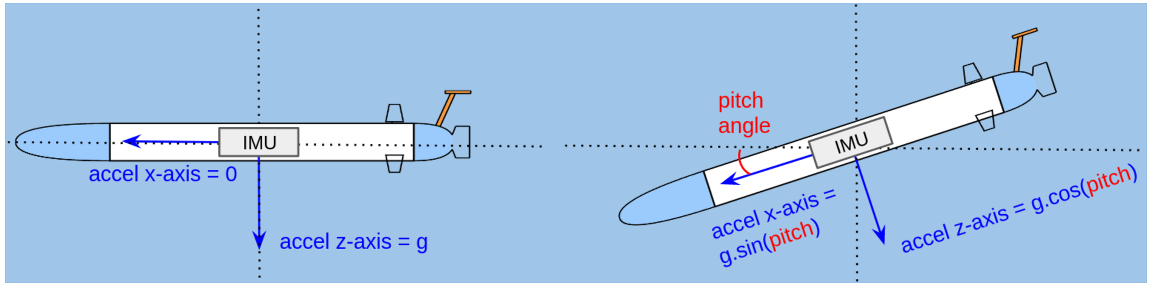
- Measures the 3D angular velocities.
- Continuously integrates the 3D angular velocities over time at a very high rate to compute the current roll, pitch and yaw angles.
- Integration of imperfect measurements can drift the roll, pitch and yaw solutions from the actual value.

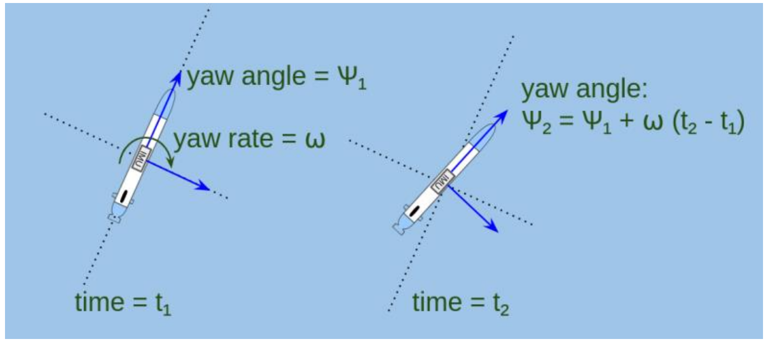


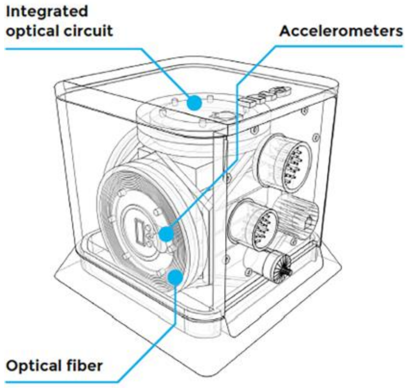
All measurements are fused together using a Kalman Filter to obtain the roll, pitch and heading solution

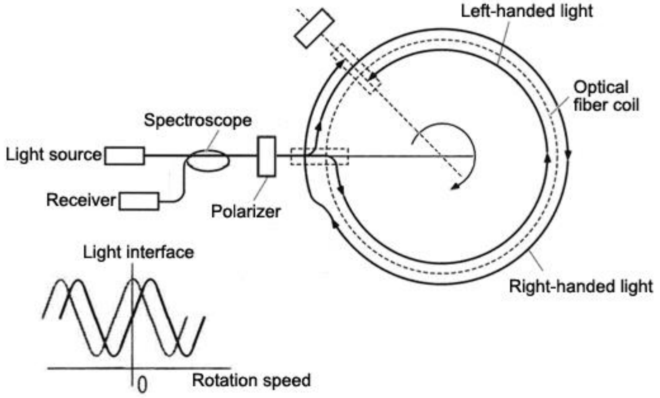
Fiber-optic gyroscopes (FOG)

- FOG IMUs consist of extremely accurate gyroscopes, removing the requirement of magnetometers.
- FOG IMUs are passive systems that use light to calculate motion.
- Rotations movements are measured by sending identical light beams, in opposite directions, through a long fiber-optic coil. The light beam travelling against the direction of rotation experiences a slightly shorter path delay than the other beam. Measuring the phase shift between the two beams reveals changes in orientation.
- FOG IMUs need to be initialized to north in order to obtain north-referenced heading









Doppler velocity log (DVL)

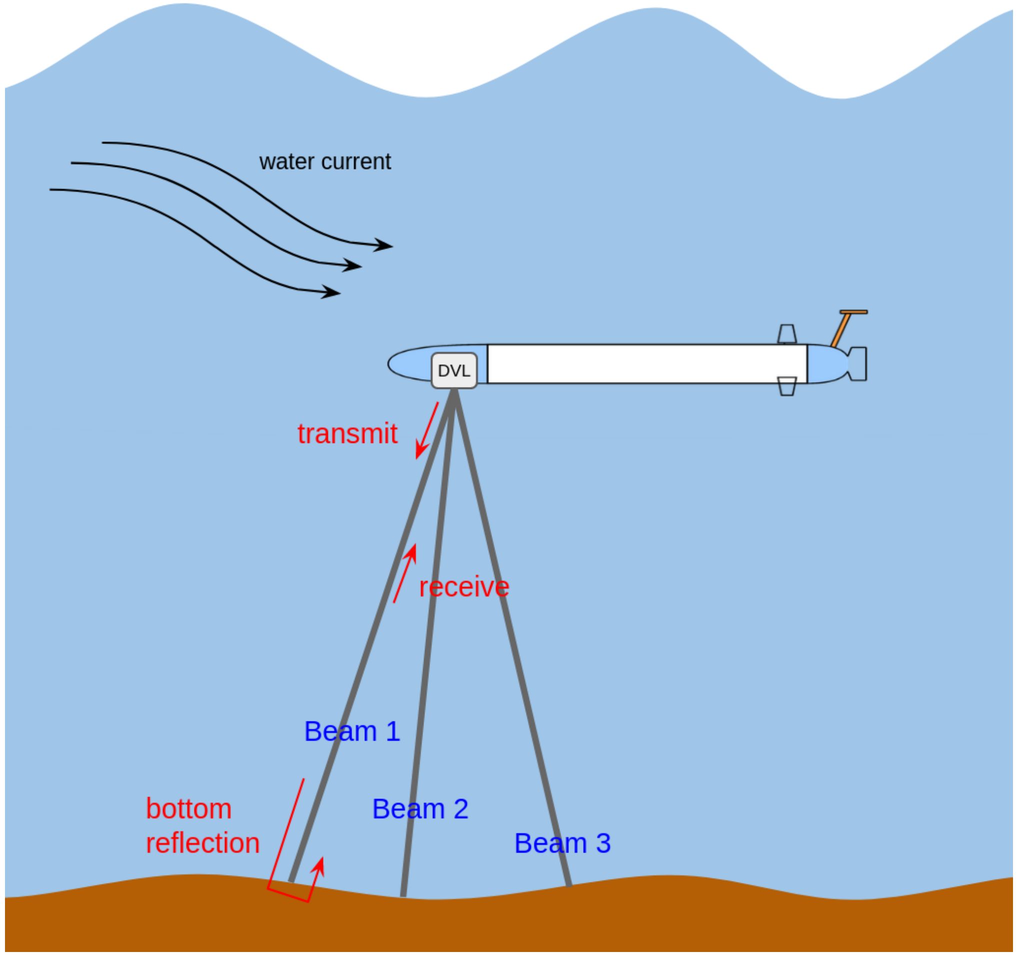
Measures the 3D body-fixed velocity of the AUV:

- Surge velocity
- Sway velocity
- Heave velocity

How does it work:

- Consists of three or more acoustic transducers (beams).
- Each beam transmits an acoustic signal with a given frequency.
- After transmission, the transducer listens for its bottom-bounced reflection.
- Measures the frequency of the received signal.
- If the AUV was moving, there will be a frequency shift between the transmit and receive signals (i.e., Doppler effect).
- The Doppler shift provides the velocity of the vehicle along the beam's axis.
- Since the sensor has 3 or more beams at known angles, we can compute the surge, sway and heave velocities of the vehicle.

DVL bottom-track + FOG IMU can provide a navigation solution with an uncertainty as small as 0.01% of the distance travelled (DT).



A Nortek DVL can be mounted on the nose-cone of SeaBeaver AUV

DVL bottom-track vs. water-track

Maximum acoustic range of a DVL is:

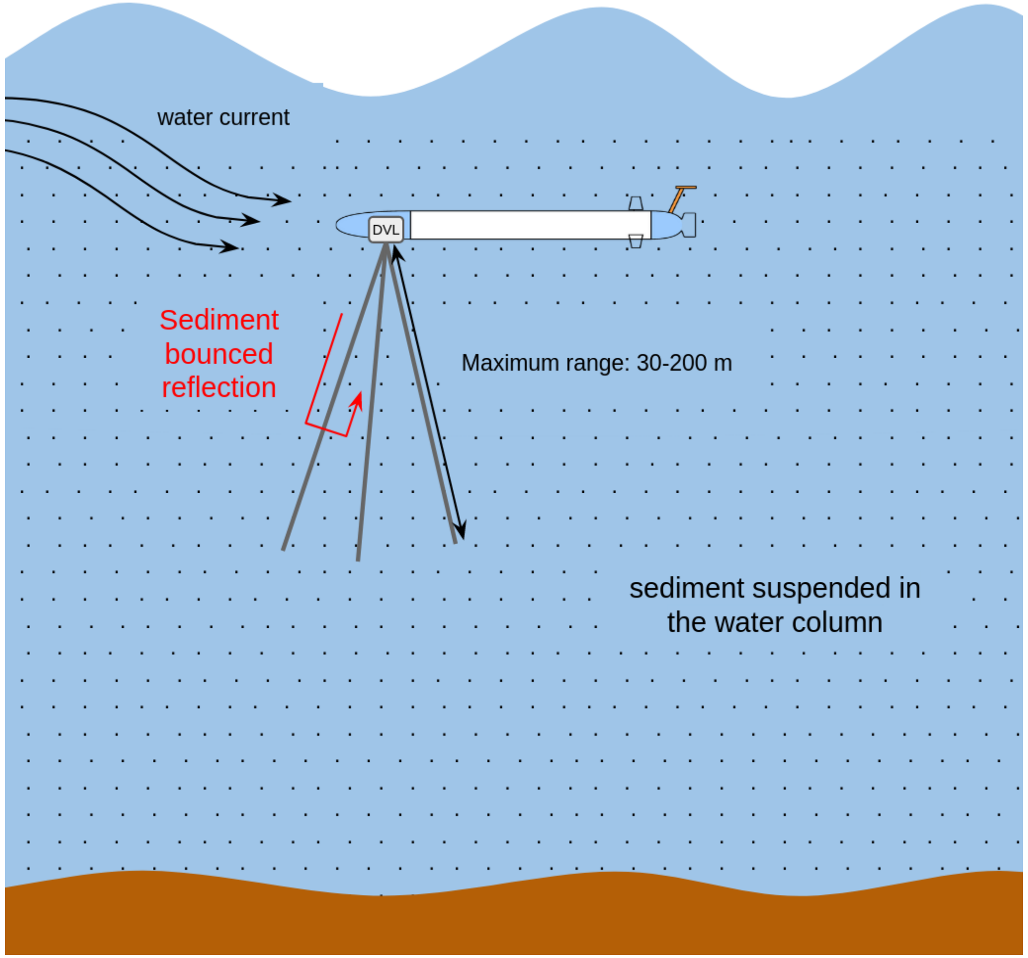
- 30 m for a 1200 kHz sensor
- 200 m for a 300 kHz sensor

If the AUV's altitude is larger than the sensor's maximum range, the DVL bottom-lock is not available.

Some sensors can operate in "water-track" mode:

- Tracks the acoustic reflection off suspended sediments in the water column.
- However, the velocity measurement is relative to sediments.
- If sediments move with water currents, the water-track velocity measurement will be relative to the water.

A navigation solution aided with water-track DVL measurements can drift due to water currents



Vehicle dynamic models

In the simplest case, a vehicle model is the relationship between the AUV's surge speed and propeller speed; e.g.,

$$\textbf{Surge velocity} = A\, n^2 + B\, n$$

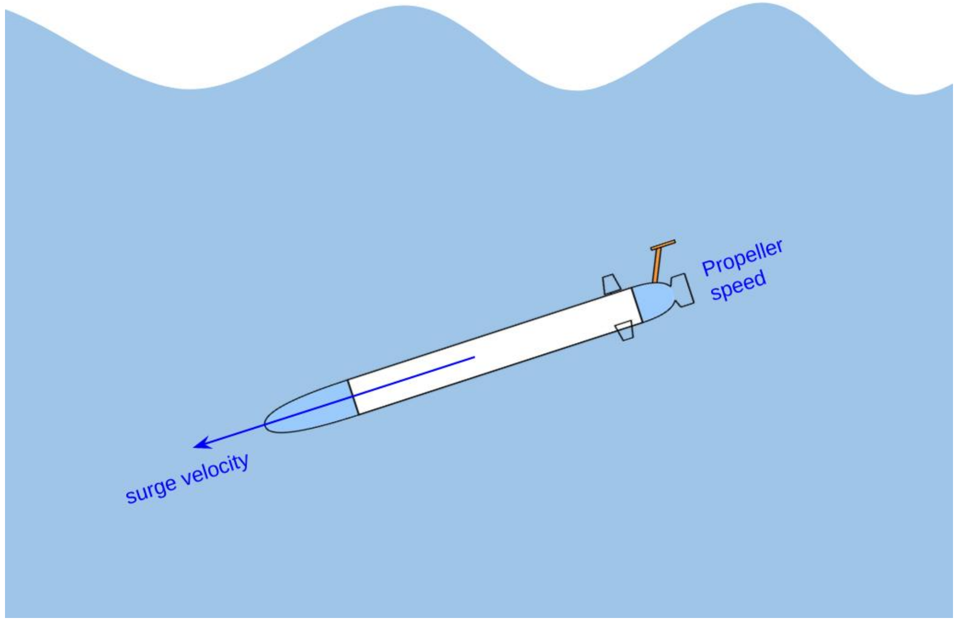
where,

- n is the propeller speed
- A and B are vehicle dependent constant

A and B can be obtained from simulated vehicle dynamics or using past experimental data.

A navigation solution aided with a dynamic model can drift due to two reasons:

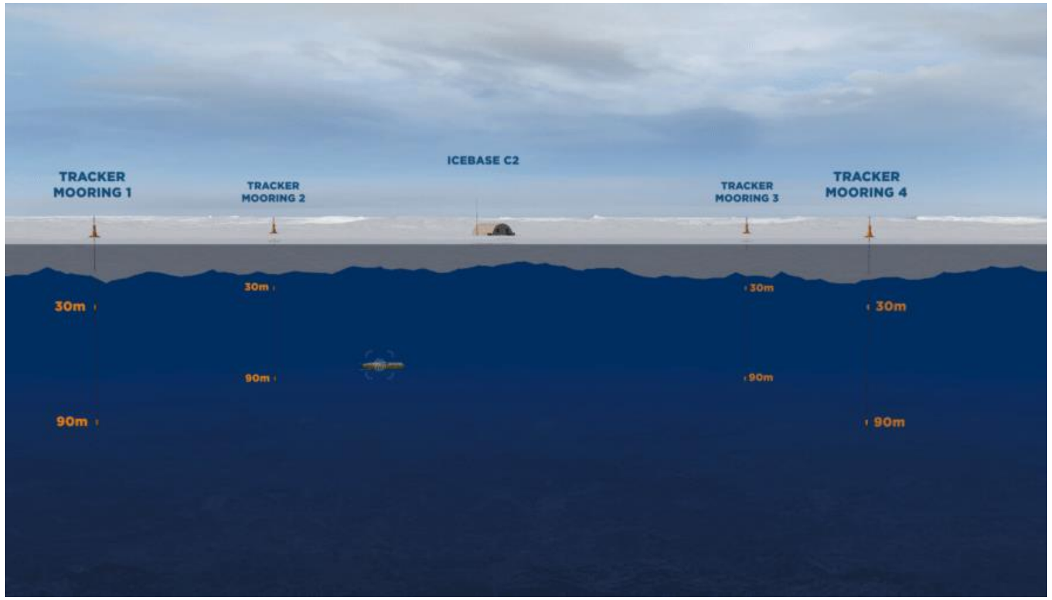
- Uncertainty of the dynamic model
- Unaccounted water currents



Long baseline (LBL) systems and their derivatives

One-way travel time (OWTT) based – Active:

- The vehicle transmits an acoustic signal precisely at a pre-scheduled time slot.
- When acoustic receivers receive the signal, they measure the arrival time to compute the OWTT.
- Using the speed of sound, OWTT is converted to a range.
- Using multiple range measurements, the vehicle position can be trilaterated.
- The trilaterated position is sent back to the AUV via acoustic communication.



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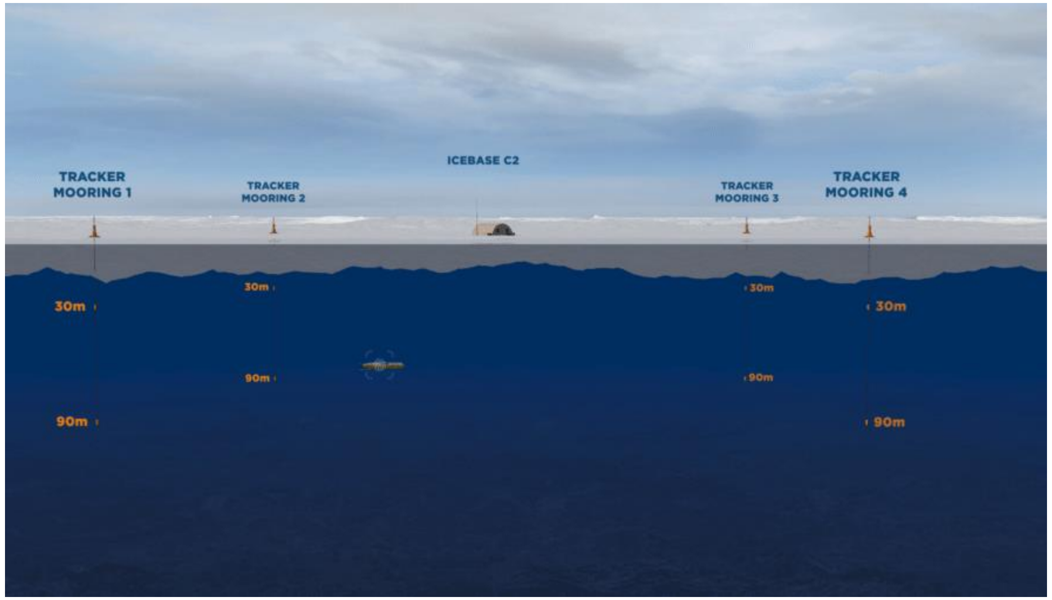
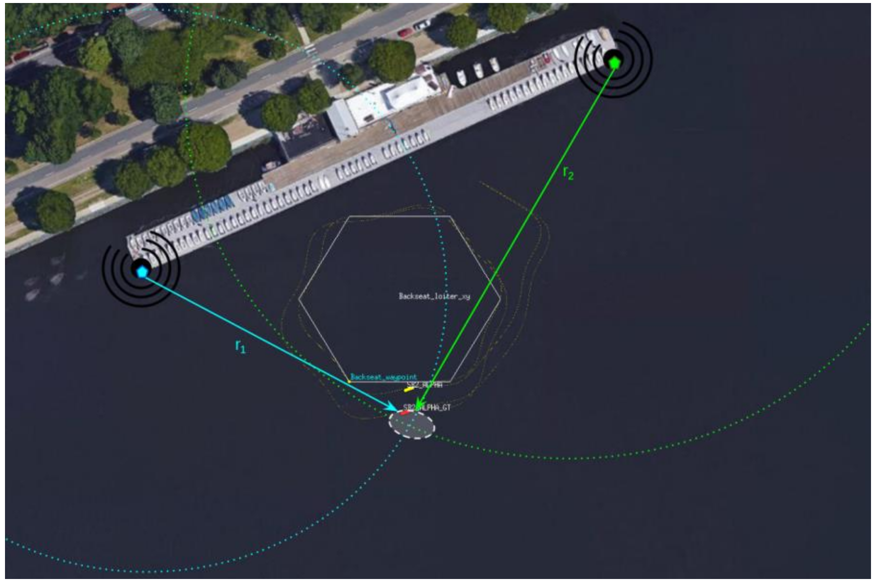


One-way travel time based – Passive:

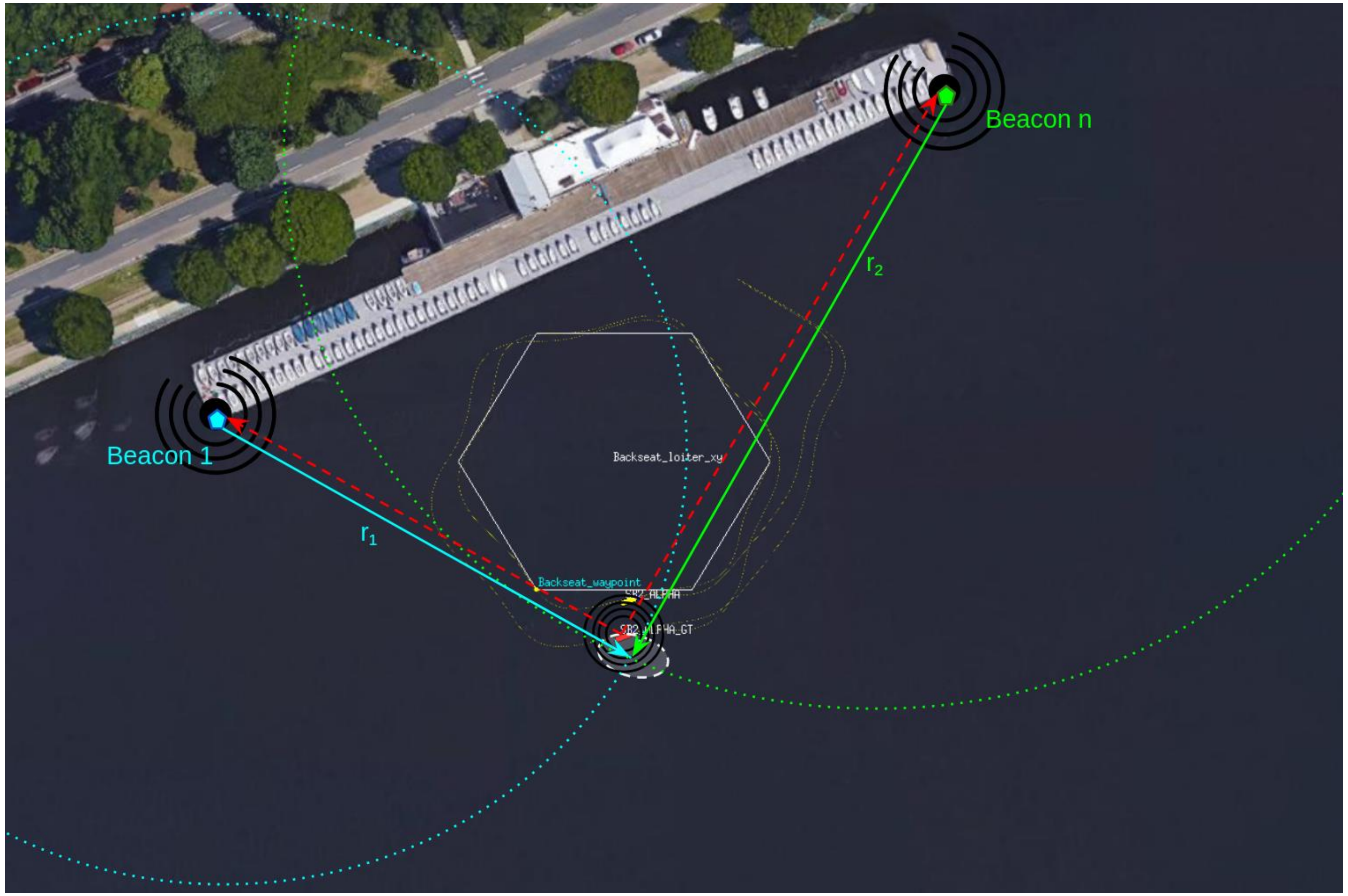
- Two or more acoustic beacons transmit a signal precisely at pre-agreed time slots.
- When the AUV receives these signals, it measures the OWTT.
- Using the speed of sound, OWTT is converted to a range.
- AUV computes sits own position by using these range measurements
- The GPS locations of the beacons should be either:
    - pre-programmed on the AUV, or
    - Included in the acoustic datagram should contain the GPS position



Long baseline (LBL) systems and their derivatives

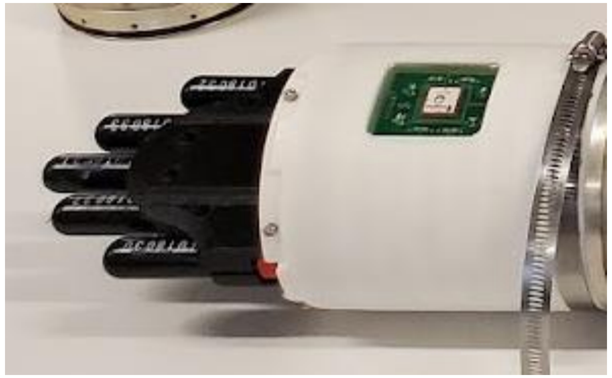
Two-way travel time (TWTT):

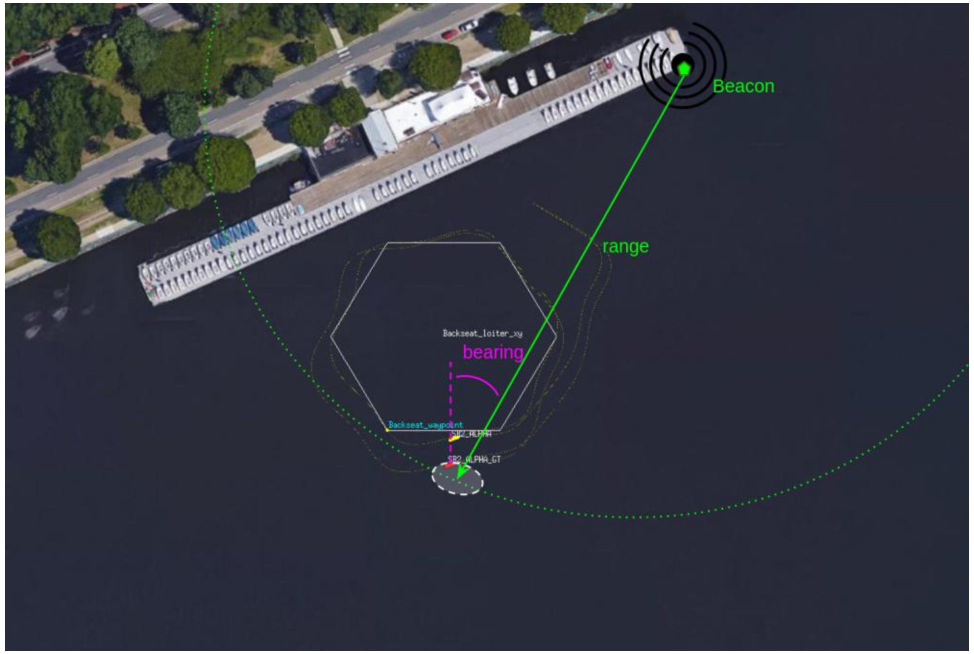
- The vehicle transmits an acoustic message, requesting the beacon(s) to respond.
- The beacon(s) immediately transmits an acknowledgement.
- When the AUV receive the signal, it measures the round-trip travel time.
- Using the speed of sound, TWTT is converted to a range.
- AUV trilaterates its own position by using these range measurements.



Ultra-short baseline (USBL) systems and their derivatives

- An array of precisely placed hydrophones measures the range and bearing to an acoustic beacon:
  - Range – using the travel time (OWTT or TWTT)
  - Bearing – using the phase swift of the signal received by each hydrophone
- Traditional USBL:
  - the AUV contains the acoustic beacon
  - Topside contains the hydrophone array
- Inverted USBL:
  - The AUV contains the hydrophone array
  - Topside contains the acoustic beacon





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