Sensors

Robots require sensors to operate. Their measurements characterise a robot's:

- State: Non-fixed parameters about the robot that are operationally relevant, e.g. location, speed, orientation, remaining battery
- Surroundings: Non-fixed parameters about the robot's enviornment that impact operations, e.g., is the planned path safe to execute?

These notes cover:

- Motivations for using sensors
- Factors that determine performance requirements
- Operating principles of sensors used in maritime robotics and constraints that limit performance

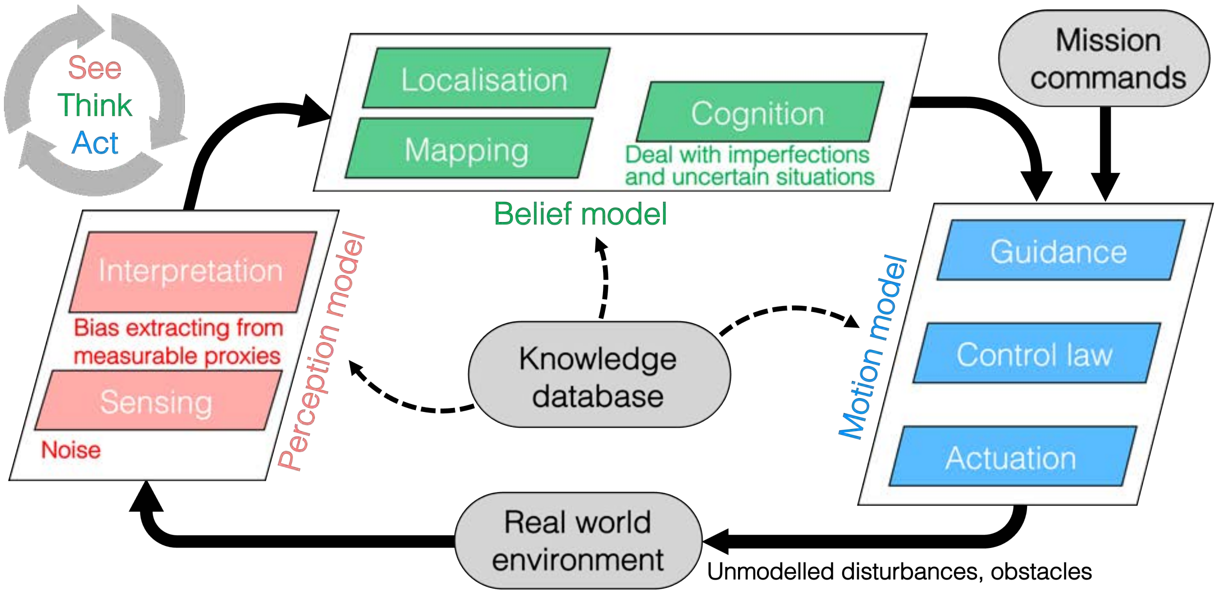
By the end of the notes, you should recognise the range of sensors used by maritime robots and understand that meeting performance requirements typically requires data from multiple sensors to be combined. These notes support [L06 System Navigation: Sensing]. You need to understand the content so that you can effectively processing sensor gathered data later in the module.

Why do we need sensors?

We learnt that robotic competance requires **localisation**, **mapping**, and the **ability to act**. Sensors are needed to achieve these things because the models we use for robot guidance and control are not perfect. In the real-world, a robot's response to actuation deviates from what a control law expects due to imperfect dynamic models and external disturbance. A robot may discover that a planned path is inappropriate if obstacles are discovered along it.

Sensors help us deal with these imperfections. At the same time, sensors are not perfect. Their measurements contain noise, and often require further interpretation to extract relevent information. Extracting relevent information from sensors (i.e., perception) also requires models and these are never perfect.

Fortunately, methods to deal with these imperfections and still make sense of uncertain situations exist, some of which will be covered later in the module. Our focus here, will be on robot self-localisation, where aspects of mapping will be briefly introduced to motivate localisation.



Field robotics acknowledges that dynamic models and sensor measurements sensors are not perfect

Localisation

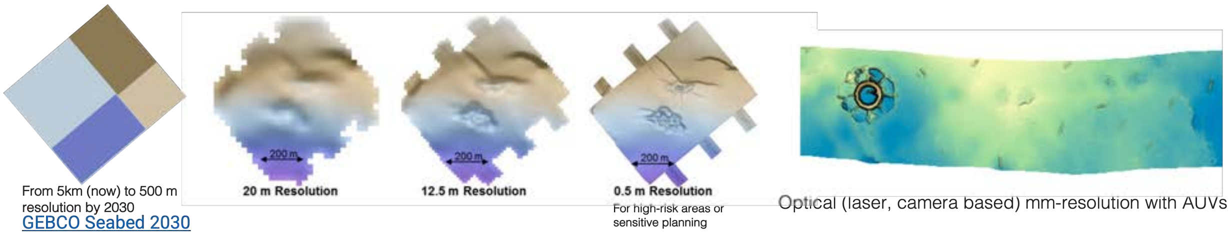
Localisation is a condition for robotic competance that considers:

- Global position, e.g., 50° 56.109'N, 1° 23.757'W
- Relative position **relative to a map**
- Relative position **based on integrated motion**

Performance requirements are task dependent. For example, mapping tasks require global position that allows scenes to be described in a self-consistent way at some desired resolution. Intervention and docking require accurate relative position information.

Drivers for global position accuracy

Below are examples of different mapping resolutions.

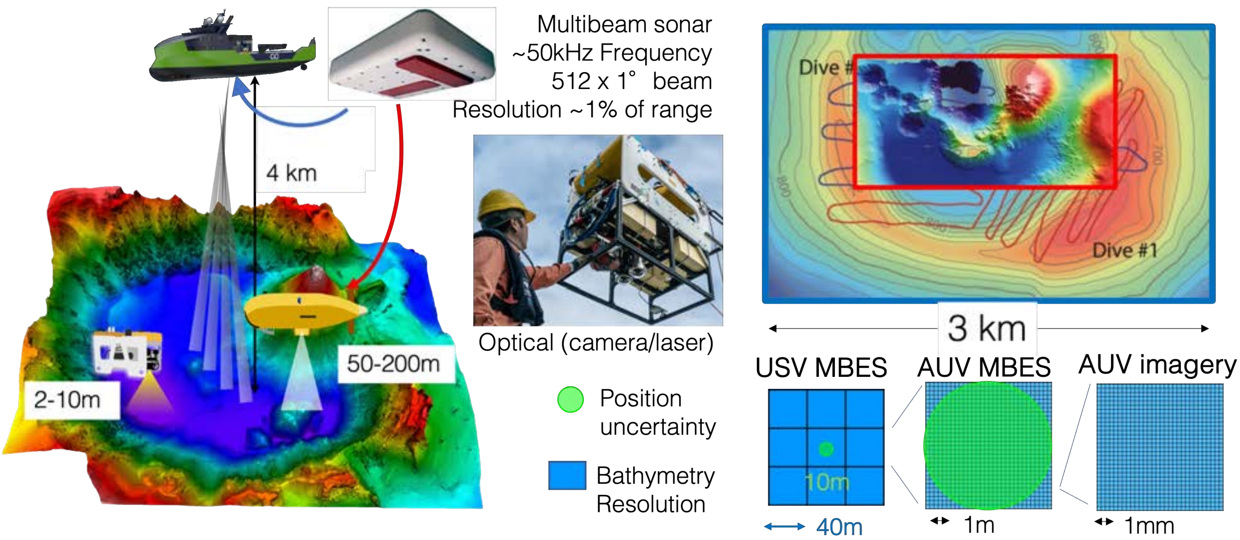


Global positioning accuracy requirements depend on resolution requirements

The entire seafloor has depth estimates at a resolution of 5km, derived from satellite radar measurements of sea surface height from the time-of-flight of an reflected electromagnetic signal the emitt. The sea surface mimics the underwater terrain due to small differences in earth's local gravitational field and this can be used to estimate the profile of the underlying terrain. In this situation, a small error in the position of the mapping measurement is not problematic at such low resolution.

Ships equipped with mapping sensors such as the multibeam echosounder (MBES) can map at a resolution of approximately 1% of range by measuring the time-of-flight of a reflected acoustic signal they emitt along different vector directions in a fan shape perpendicular to their motion. If the seafloor has depth 4000m, we can expect a resolution of 40m. If an MBES is then mounted on an AUV that flies 100m from the seafloor, map resolution would be 1m.

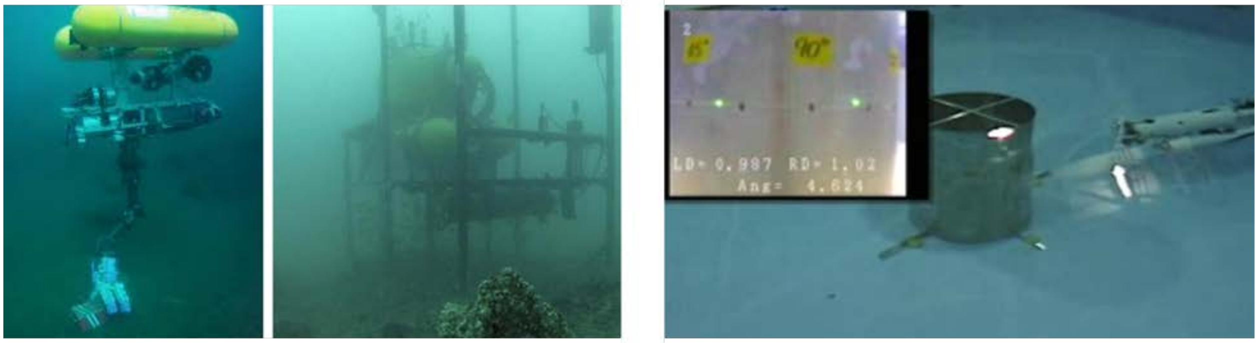
Some AUVs use lasers and offset cameras to triangulate based on geometric constraints to deterine the position of a seafloor observation from a few metres altitude, achieving resolutions of <1mm. To build a self-consistant map, location uncertainty becomes problematic. The following sections will explore these points.



Sensors used for mapping use principles such as time-of-flight of an acoustic beam, or solve geometric relationships to triangulate the position of an observation.

Drivers for relative position accuracy

If a robot needs to observe infrastructure, dock or perform intervention, the global position of the target is not important once it has been located. In such situations it is enough to know the relative position to that target. In such situations, high-resolution acoustic sensors or visual landmarks on the target may be used. Both time of flight and geometric measurements may be made



Relative position accuracy can be more impotrant that global position in many tasks.

Approaches for localisation

There are two sensing approaches:

- Exteroceptive: Solve geometric constraints to identify pose, e.g., stereo vision, GNSS (e.g., GPS), acoustic positioning, radar/laser/acoustic ranging
- Prioprioceptive: Involve differential equations that relate to motion, e.g., intertial sensors, Doppler effects, encoders, pressure

Regardless of the application or the approach, there are basic criteria navigational sensors need to satisfy:

- Sufficient precision and accuracy for the task
- Fast enough compared to the dynamics of the system
- Available when and where operations take place

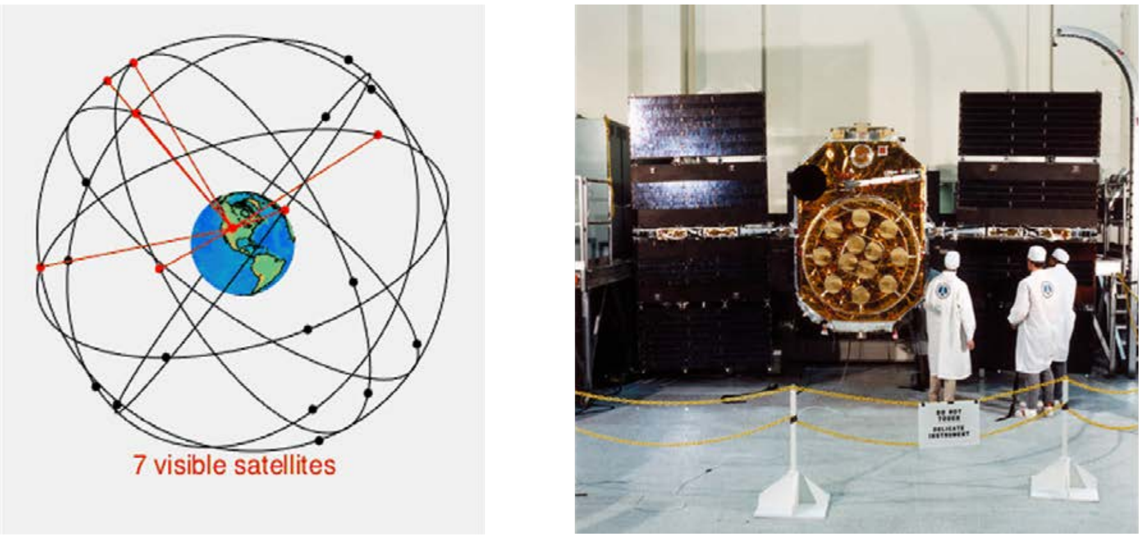
Note that these all depend on the application.

Global Navigation Satellite Systems (GNSS) - for USVs

The Global Positioning System (GPS) is the best known GNSS network. It consists of 24 US government owned, medium earth orbit satellites operated by the US Air Force **since 1995**. They orbit 20,180km above sealevel along 6 planes at 55 degrees inclination from the equator. They travel at 14,000km/h to orbit Earth in 12h and provide 100% cover of earth's surface.

The figure below shows a NAVigation System with Timing And Ranging (NAVSTAR) satellite used for GPS. The important functions of NAVSTAR are:

- 10.23 MHz clocks for accurate time keeping
- Standard positioning system (SPS) with a L1 band (1575.42 MHz) broadcast - accessible to anyone
- Precise positioning system (PPS) with L1 and L2 band (1227.6MHz) broadcast - accessible to US federal agencies US armed forces and allied forces



Left illustrates the GPS constillation and satellites visible to a point receiver on earth's surface. Right is a NAVSTAR satellite prior to 1978 launch. The satellite is 5.3m across, weighing 450kg and it consumes 400W. Images - https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1978-020A

GNSS systems are **exteroceptive** sensors that solve geometric constraints on multiple received satellite ranging signals. The illustration below shows the principle with known ranges from four satellites at known positions intersecting at a receiver's location.

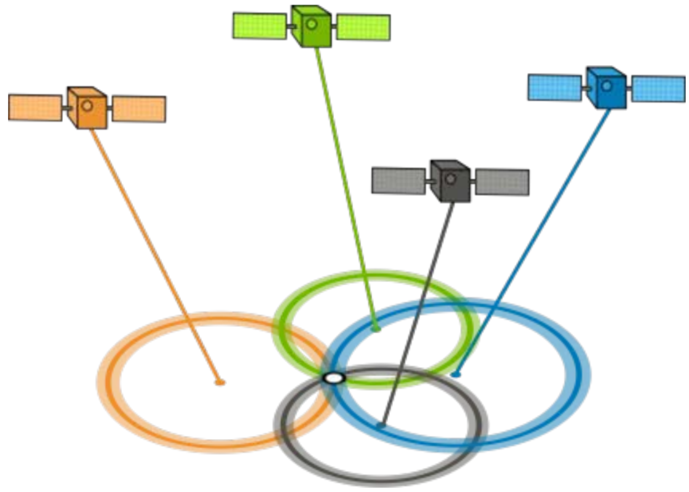


Illustration of GNSS working principle. The circles represent the range between the receiver and each satellite

For the 3d case each satellite, i, broadcasts the following information at $50Hz$

$$[x_i, y_i, z_i, s_i]$$

where x_i, y_i, z_i are each satellite's position and s_i is the satellite's time when it sends the signal. These signals are received at times t_i, and the receivers position can be determined by:

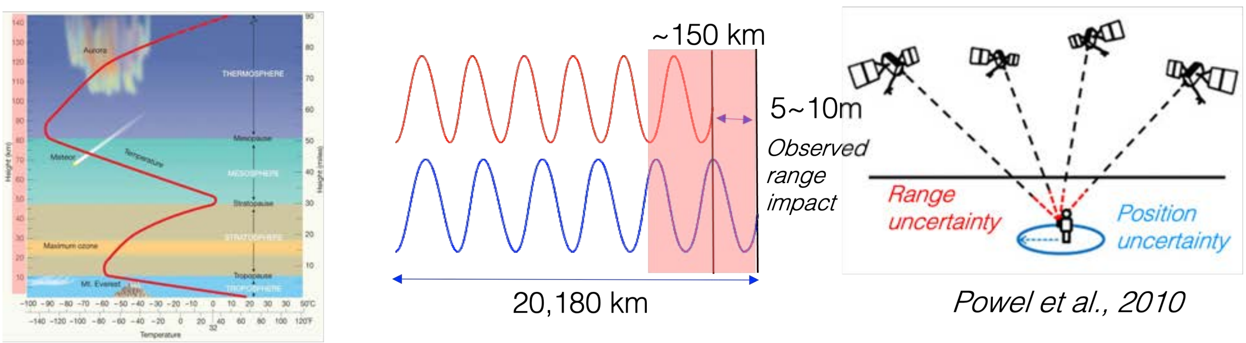
$$(x - x_i)^2 + (y - y_i)^2 (z - z_i)^2 = ([t_i - b - s_i]c)^2, i = 1, 2, \ldots, n$$

This has the form **range = time** $\times$ **speed**, where the signal transit time $[t_i - b - s_i]$ is **time received - receiver bias - satellite sent time** and $c = 3 \times 10^8 m/s$ is the speed of light in a vacuum. The receiver position and time bias $[x, y, z, b]$ can be determined when $n \geq 4$.

The accuracy of GNSS is limited by the environment. The previous equation assumes the speed of light to be constant. This is reasonable as most of the 20,180km distance is a vacuum, but when light travels through media (e.g., the atmosphere), its speed ν varies according to the refractive index, defined by:

$$n = \frac{c}{\nu} \approx 1$$

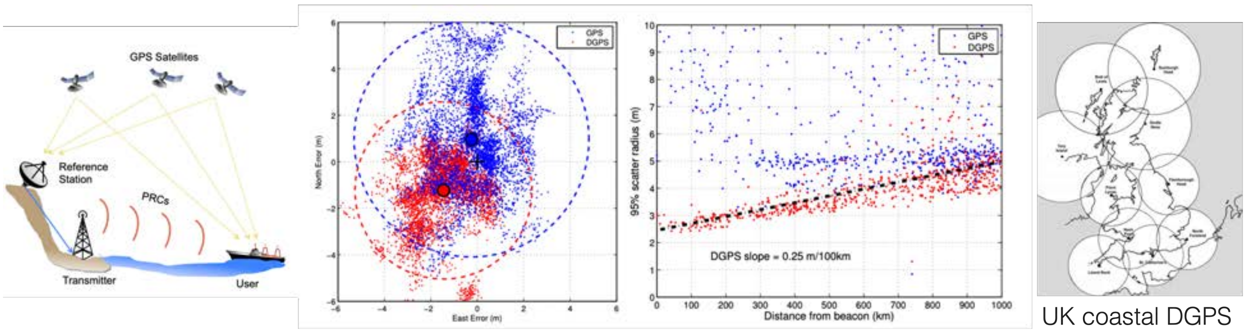
which is not perfectly known. The unknown atmospheric refractive index profile results in a range uncertainty of 5~10m over the 20,180km, which in turn translates to a **standard position uncertainty of ~15m**. Although this is only ~0.00007% of the total range, it is significant for many practical applications (e.g., inspecting infrastructure, staying in lane on a car) and so requires augmentation.



The dynamic nature of the atmosphere makes range calculations uncertain

GNSS uncertainty can be reduced to <3m by using ground-based reference stations. These have precisely known locations, and allow the impact of the atmosphere on range to be estimated for nearby receivers. Limitations are that this approach is only effecting with a few 100km of reference stations (which are on land), and require more complex hardware. However, use of DGPS is recommended for uncrewed operations in ports, and for detailed coastal hydrographic survey.

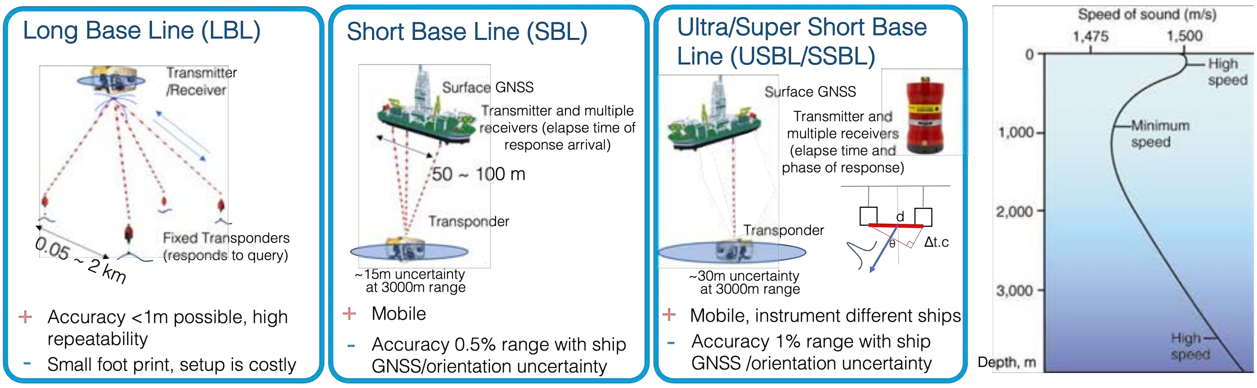
Considering our criteria, we can say that for most applications, GNSS solutions provide position data that is accurate enough (3-15m, when considering ships that can be x10 that size), fast enough (dynamics are slower than 50Hz), and available enough (apart from places that overshadow GNSS receivers, or where precise positioning is needed far out at sea - imagine a drill hole reentry in the deep ocean). Where criteria are unmet, other sensors can be introduced as is common for AUVs



Reference stations with known location can be used to correct for atmospheric effects and improve the accuracy of nearby (within a few 100km reference stations). The figures show the working principle (left), impact on position uncertainty (centre-left), dependency on distance from the reference station (centre-right) and distribution of reference stations in UK waters (right). [Barr, S. “Networked Differential GPS Methods.” (2013)] (!https://digitalcommons.uri.edu/cgi/viewcontent.cgi?article=1022&context=theses).

Acoustic localisation - for AUV/ROVs

Earlier in the module we learnt that electromagnetic waves such as those used by GNSS do not penetrate water. Therefore, acoustic solutions are required, where frequency ranges of 5-30kHz are needed to achieve practical (km-order) range, where lower frequencies provide longer range, but at the cost of resolution. These ranges cannot provide a global positioning solution like GNSS, and instead rely on local support infrastructure. Three common acoustic localisation solutions are illustrated below.



LBL is typically used in developed seafloor sites where submersibles regularly operate. They are expensive to install, but can remain in place for years and provide the most accurate, repeatable positioning solution. SBL and USBL are similar, in that both rely on surface vessel support. SBL systems are now rare, and although they provide more accurate position information than USBL, systems cannot easily be moved between ships. USBL units can be used on ships of opportunity, and the large integration with submersible navigation means AUVs would typically prefer to use their own USBL solution even if the ships they operate on change. The right shows a typical acoustic velocity depth profile, which would ideally by measured prior to use of SBL/USBL systems.

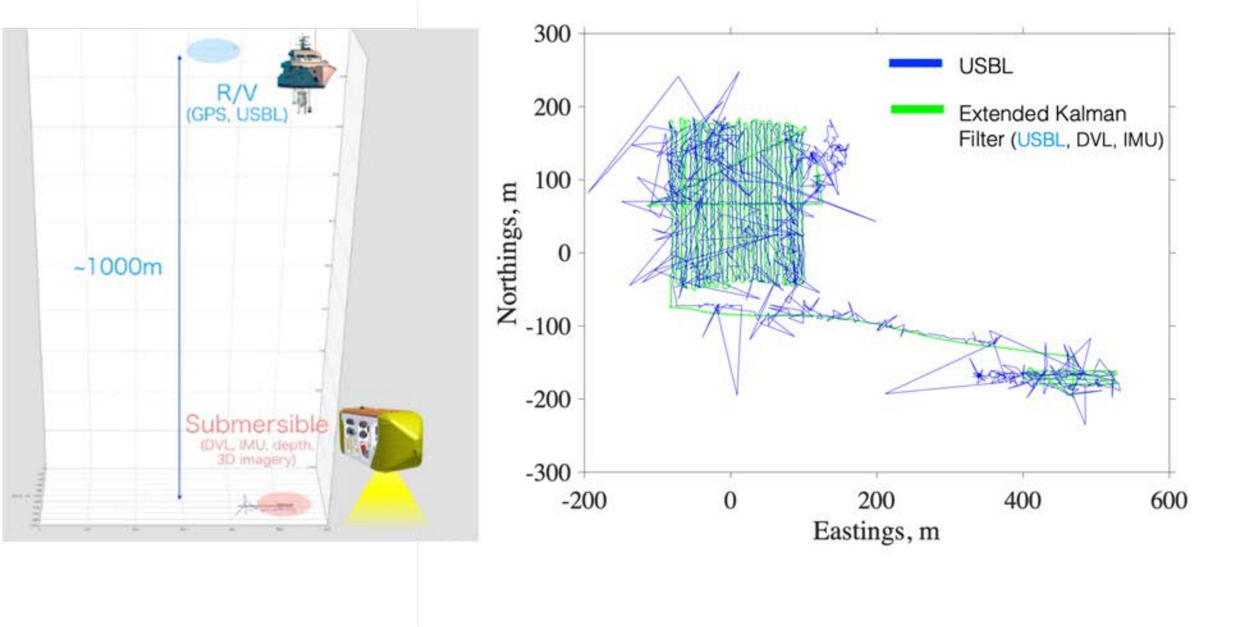
Setups typically use transponders that respond to query signals. Transmitters determine range based on the two-way travel time from when a signal is transmitted to when a corresponding response signal is recieved.

$$4[(x-x_i)^2+(y-y_i)^2(z-z_i)^2] = ([t_i-b-s_i]c)^2, i=1,2,\ldots,n$$

where $c = 1500m/s$ is the speed of sound in water. Limitations of acoustic localisation methods are:

- Large position uncertainty due to variable acoustic velocity profiles in seawater, which are compounded by surface GNSS and attitude uncertainty with large range lever arms for ship based SBL and USBL systems, and also contain noise from surface/seafloor reflections and other sources of sound in the environment.
- Slow update and large lag times due to the relatively slow speed of sound in water compared to measurement ranges (return signals can take several seconds, 4s for 3000m depth return)
- Availability bounded to local infrastructure or ship support

Below is an example of some realworld data showing a high-grade USBL's data when tracking an AUV at 1km depth that illustrates the challenge of using acoustic positioning for real-time control.

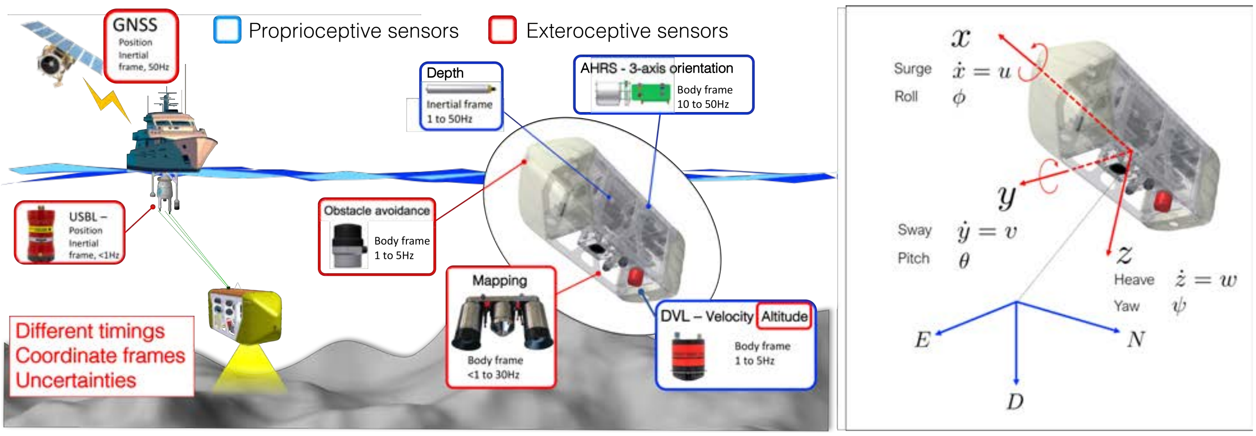


USBL tracking of an AUV surveying the seafloor at 1000m depth.

The limitations above mean that acoustic positioning systems alone are insufficient for realtime self-locatisation needed for AUVs, and this drives the need for multi-sensor integration.

Sensor suites for realtime AUV/ROV localisation

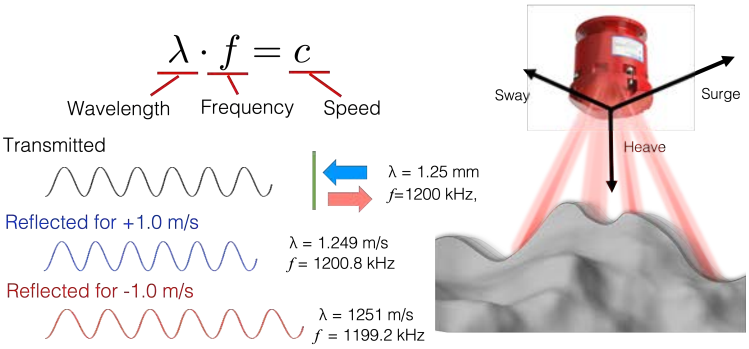
The figure illustrates a typical sensor suite for realtime underwater localisation. Both proprioceptive and exteroceptive sensors are used. Some make measurements in the intertial frame, others in the vehicle frame. They typically have different data acquisition rates. **We deal with these points later in the module**. Here our focus is on their operating principles and the factors that limit their performance.



Realtime underwater localisation requires suites of sensors

Doppler Velocity Log (DVL) - Speed over terrain and altitude

Marine vehicles need to know their speed over ground so that performance is not compromised by currents. The DVL is an acoustic sensor that emits multiple (typical 4) beams of fixed frequency at the seafloor, and measures the shift in frequency of reflections to determine the speed of the moving body. The maximum operating altitude of DVLs varies with frequency (between 0.5 to 200m), which can be determined by the time-of-flight of the emitted signal. The 3-axis velocity can be measured with uncertainties in the mm/s range. As such, any position estimates generated based on DVL velocity measurements increase in uncertainty with time.



	300 kHz	600 kHz	1200 kHz
Std dev at 1m/s	±0.4 cm/s	±0.35 cm/s	±0.3 cm/s
Minimum altitude	1.0 m	0.7 m	0.5 m
Maximum altitude	200 m	90 m	25 m

http://www.teledynemarine.com/workhorse-navigator-doppler-velocity-log

$$x = \int v \,\mathrm{dt}$$

Travel 10km @1.0m/s
→ 30 m error build up in 2h 45min

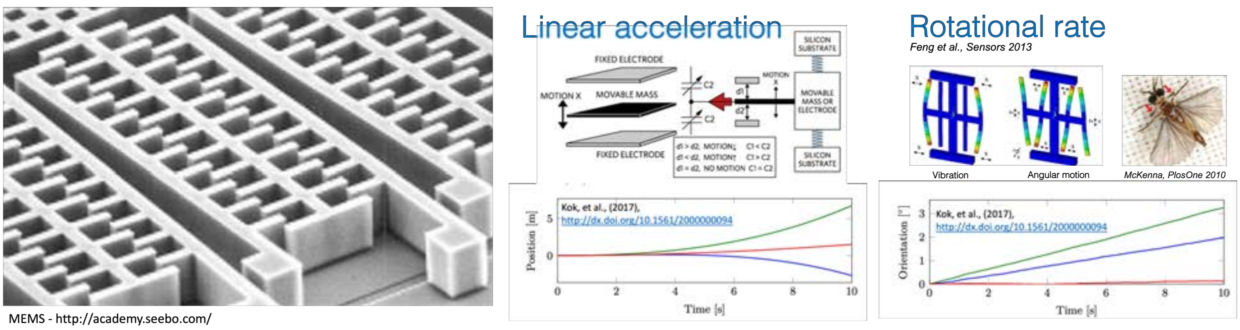
DVLs measure the Doppler shift in frequency of four emitted beams to determine 3-axis velocity relative to a static seafloor

Attitude Heading Reference System (AHRS) - 3 axis orientation

To determine and control position, body frame velocity components need to be converted to the inertial frame prior to integration. AHRS systems determine the roll (x-axis), pitch (y-axis) and yaw (z-axis) orientations to do this by combining information from the following sensors:

- 3 axis accelerometers: Microelectromechanical systems (MEMS) used to measure roll, pitch angles (**inertial frame**)
- 3 axis gyroscopes: MEMS (low-cost) or optical (crazy expensive) gyroscopes to measure roll, pitch and yaw rates (**body frame**)
- 3 axis compass: Either magnetic for magnetic north, or gyro based for true north heading angle (**inertial frame**)

MEMS technology uses capacitance to capture different forms of motion. Acceleration can be captured through movement of a sprung mass with respect to fixed electrodes, rotational rates can be captured through Coriolis effects on vibrating arms that deform. However, their measurements have high uncertainty and so integration of acceleration or rotation to estimate position and orientation directly is not possible, where the figure below shows how static units can register several metres and degrees of motion in just a few seconds.



MEMS technologies use capacitance measurements to capture different types of motion, but high levels of noise mean that integration to estimate velocity, position and orientation result in unacceptably large uncertainties.

Roll and pitch

In robotic applications with small accelerations accelerometers are used to measure the gravity vector to compute roll (comparing x-axis and z-axis) and pitch (comparing y-axis and z-axis), where this involves trigonometry but not integration so does not suffer error build up. The relationship between Euler angles (roll ϕ, pitch θ, yaw ψ) and acceleration due to gravity g is:

$$\begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\psi s\theta s\phi & -c\psi s\phi + s\psi s\phi c\theta \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}$$

Where details of coordinate transformations will be covered in the deadreckoning lectures. Assuming platform accelerations are small compared to $g = 9.81 m/s^2$, after some trigianometry we can compute roll ϕ and pitch θ as:

$$\phi = \arctan \frac{a_y}{a_z}$$

$$\theta = \arctan \frac{-a_x}{\sqrt{a_y^2 + a_z^2}}$$

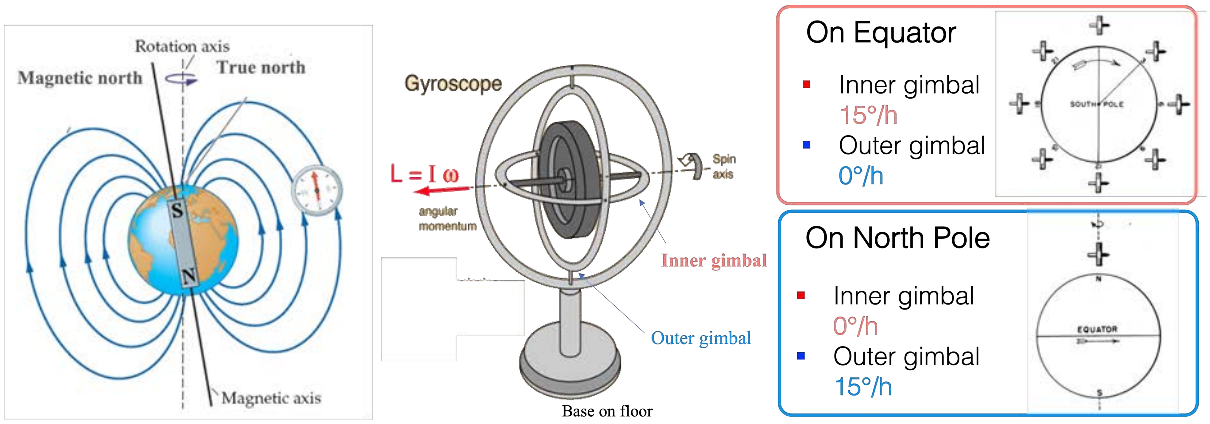
Where measurements down to 0.1^o uncertainty can be achieved with standard MEMS sensors.

Heading

Heading can be measured relative to:

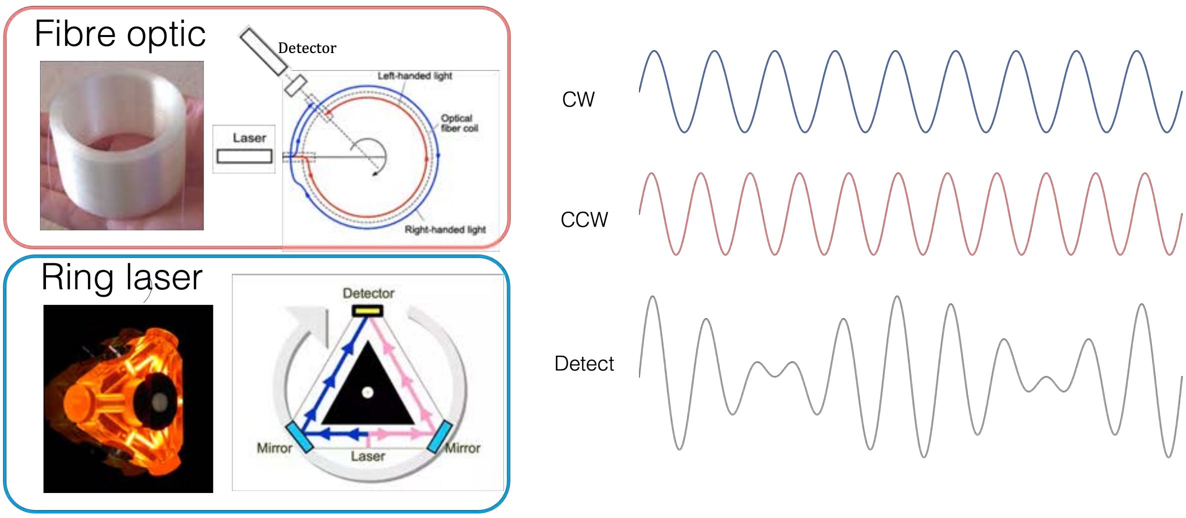
- Magnetic north - using magnetic compasses
- True north (axis of Earth's spin) - using optical gyrocompasses

These are offset by $\sim 5^o$. Magnetic compasses are significantly cheaper, smaller and use less energy than optical gyrocompasses typically used to find true north. However, magnetic north fluxtuates over time, and magnetic compasses are suceptable to local magnetic disturbances, making it less reliable for navigation. True north can be determined by measuring the relative rotation along different gyroscope axes as Earth rotates, provided sufficiently accurate gyroscopes are used and that any local motion can be compensated.



Magnetic and True North. Right shows how double-axis gyroscopes can be used to determine true north, where the same principle can be applied to orthogonally oriented 3-axis gyros.

Optical gyroscopes such as Fibre optic gyros and Ring laser gyros measure the inteference patterns of monochromatic light (i.e., lasers that emit a single narrow wavelength of light), that is split and travels clockwise and anti-clockwise about the measured axis through fibres or using mirrors. Both are capable of extremely accurate rotation rate measurements ($\sim 0.001^o/h$), which in turn allows true north to be measure with small angular drift over time.

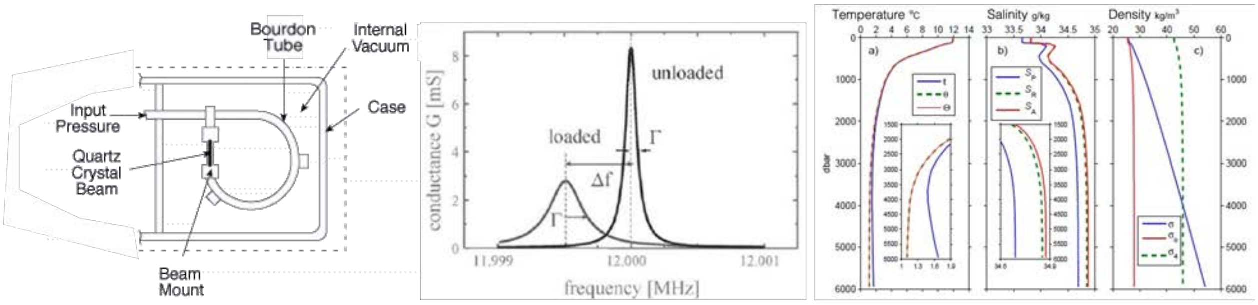


Fibre optic gyros and Ring laser gyros split a coherent beam of light so that it travels clockwise and anticlockwise about a measurement axis. Rotation about that axis causes an interference aptter that can be used to determine rotational rate.

Depth

Depth sensors measure pressure. They do this by determining changes in the resonant frequncy of a quartz crystal as it is externally loaded. High accuracies (typically <0.01% uncertainty of full measurement range) can be achieved as the resonant cycles can be recorded over longer periods to increase resolution and accuracy of pressure measurements.

Pressure can be converted to water depth based on the assumed density of seawater in the water column, where this is typically not precisely known. Uncertainty when converting pressure to water depth results in ~ 0.3 uncertainty in depth (order of metres for every kilometre).



Operation of depth sensors. The resonant frequency of a quartz crystal decreases and this decrease can be measured by counting the number of cycles in a given period. Pressure can be converted to water depth based on the assumed density of seawater.

Summary

The main take homes of these notes are:

- The impact of environmental uncertainty when converting measurable proxies to required states (i.e., perception) is typically larger than direct measurement uncertainty (i.e., sensing).
- Multiple sensors are typically needed to capture required states
- Applications determine how accurately and precisely robots need to know their state

We're done! The next set of notes will cover how we deal with the different sampling frequencies, reference frames and uncertainties of data from multiple sensors.